A Safety Assessment Framework for Automatic Dependent Surveillance Broadcast (ADS-B) and its Potential Impact on Aviation Safety

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Declaration of Originality

I hereby declare that I have personally carried out the entire work described in this thesis. Where sources of information or the work of others have been used, they are fully cited and referenced and/or with appropriate acknowledgement given.

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Copyright Declaration

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Abstract

The limitations of the current civil aviation surveillance systems include a lack of coverage in some areas and low performance in terms of accuracy, integrity, continuity and availability particularly in high density traffic areas including airports, with a negative impact on capacity and safety. Automatic Dependent Surveillance Broadcast (ADS-B) technology has been proposed to address these limitations by enabling improved situational awareness for all stakeholders and enhanced airborne and ground surveillance, resulting in increased safety and capacity. In particular, its scalability and adaptability should facilitate its use in general aviation and in ground vehicles. This should, in principle, provide affordable, effective surveillance of all air and ground traffic, even on airport taxiways and runways, and in airspace where radar is ineffective or unavailable.

The success of the progressive implementation of ADS-B has led to numerous programmes for its introduction in other parts of the World where the operational environment is considerably different from that of Australia. However, a number of critical issues must be addressed in order to benefit from ADS-B, including the development and execution of a safety case that addresses both its introduction into legacy and new systems' operational concepts, the latter including the Single European Sky (SES) / Single European Sky ATM Research (SESAR) and the US' Next Generation Air Transportation System (NexGEN). This requires amongst others, a good understanding of the limitations of existing surveillance systems, ADS-B architecture and system failures and its interfaces to the existing and future ATM systems. Research on ADS-B to date has not addressed in detail the important questions of limitations of existing systems and ADS-B failure modes including their characterisation, modelling and assessment of impact. The latter is particularly important due to the sole dependency of ADS-B on GNSS for information on aircraft state and its reliance on communication technologies such as Mode-S Extended Squitter, VHF Data Link Mode-4 (VDLM4) or Universal Access Transceiver (UAT), to broadcast the surveillance information to ground-based air traffic control (ATC) and other ADS-B equipped aircraft within a specified range, all of which increase complexity and the potential for failures.

This thesis proposes a novel framework for the assessment of the ADS-B system performance to meet the level of safety required for ground and airborne surveillance operations. The framework integrates various methods for ADS-B performance assessment in terms of accuracy, integrity, continuity, availability and latency, and reliability assessment using probabilistic safety assessment methods; customized failure mode identification approach and fault tree analysis. Based on the framework, the thesis develops a failure mode register for ADS-B, identifies and quantifies the impact of a number of potential hazards for the ADS-B. Furthermore, this thesis identifies various anomalies in the onboard GNSS system that feeds aircraft navigation information into the ADS-B system. Finally, the thesis maps the ADS-B data availability and the quantified system performance to the envisioned airborne surveillance application's requirements. The mapping exercise indicates that, the quantified ADS-B accuracy is sufficient for all applications while ADS-B integrity is insufficient to support the most stringent application: Airborne Separation (ASEP). In addition, some of the required performance parameters are unavailable from aircraft certified to DO-260 standard. Therefore, all aircraft must be certified to DO-260B standard to support the applications and perform continuous monitoring, to ensure consistency in the system performance of each aircraft.

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List of Abbreviations

ADS	Automatic Dependent Surveillance
ADS-B	Automatic Dependent Surveillance Broadcast
AMSS	Aeronautical Mobile Satellite Service
ANSP	Air Navigation Service Provider
ASAS	Airborne Separation Assistance System
ASDE	Airport Surface Detection Equipment
ATC	Air Traffic Control
ATCo	Air Traffic Controller
ATM	Air Traffic Management
ATN	Aeronautical Telecommunication Network
ATS	Air Traffic Services
CAA	Civil Aviation Authority
CDTI	Cockpit Display of Traffic Information
CNS	Communication, Navigation and Surveillance
CNS/ATM	Communications Navigation Surveillance / Air Traffic Management
DL	Data Link
DME	Distance Measuring Equipment
EEC	EUROCONTROL Experimental Centre
FAA	Federal Aviation Administration
FIR	Flight Information Region
FIS-B	Flight Information Service Broadcast
FMECA	Failure Mode Effects and Criticality Analysis
FOM	Figure of Merit
FSPN	Fluid Stochastic Petri Nets
FTA	Fault Tree Analysis
GBAS	Ground Based Augmentation System
GBT	Ground Based Transceiver
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HF	High Frequency
HFDL	High Frequency Data Link
HFOM	Horizontal Figure of Merit
HPL	Horizontal Protection Level
IATA	International Air Transportation Association
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Region
ILS	Instrument Landing System
INS	Inertial Navigation System
IRS	Inertial Reference System
ISO	International Organization for Standardization
ITP	In-Trail Procedure
MLAT	Multilateration System

MSSR	Monopulse Secondary Surveillance Radar
NAC	Navigational Accuracy Category
NIC	Navigational Integrity Category
NUC	Navigational Uncertainty Category
OEM	Original Equipment Manufacturer
OSI	Open System Interconnection
PBN	Performance Based Navigation
PSA	Probabilistic Safety Assessment
PSR	Primary Surveillance Radar
QoS	Quality of Services
RAIM	Receiver Autonomous Integrity Monitoring
RCP	Required Communication Performance
RNAV	Area Navigation
RNP	Required Navigation Performance
RSP	Required Surveillance Performance
RTCA	Radio Technical Committee for Aeronautics
SADT	System Analyses and Design Technique
SBAS	Satellite Based Augmentation System
SIL	Source Integrity Level
SIS	Signal In Space
SL	Safety Level
SMR	Surface Movement Radar
SSR	Secondary Surveillance Radar
TDOA	Time Difference of Arrival
TIS-B	Traffic Information Service Broadcast
TSO	Technical Standard Orders
UAT	Universal Access Transceiver
UAV	Unmanned Aerial Vehicle
VDL	VHF Data Link
VFR	Visual Flight Region
VHF	Very High Frequency
VOR	VHF Omnidirectional Radio Range
WAAS	Wide Area Augmentation System
WAM	Wide Area Multilateration
WGS	World Geodetic System

Chapter 1

Introduction

1.1 Background

Air transport is one of the fastest growing means of transportation. This is due to, amongst other factors, increased globalization and the freedom of movement of people and goods within and between regions. A long term traffic forecast conducted by EUROCONTROL (2010b) based on the air traffic in 2009, indicates an average annual increase of 4% in the European airspace till the year 2030. This is corroborated by the International Air Transport Association (IATA, 2010) and Boeing (2010).

The current Communication, Navigation, and Surveillance (CNS) systems that support Air Traffic Management (ATM), and in particular ATC, are at their operational limit (SESAR, 2008) and therefore, cannot accommodate the increasing traffic. This is particularly acute in the provision of the ATC services in low altitude, remote and oceanic areas. Limitations in the current surveillance systems include unavailability of services in oceanic and remote areas, limited services during extreme weather conditions and outdated equipment with limited availability of spare parts to support system operation (ICAO, 2000). These limitations have the potential to result in fatal accidents. For example, the Federal Aviation Administration (FAA) (Esler, 2007) predicts that there is a 13% chance of fatal accidents in a terrain-incursion accident in Alaska due to a limited surveillance service as a result of difficulties in siting radar in the area.

1.1.1 Meeting the demand

In order to meet increasing air travel demand and traffic, airspace capacity must be increased, which in turn depends to a large extent on the ATM/ATC technology and the capability of ATC and associated functions to manage the airspace. One way of increasing airspace capacity is to reduce the required separation minima between aircraft, which demands very high performance (accuracy, integrity, continuity and availability) of the navigation and associated functions of communications and surveillance. This is also conditioned upon three main factors; safety, environment and the airport operation itself. Reducing the separation between aircraft to increase airspace capacity, without considering the constraints will cause an increase in the risk of collision.

In order to overcome the limitations and to meet the future air travel demand, the International Civil Aviation Organization (ICAO) established a special committee on Future Air Navigation Systems (FANS) to develop a plan and programme for future ATM. This introduced the Communication, Navigation, Surveillance and Air Traffic Management (CNS/ATM) concept (Whelan, 2001) as an improved ATM concept. According to Oliveira et al. (2009), the idea of the CNS/ATM concept arose from the existence of Global Navigation Satellite System (GNSS) and Aeronautical Telecommunication Network (ATN). GNSS has the capability to provide the functionality of navigation to aircraft and aircraft positioning information to the ATC, while the ATN enables the exchange of all aeronautical information between various system users in a safe and efficient manner. As a result, a new surveillance technology referred to as Automatic Dependent Surveillance Broadcast (ADS-B) was proposed by the ICAO and is envisioned to fill the gaps in the current surveillance systems. In line with this, the FAA's Next Generation Air Transportation System (NextGen) (FAA, 2010, FAA, 2012) and EUROCONTROL's Single European Sky (SES) and its ATM Research (SESAR) programme (SESAR, 2012) recognize ADS-B as key to the respective goals to modernize the ATM operations and address the limitations in the current surveillance systems.

1.2 Automatic Dependent Surveillance Broadcast (ADS-B)

The Radio Technical Commission for Aeronautics (RTCA) (2002) defines ADS-B as a function on an aircraft or a surface vehicle operating within the surface movement area that periodically broadcasts the aircraft/vehicle state vector and other information without knowing the recipients and without expecting acknowledgements as the system only supports one-way broadcast. The system is automatic in the sense that it does not require external intervention to transmit information. ADS-B is considered to be a dependent and cooperative surveillance system. The former is due to its dependency on aircraft navigation avionics to obtain the surveillance information. ADS-B is a cooperative system, because it requires common equipage for aircraft or vehicles to participate in the system. The ADS-B system has the potential to support surveillance services in the terminal and en-route airspace including remote and oceanic areas. According to Lester and Hansman (2007), ADS-B has the potential to increase capacity, improve efficiency, reduce costs and improve safety with its envisioned high performance. Furthermore, it should enable many new surveillance applications such as synchronized situational awareness (crew-crew, crew-ATC and ATC-ATC). These benefits have the potential to enhance the current operational paradigm of ATM in non-radar and remote areas without jeopardizing the required level of safety. However, the close link between ADS-B and external systems such as GNSS and communication infrastructure increase its complexity with the potential for associated failures. Therefore, to accrue maximum benefit from ADS-B, a number of issues must be addressed before implementation (Boeing, 2009):

- Identification of future operational needs.
- Determination of surveillance requirements and the capability of ADS-B to satisfy them.
- Establishment of ADS-B performance standards.
- Development of the optimum architecture.
- Establishment of ADS-B procedures.
- Development of a roadmap, transition strategy and plan including operational incentives and mandates.

However, safety underlies most of the issues above. ICAO envisages that the ADS-B system should resolve the problems faced in the current surveillance systems. ADS-B is designed to improve safety through enhanced surveillance coverage in non-radar areas, enhanced and common situational awareness to the pilots and controllers on the ground, and conflict detection on runways and taxiways in all visibility conditions. Therefore, ADS-B is critical to the requirement to accommodate increase in air travel demand in the future. However, despite few studies to date, the actual and practical level of safety of ADS-B is still to be analysed in detail and quantified. The issues with the state-of-the art are discussed in detail in Chapter 5.

In addition, research on ADS-B to date (ICAO, 1998c, Butcher, 2002, Vismari, 2005, Vismari, 2008, Vismari, 2011, EUROCONTROL, 2008c, EUROCONTROL, 2010c, Zeitlin, 2001), in particular, has not addressed in detail the important questions of limitations of existing systems and ADS-B failure modes including their characterisation, modelling and assessment of impact. The latter is particularly important due to the sole dependency of ADS-B on GNSS for information on aircraft state and its reliance on communication technologies such as Mode-S Extended Squitter, VHF Data Link Mode-4 (VDLM4) and Universal Access Transceiver (UAT), to broadcast the surveillance information to ground-based air traffic control (ATC) and other ADS-B equipped aircraft within a specified range, all of which increase complexity and the potential for failures.

Therefore, a comprehensive and rigorous safety assessment framework is required for ADS-B system to ensure that the system is acceptably safe to operate in any particular operational environment to support the ATC surveillance and aircraft flight navigation operations.

1.3 Aim and objectives

Given the background above, the aim of this thesis is to quantify the safety level of the ADS-B system in its operational environment particularly in dense airspace by developing a comprehensive, rigorous and reliable safety assessment framework. Six research objectives have been formulated to achieve this aim:

- Identify the deficiencies of current surveillance systems in supporting increasing air traffic;
- Identify the capabilities of ADS-B to address the limitations of the current surveillance systems;
- Develop a comprehensive, rigorous and reliable safety assessment framework for ADS-B;
- Identify the failure modes of the ADS-B system, establish a failure mode register and specify failure models;
- Assess and quantify ADS-B performance in an operational environment; and
- Derive a mapping between ADS-B performance quantified and the required performance of the various applications to be supported by ADS-B.

1.4 Research Methodology

In order to achieve the objectives, a complete step-by-step research methodology is developed (Figure 1-1). The methodology describes the flow of the research, methods used (arrow from bottom), planned inputs (arrow from left), expected outputs (arrow from right) and the constraints (arrow from top) to accomplish each objective. The first part of the research mainly involves literature review supported by limited qualitative analysis to justify the need for ADS-B, including its capabilities. Each step is explained briefly in the following sub-sections.

1.4.1 Deficiencies in the current surveillance systems to meet the future demand

A detailed literature review is conducted on the existing surveillance system in Chapter 2. Based on the review, the limitations of the radar to support ATC in various operational environments are identified and verified by analyzing five years of safety data from Avinor, the Air Navigation Service Provider (ANSP) in Norway (Chapter 4).

1.4.2 Capabilities of ADS-B to close the gaps identified in the current surveillance system

A detailed review of the ADS-B system is conducted in Chapter 3. The inputs are various technical documents from ICAO, RTCA, Original Equipment Manufacturers, and discussions with ANSPs (NATS, EUROCONTROL). Based on the review, the capabilities of ADS-B system are mapped to the limitations in the radar system identified in Chapter 4.

1.4.3 Develop a safety assessment framework for ADS-B

Various existing safety assessment approaches for ADS-B system are reviewed, analyzed and the limitations are identified in Chapter 5. The limitations are addressed in the specification of a comprehensive, rigorous and reliable safety assessment framework developed for the ADS-B system in Chapter 5. The subsequent objectives are addressed using the framework.

1.4.4 Failure modes, failure mode register and failure models for ADS-B

ADS-B is an integrated system, relying on the navigation and communication sub-systems specified in Chapter 3. Hence, each subsystem has the probability to affect the ADS-B data integrity. Therefore, further literature review is conducted on each sub-system to identify possible failures. Furthermore, safety reports on ADS-B from various ANSPs such as Airservices Australia, Federal Aviation Administration (FAA) and NATS are reviewed and analyzed. In addition, analysis of ADS-B data and GNSS data from onboard navigation system analysis in Chapter 6 also contribute to the failure modes. As a result, a failure mode register is developed for ADS-B is Chapter 7. Each identified failure modes is mapped to its corresponding failure model. Finally fault tree analysis (FTA) is used to quantify the risks in Chapter 7.

1.4.5 Assessment and quantification of ADS-B safety level in an operational environment

A novel method is developed in Chapter 6 to assess the ADS-B system performance in terms of accuracy, integrity, continuity, availability and latency. The ADS-B data is obtained from the NATS ADS-B trial; the Cristal Project. Processes and formulae to measure the parameters are developed and explained in Chapter 6 in order to quantify the system performance.

1.4.6 Derive a mapping between ADS-B performance quantified and the required performance of the various applications to be supported by ADS-B

The performance quantification values measured in the previous objective are mapped to the requirements of the enhanced airborne surveillance applications envisioned to use ADS-B as the source for the applications in Chapter 8.

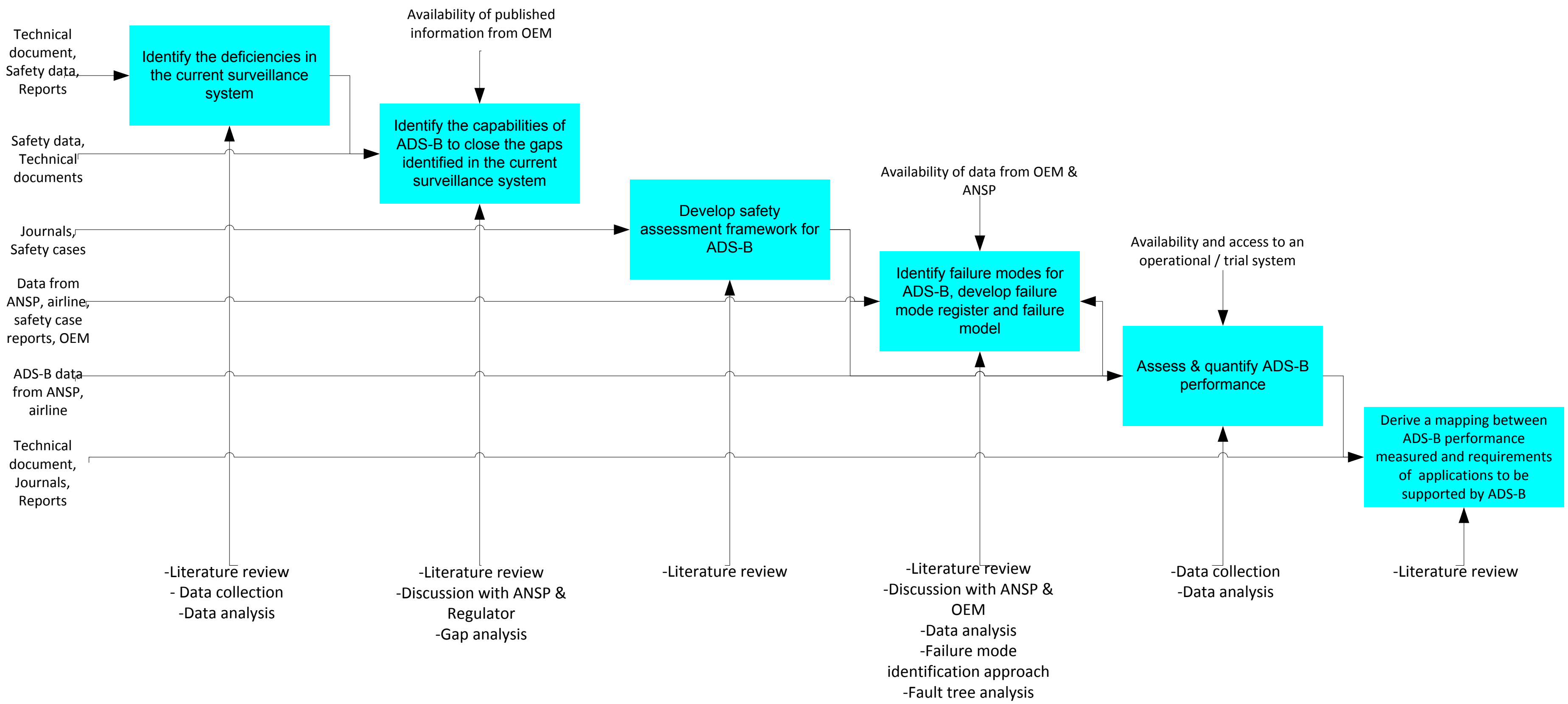


Figure 1-1: Flow of the research, methodology used, planned input, expected output and the constraints to perform the task

1.5 Novel Contributions and Dissemination

In order to achieve the objectives identified in section 1.3, the thesis has realised a set of novel contributions. These are listed below:

I. As a result of identification and verification (safety data analysis) of limitations in the current surveillance system in Chapter 4, the thesis derives a set of taxonomy (causal factors for incidents due to limitations in the current surveillance system). Based on the taxonomy, the thesis further developed a causal model for incident/accident due to limitations in the surveillance system. The taxonomy provides a new method for ANSPs to categorize incidents while the causal model is useful for incident/accident investigations of the relevant nature.

II. The thesis provides in Chapter 4, theoretical justifications for the use of ADS-B to overcome the limitations of the current surveillance system. This is important to realize the areas of improvements to enable seamless ATC services.

III. The thesis develops in Chapter 5, a novel, comprehensive, rigorous and reliable safety assessment framework for ADS-B. The framework is important for implementation by ANSPs in collaboration with airline operators to ensure ADS-B safety. It can also be implemented as part of ADS-B monitoring to ensure ADS-B performance consistency.

IV. The thesis develops in Chapter 6, a novel validation approach for ADS-B horizontal position performance using onboard navigation positioning information. The approach provides a reliable reference with significantly higher performance than the radar system with a constant update rate of one second, accuracy of +/- 6.3 meters and integrity level of 10^{-7}. The approach enables the measurement of absolute errors accumulated in the ADS-B horizontal position beyond the onboard GPS receiver until it is received at the ground station (which includes errors in the avionics such as FMS, interfaces, ADS-B specific components, communication link and ground station) with the assumption that the GPS position is error free (based on the availability of SBAS, GBAS and RAIM integrity monitoring).

V. The thesis further develops a novel correlation method in Chapter 6 to correlate the ADS-B data with the corresponding GPS data. This method is crucial to conduct horizontal position performance assessment particularly in terms of accuracy and latency. The correlation method is complicated by the non-deterministic pattern of the ADS-B data update rate and the differences between the horizontal position values in ADS-B dataset and GPS dataset.

VI. The thesis in Chapter 6 develops a latency model and budgeting for the ADS-B Out system. This is important to improve the ADS-B position accuracy transmitted to the ATC.

VII. The thesis develops in Chapter 6, a mechanism to validate the ADS-B horizontal position integrity quality indicator (FOM/NUC/NIC) against the actual system performance. This mechanism is important to be implemented at the ADS-B ground station to ensure the horizontal position data integrity and hence safety, before being transmitted to ATC for operational use.

VIII. As a result of rigorous ADS-B and the corresponding GPS data analyses in Chapter 7, the thesis identifies various anomalies in both systems that could affect the ADS-B data integrity broadcast to the users. It is important for the airline operators, ANSPs and equipment manufacturer to note and rectify these anomalies to ensure that reliable ADS-B data are transmitted to the users.

IX. Based on extensive search and data analysis, the thesis develops a failure mode register for the ADS-B system in Chapter 7. The failure mode register is a living document, vital for system maintenance, failure observation, investigation and rectification.

X. The thesis identifies and quantifies a number of risks as a result of the failure modes for ADS-B system in Chapter 7. This is important for the formulation and implementation of safety measures against the risks.

XI. Finally, the thesis maps the ADS-B performance quantified in Chapter 6 to the requirements of various established applications to be supported by ADS-B In the future. This gives an overall picture of the system performance to the stakeholders.

Based on the work in this thesis, several papers have been published and some are still in the process of publication.

- Ali, B. S., Majumdar, A., & Ochieng, W.Y. 2011. Technological Evolution - A Paradigm Shift in Future ATC based on ADS-B. 1st International Conference on Application and Theory of Automation in Command and Control Systems (ATACCS). Barcelona, Spain, May 26-27 2011.

- Ali, B. S., Schuster, W., Ochieng, W. Y. & Majumdar, A. 2013. A Study of ADS-B Data Evaluation and Related Problems. 2013 International Technical Meeting, Institute of Navigation. San Diego, Calfornia, USA.

- Ali, B. S., Majumdar, A., Ochieng, W. Y. & Schuster, W. 2013. ADS-B: The Case for London Terminal Manoeuvring Area (LTMA). Tenth USA/Europe Air Traffic Management Research and Development Seminar (ATM2013). Chicago, USA.

- Ali, B. S., Schuster, W., Ochieng, W. Y. & Majumdar, A. 2013. Framework for ADS-B Performance Assessment: the London TMA Case Study. Journal of Institute of Navigation (Resubmitted following review).

- Ali, B. S., Majumdar, A., Ochieng, W. Y. & Schuster, W. 2013. ADS-B System Failure Modes and Models. Journal of Navigation (Resubmitted following review).

- Ali, B. S., Majumdar, A., Ochieng, W. Y. & Schuster, W. 2013. A safety assessment framework for the Automatic Dependent Surveillance Broadcast (ADS-B) system. Reliability Engineering & System Safety (In-press).

1.6 Thesis structure

This thesis is organized into nine chapters according to the research objectives. Each chapter is divided into subsections, starting with a brief introduction and ending with a summary.

Chapter Two: Communication, Navigation and Surveillance Air Traffic Management (CNS/ATM)

This chapter describes the role of Communication, Navigation and Surveillance systems to support Air Traffic Management (ATM), highlighting various current surveillance technologies, and analysing the advantages and disadvantages of each technology to accommodate the increasing air traffic by reducing the separation between aircraft.

Chapter Three: Automatic Dependent Surveillance Broadcast (ADS-B)

This chapter introduces a new surveillance technology: Automatic Dependent Surveillance Broadcast (ADS-B), including requirements (operational and system) and architecture (functional and physical). It also reviews the system implementation progress worldwide.

Chapter Four: Limitations of the current surveillance systems and the potential of ADS-B

This chapter identifies and analyses the limitations in the current surveillance systems (identified in Chapter Two) using safety data analysis, develops a taxonomy (causal factors) and a causal model for incidents/accidents due to the limitations, and finally maps the causal factors derived to the capabilities of ADS-B (identified in Chapter Three) to close the gaps.

Chapter Five: Safety Assessment Framework for ADS-B

This chapter reviews existing ADS-B safety assessment approaches and safety cases by various ANSPs. Due to the limitations identified in the existing approaches, a novel, comprehensive, rigorous and reliable safety assessment framework is developed to assess and quantify ADS-B performance. The framework is used to underpin the work in the next two chapters.

Chapter Six: Performance Based Safety Assessment (PBSA)

This chapter presents the methods and algorithms developed to compute each performance parameters (accuracy, integrity, continuity, availability, latency) using real time data, and identifies the potential factors that affect the performances, and anomalies in the data with the potential to cause failure and significantly affect performance results.

Chapter Seven: Fault Based Safety Assessment (FBSA)

This chapter develops a method to identify failure modes for ADS-B, identifies the failure modes, categorizes the failures into classes, specifies a model for each class and finally quantifies the risks to the hazards identified as the result of the failures using Fault Tree Analysis (FTA).

Chapter Eight: ADS-B as the source for Enhanced Surveillance Application

In this chapter real data performance quantified in Chapter Six is used to validate ADS-B as the source for the various enhanced surveillance applications by mapping the performance to the application requirements. The output of the mapping is discussed.

Chapter Nine: Conclusion and Recommendations

This chapter presents the conclusion of the research, recommendations and suggestions for the future work.

Chapter 2

Communication, Navigation and Surveillance Air Traffic Management (CNS/ATM)

This Chapter introduces the concept of Communication, Navigation and Surveillance Air Traffic Management (CNS/ATM) and contributes to the achievement of the first research objective; 'to identify the limitation in the current surveillance systems' in several ways. Firstly it highlights the role of the CNS systems in ATM. Air Traffic Management is achieved through the collaborative and integration of humans, information, technology, facilities and services, and supported by CNS capabilities that are dependent on each other (ICAO, 2006c). Secondly, it discusses in detail the need for surveillance systems of Air Traffic Control (ATC) operations. Thirdly the Chapter sets the scene for the analysis of the limitations in the current surveillance systems, for further analysis in Chapters 3 and 4. The Chapter also discusses the separation management concept and the constraints to reducing the separation between aircraft. Finally the Chapter concludes with discussions on the role of new surveillance technologies in meeting the increasing demand for air travel and hence traffic.

2.1 Background

Conventional air navigation systems such as radars, Instrument Landing System (ILS), VHF Omnidirectional Radio Range/Distance Measuring Equipment (VOR/DME), used for airspace surveillance, navigation and communication are ground-based systems. However, these systems suffer from a number of drawbacks including accuracy limits, range and line-of-sight limitations, are site-critical, its requirement for many installations and considerable expense required for acquisition and maintenance. While significant advances have been made in hardware and software, the technology principle employed is typically more than 40 years old. Furthermore these systems are unable to evolve to meet increasing traffic demands around airports, and are difficult to implement over large parts of the earth for example, because of remoteness and inhospitable terrain.

In 1983, the International Civil Aviation Organization (ICAO) gave the task of studying, identifying and assessing new concepts and technologies in the field of air navigation, including satellite technology, to a special committee. The Future Air Navigation Systems (FANS) Committee, gathered together aviation specialists from around the world. In such a global forum, these specialists developed the blueprint for the system that would meet the needs of the aviation community well into the next millennium (ICAO, 1998a). The FANS concept, which came to be known as the Communication, Navigation and Surveillance/Air Traffic Management (CNS/ATM) system, involves a complex and interrelated set of technologies, largely dependent on satellites, in order to overcome certain limitations of the existing systems.

By adopting an approach whereby satellites would play a major role in the communications, navigation and surveillance, the FANS Committee determined that States could substantially increase signal coverage over large parts of the earth with fewer infrastructures.

ICAO in 1992 endorsed CNS/ATM as the sole Air Navigation Services (ANS) system for global application (ICAO, 1998b).

2.2 Communication, Navigation and Surveillance /Air Traffic Management (CNS/ATM)

ICAO defined CNS/ATM as "Communication, Navigation and Surveillance systems, employing digital technologies, including satellite systems together with various levels of automation, applied in support of a seamless global air traffic management system" (ICAO, 2000). The aim of CNS/ATM is to develop a comprehensive and unified system to support the provision of Air Traffic Services (ATS) to meet growth in air travel demand with associated improvements in safety, efficiency and regularity of air traffic, providing the desired routes to the airspace users, and homogenizing the use of equipment in different regions. CNS/ATM is underpinned by a high level of automation which reduces the dependency on the human and eliminates the current constraints to optimise the airspace (refer section 2.7.2). The distinct features of CNS/ATM are (ICAO, 2000):

- Mix of satellite and ground-based systems; which enable internetworking for data transfer of communication, navigation and surveillance systems from technical sites to operational units to provide complete situational awareness to controllers and pilots;
- Global coverage; which enables complete ATC services despite the geographical structure obstacles;
- Seamless; whereby continuous and reliable services are available without fail to ensure safety;
- Interoperable systems; whereby the system is designed as redundant architecture to provide uninterrupted services;
- Use of air-ground data link; which enables synchronised situational awareness to controllers and pilots;

- Use of digital technologies; to mitigate the limitations of analogue technologies such as noise interruption and adapt to new digital application systems;
- Various level of automation; whereby more computer applications are used to aid controllers and pilots to perform the various job functions.

Figure 2-1 depicts the paradigm shift in ATM technologies, from the current CNS systems to the new CNS/ATM systems that are a mix of satellite technology and the best of the line-of-sight systems. The new technologies have the potential to support advanced ATM applications such as Cockpit Display of Traffic Information (CDTI) (ICAO, 2003a) that provides situational awareness to pilots and In-Trail Procedure (ITP) (EUROCONTROL, 2009a) to give the aircraft more flexibility for efficient navigation especially in oceanic en-route areas. This in return, benefits the airlines in terms of fuel consumption and most importantly reduces the environmental effects (Federal Aviation Administration, 2012). Detailed descriptions of the new supported applications are given in Chapter 8.

ICAO has developed a Global CNS/ATM Plan (ICAO, 2002a). Contracting states are to develop and implement a National CNS/ATM Plan (ICAO, 2000) based on the ICAO Global Plan. For a period, current technology systems will co-exist with CNS/ATM system until the transition to CNS/ATM is complete, an event planned for 2015. The main elements of CNS/ATM are addressed in the following sub-chapters.

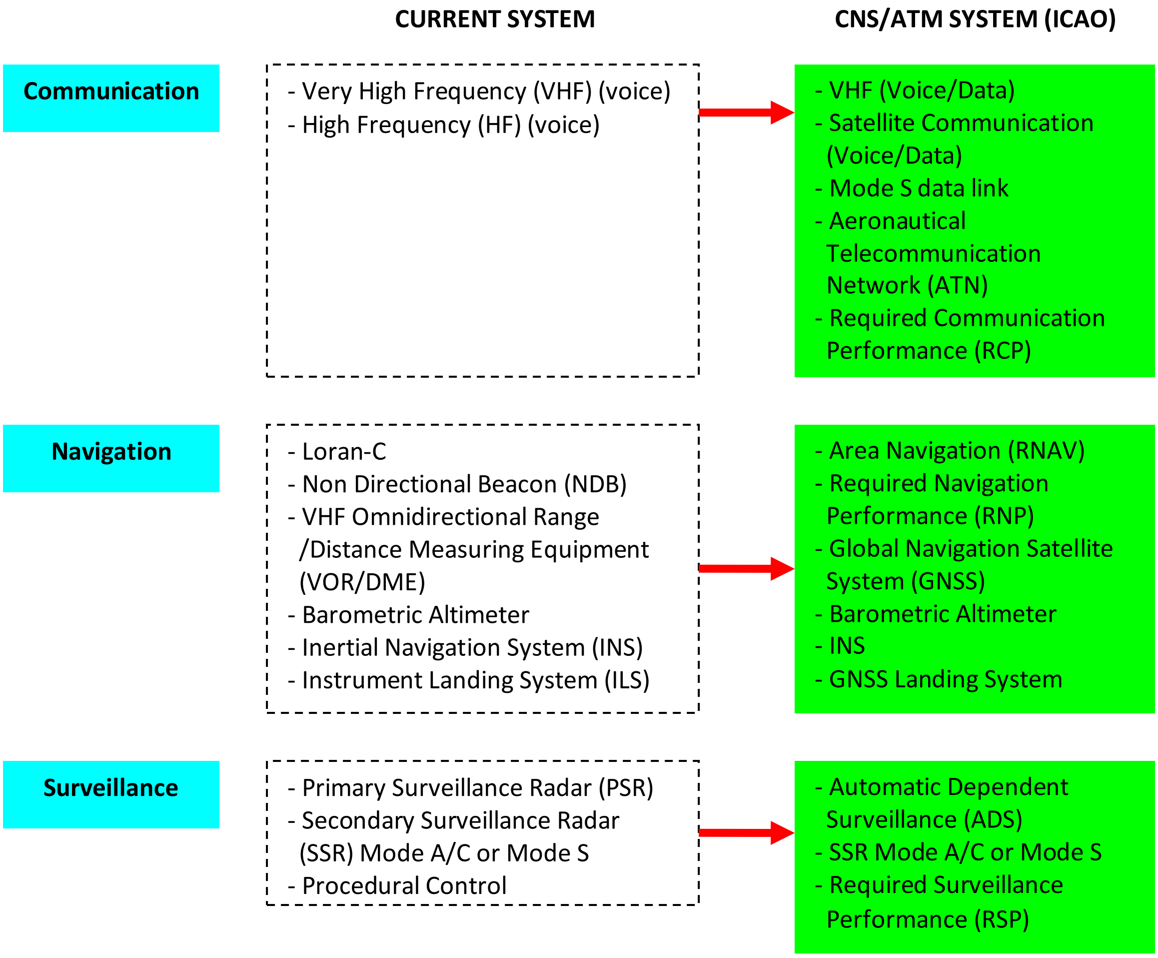


Figure 2-1: Paradigm shift in ATM technologies (modified from (Vismari, 2005))

2.2.1 Communication

People and systems on the ground must communicate with aircraft during all phases of flight. Good communications with timely and dependable availability are the cornerstone of operational safety and efficiency. Currently communication is primarily by means of voice. However, such analogue transmissions suffer from a number of shortcomings: they do not permit high rates of transmission of data and take up a great deal of valuable and diminishing frequency spectrum. This limits automation of routine functions and consequently the decision making process for both the pilots and controllers.

In CNS/ATM systems, communications will increasingly be carried out using digital data links as these allow a high rate of data transfer, high reliability and integrity, improved frequency spectrum utilization and crucially, better interfacing with automated systems. There are two types of communication systems in place; air-ground communication and ground-ground communication.

The current air-ground communication system relies on Very High Frequency (VHF) , High Frequency (HF) and Ultra-High Frequency (UHF) analog data links (Radio Frequency) for en-route and terminal areas; and Aeronautical Mobile Satellite Service (AMSS) for oceanic and remote continental airspace (ICAO, 2000), while the ground-ground communication relies on VHF data link. According to (Hansman, 1997), the current flight procedures and route structures have been developed and named based on the voice communication capabilities over low bandwidth VHF and HF links, resulting in limited coverage. Figure 2-1 shows the evolution of the communication technologies.

Future communication systems are based on digital data links such as High Frequency Data Link (HF DL), VHF Data Link Mode 4 (VDL-Mode 4), Mode-S Extended Squitter, and Universal Access Transceiver (UAT). Data link technologies enable uplink and downlink of 4 dimensional (4D) waypoints (latitude, longitude, altitude, time) and other data to pilots and controllers. Controller-Pilot Data Link Communication (CPDLC) is an example of a data link application that relies on HF DL, VDL and satellite communication (SATCOM). The implementation of the digital data links has the potential to change the communication of control instructions in the event of analogue voice link failure (Hansman, 1997). Moreover, the analogue voice communication is prone to many limitations to the users e.g. limited coverage, accessibility, capability, integrity and security. The voice communication performance, based on the radio frequency can reduce due to interference issues, frequency congestion and noise. This can happen, even though there are specific aviation frequency bands allocated for the ATC use. In addition, due to the different accents of the pilots and controllers, voice communication can lead to misinterpretation of information, which may cause undesired incidents. Despite its limitations, voice communication via radio frequency is still the main mode of communication between pilots and controllers in the ATC environment. Voice communication channels are regarded essential for ATC, since they act as a backup during the worst case (unavailability of surveillance and navigation functions) to enable continuous air traffic services to the users.

The implementation of enhanced modes of data link is envisioned to overcome the limitations discussed above. Therefore, the need for reliable digital data link technologies is crucial. However, the new digital communication technologies have to comply with the Required Communication Performance (RCP) (ICAO, 2006c) set by ICAO. The future communication systems in ATM are envisioned to be a mix of voice and data communication via high-speed digital data links.

2.2.1.1 Aeronautical Telecommunication Network (ATN)

The first step in implementing CNS/ATM, is the establishment of an efficient networking system for the communication of different forms of data including; text, radar, graphics and voice. This requires the use of a combination of terrestrial and satellite based systems. The current system, the Aeronautical Fixed Telecommunication Network (AFTN), does not have the capability to support the future data requirements of CNS/ATM (ICAO, 2000). Therefore, ICAO proposes the use of the Aeronautical Telecommunication Network (ATN) that comprises of application entities and communication services. These make the ground elements, air-ground networks and airborne data networks interact via the International Organization for Standardization (ISO) Open System Interconnection (OSI) reference model based protocol and services interface (ICAO, 1999a). ICAO has standardized the following data links in the context of ATN (ICAO, 1999c):

- Aeronautical Mobile Satellite Service (AMSS), using satellites for communication, both geostationary and non-geostationary satellites, allowing communication by voice and data on a global range.
- VHF Datalink (VDL), using techniques of data communication in VHF bands. They are of types; Mode 2, Mode 3 and Mode 4 with differentiation by their characteristics of modulation, control for access to the physical environment and, especially, data transfer rates.
- Mode S Extended Squitter, using the Mode S SSR ability to communicate data in a bidirectional manner between air and ground elements with nominal rates of 4Mbits/s (uplink) and 1Mbits/s (downlink) (ICAO, 1998b).
- Universal Access Transceiver (UAT), a broadcast data link operating on 978 MHz, with a modulation rate of 1.041667 Mbps (ICAO, 2009b).
- HF Data Link (HFDL) which is the union between the characteristics of long-range electromagnetic propagation in the HF spectrum and digital data modulation, providing data communication in remote areas.

Vismari (2007) illustrates the CNS/ATM communication environment based on the ATN in Figure 2-2. ICAO categorized the application entities (AE), which are the functionalities of the ATN used by end systems (ES) in the air traffic system into air-ground application entity and ground-ground application entity (ICAO, 1999a). The air-ground AE enables communication between ES in the ground (ATS units) and ES in the air (aircraft). Examples of applications in this category are the:

- Automatic Dependent Surveillance Broadcast (ADS-B), which provides the aircraft position and other important information to the ES;
- Controller-Pilot Data Link Communication (CPDLC), which provides the ability to establish a peer-to-peer message communication between pilots and controllers;
- Flight Information Services (FIS), which allows pilots to request and receive flight information services; and
- Traffic Information Service Broadcast (TIS-B), which transmits radar surveillance information from the ground to the aircraft in the air.

The ground-ground AE allows communication between ES in the ground (ATS units). The AE in this category are the ATS Message Handling Service (ATSMHS), enabling the exchange of messages between ATS end users; and the Inter-Communication Center (ICC), which provides message communication between ATS centers for notification, coordination, and transfer of control activities.

An application developed based on the ATN, is the SESAR's and NextGen's System Wide Information Management (SWIM) (SESAR Joint Undertaking, 2011). SWIM is a holistic approach enabling information sharing including flight information, weather, aeronautical information and surveillance information among the stakeholders and the airspace users using a secure and flexible system (an intranet). SWIM infrastructure is interoperable (ground/ground and air/ground) over which the data are distributed. Its data communication link may differ from one user to another depending on available facilities. For SESAR's SWIM, the PAN European Network System (PENS) will provide the ground/ground data link.

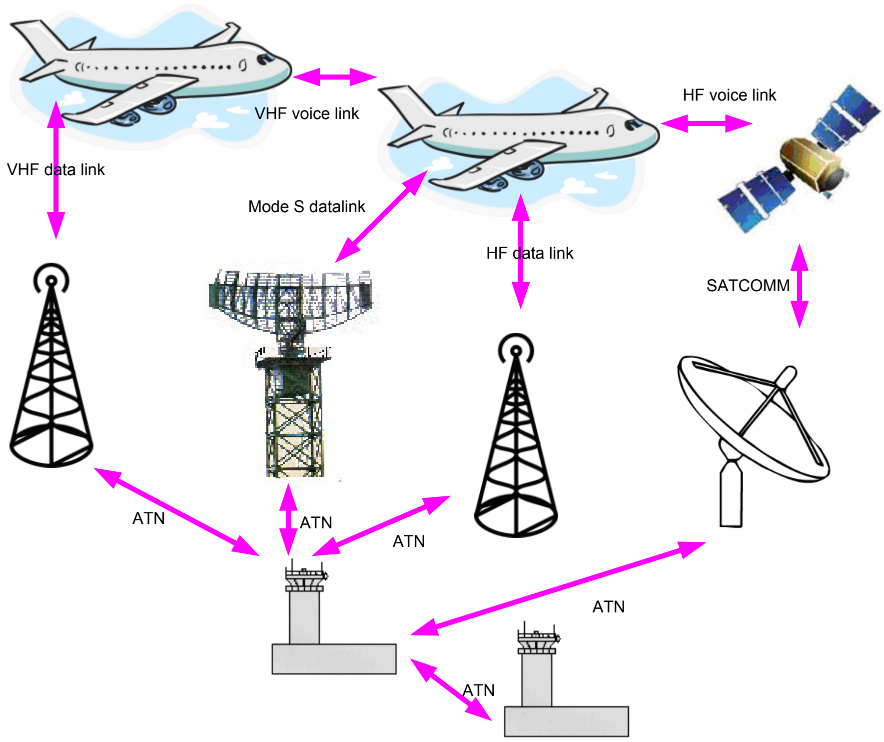


Figure 2-2: CNS/ATM Communication Environment (modified from (Vismari, 2007))

2.2.1.2 Required Communication Performance (RCP)

The communication function is one of the important elements of the ICAO's Future Navigation System – FANS concept (ICAO, 2007e). The Required Communication Performance (RCP) concept ensures that the communication system performance implemented within the ATM system is acceptably safe and reliable to operate in the ATM operational environment. It also includes the ATC ground equipment and aircraft equipage requirements for communication. The RCP concept is applicable to any communication capabilities to support the ATM functions despite technology type. Hence the concept can be applied to any new communication technology. The RCP concept assesses operational communication in the context of an ATM function, taking into account human interactions, procedures, and environmental characteristics (ICAO, 2006c). According to National Aeronautics and Space Administration (NASA), the concept enables diverse communication technologies to be measured in terms of communication process time (i.e. delay), integrity, availability, and continuity of function (NASA, 2000). Therefore the concept provides means to quantify the communication system performance, essential to ensure the system safety. However, accuracy in predicting the process time can only be attained through monitoring during continuous operation. The accuracy parameter is not provided under the RCP concept.

2.2.2 Navigation

Navigation refers to the ability to determine the correct state of an object then to determine the course to steer and arrive at the next desired point (ICAO, 1998a).

The current ground based navigation system consists of the use of VHF Omnidirectional Radio Range/Distance Measuring Equipment (VOR/DME), Non-Directional Beacon (NDB) and Long-Range Navigation (LORAN) for area navigation (RNAV) while Instrument Landing System (ILS) and Microwave Landing System (MLS) are used for precision approaches and landing (ICAO, 2000). In addition to these, ground navigation aids also include: Aeronautical Ground Lighting (AGL) system (e.g. status of runway, taxiway lighting panel), warning system (e.g. runway in use), internal lighting, meteorological equipment status, and alarming and reporting systems. Despite the system's good performance, a small number of significant deviations from cleared tracks still occur. These are mainly due to human error such as ATC loop errors (e.g. ATC issues incorrect clearance or flight crew misunderstands clearance message) or on-board navigation system error (ICAO, 1990). Onboard navigation systems include Inertial Navigation System (INS) and the Global Positioning System (GPS) and its augmentations. These systems are described in detail in Chapter 3. The evolution of the current navigation systems is shown in Figure 2-1.

Improvements in navigation in CNS/ATM systems include the progressive use of Global Navigation Satellite Systems (GNSS), which provides world-wide coverage. It enables the aircraft to determine its own position on-board, from the information, broadcast by the GNSS satellites. This advancement is envisaged to provide more flexibility to the pilot and to reduce the air traffic controller's workload. The availability of new GNSS constellations (e.g Galileo) and the further development of augmentation means (Aircraft based augmentation system (ABAS), Ground based augmentation system (GBAS), Satellite based augmentation system (SBAS)) will improve the accuracy, availability and the integrity of the navigation signal thus allowing enhanced positioning services in all phases of flight, including the airport surface (SESAR, 2008). For example, surface navigation based on GBAS (using enhanced positioning based on Galileo/GPS L5) should enable aircraft to navigate autonomously on the ground to the gate. The GNSS concept is explained further in Chapter 3.

2.2.2.1 Required Navigation Performance (RNP)

The need for the optimum utilization of airspace, which in turn depends on very high performance navigation systems, has resulted in the concept of Required Navigation Performance (RNP) by ICAO.

The RNP is the navigation specification that includes a requirement for on-board navigation performance monitoring and alerting to enable an aircraft to fly a specific path between two three-dimensionally defined points in space. The RNP (ICAO, 1999b) concept applies to navigation performance within airspace; hence it covers both the airspace and aircraft that fly within it. The purpose of the RNP is to characterize airspace through the navigation performance accuracy value to be achieved within the airspace. Accuracy was the only parameter used to quantify the RNP characterization in the beginning. According to ICAO, navigation performance accuracy is based on the combination of the navigation sensor error, airborne receiver error, display error and flight technical error (ICAO, 1999b). It refers to the level of accuracy required for a given block of airspace and/or a specific instrument procedure, e.g. a RNP of 10 means that a navigation system must be able to calculate its position to within a circle with a radius of 10 nautical miles. The level of RNP that an aircraft is capable of determines the separation required between it and other aircraft. Hence, the RNP values have to be more stringent for dense airspace, around noise sensitive areas or terrain areas compared to oceanic airspace.

The RTCA extended the RNP definition to include integrity, continuity and availability (RTCA, 1998). It was then known as Required Navigation Performance for Area Navigation (RNP-RNAV). The difference between RNP and area navigation (RNAV) is that the RNAV is a navigation specification that does not include a requirement for on-board navigation performance monitoring and alerting.

In order to implement a more practical navigation specification, ICAO developed the Performance Based Navigation (PBN). PBN specifies that the aircraft RNP and RNAV system performance requirements to be defined in terms of accuracy, integrity, continuity, availability and the functionalities required to operate in particular airspace supported by appropriate navigation infrastructure (ICAO, 2008). The performance requirements are identified in the navigation specification, which also states the choice of navigation sensor and equipment that may be used to meet the performance requirements. PBN requirements depends on the ATC environment, communication, surveillance, navigational aids infrastructure, non-RNAV means of navigation available, functional and operational capabilities required to meet the Air Traffic Management application and the degree of redundancy required to ensure continuity of operations. The PBN provides specific implementation guidance in order to facilitate global harmonization. In this thesis, the term ‘RNP parameters’ will refer to accuracy, integrity, continuity and availability which are defined in Chapter 3.

2.2.3 Surveillance

Surveillance, which refers to the methods used for keeping track of aircraft, is the third element of CNS/ATM. The surveillance function, whose implementation includes sensors, display system and operational procedures, provides air traffic controllers with the position of aircraft in order to perform separation management and to effectively manage a given airspace. Depending on the type of the surveillance sensor, additional information is presented also such as aircraft identification and velocity. Furthermore, the surveillance function supports a number of other applications such as trajectory prediction, conflict detection and situational awareness.

Requirements for an Air Traffic Control (ATC) surveillance system depend on the applications. However, no single surveillance system is capable of meeting the surveillance requirements for all phases of flight in all types of airspace with traffic conditions that vary significantly from low to high-density traffic terminal areas. The current surveillance system in use consists of: Primary Surveillance Radar (PSR), Secondary Surveillance Radar (SSR), Monopulse Secondary Surveillance Radar (MSSR), Surface Movement Radar (SMR) and Multilateration (MLAT) systems. These technologies are explained in detail in the following sections. The evolution of the surveillance systems is illustrated in Figure 2-1. Recently a new surveillance technology called Automatic Dependent Surveillance (ADS), has emerged, and envisioned to support many new surveillance applications to meet the future air traffic forecasts. The ADS exploits the navigation and communication functions. The availability of different types of surveillance technologies provides flexibility to choose the most affordable and effective surveillance system suitable for the required operations, based on the operational environment. However, in order to maintain harmonization of the surveillance function, all the operational requirements have to be translated into a series of surveillance performance parameters irrespective of the surveillance technology.

2.2.3.1 Required Surveillance Performance (RSP)

The Required Surveillance Performance (RSP) is a set of well-quantified surveillance performance requirements such as capacity, availability, accuracy and update rate. Any single or combination of surveillance systems meeting the targets set for the parameters is considered operationally acceptable (ICAO, 2000). The only RSP document available to date is known as the Blue Book (EUROCONTROL, 1997), which is specifically meant for Primary Surveillance Radar (PSR) and classical Secondary Surveillance Radar (SSR Mode A/C)). Therefore, it is not applicable to any new surveillance technology performance requirements. With the emergence of new surveillance technologies, all surveillance systems in the European Union are legally obliged to comply with the Single European Sky Essential Requirement (ER), which states:

- "Surveillance systems shall be designed, built, maintained and operated using appropriate and validated procedures in such a way as to provide the required performance applicable in a given environment (surface, TMA, en-route) with known traffic characteristics and exploited under an agreed and validated operational concept, in particular in terms of accuracy, coverage, range and quality of service.
- The surveillance network within the European Air Traffic Management Network (EATMN) shall be such as to meet the requirements of accuracy, timeliness, coverage and redundancy. The surveillance network shall enable surveillance data to be shared in order to enhance operations throughout the EATMN (EUROCONTROL, 2008a)" .

This high level requirement will be augmented by an Implementing Rule (IR), the Surveillance Performance and Interoperability Implementing Rule (SPI-IR) (EUROCONTROL, 2011d), which specifies how the essential rule is to be achieved. The SPI-IR is a legal requirement and includes regulations and general surveillance performance requirements for ADS-B OUT (explained in Chapter 3). This implementing rule will remain in place until a generic global RSP is mandated by ICAO. This thesis adopts the surveillance performance requirements stipulated in this implementing rule.

2.2.4 Air Traffic Management

ATM is a broadly defined function that includes air traffic services, air traffic flow management and airspace management. Its objective is to keep aircraft separated and enable aircraft operators to meet their planned times of arrival and departure whilst adhering to preferred flight (ICAO, 2002a). Integration of the new CNS technologies into the ATM will enable Air Traffic Services (ATS) providers to improve efficiency. By being better able to both accommodate an aircraft's preferred flight profile and reduce the minimum separation, aircraft operators and service providers could achieve reduced operating costs and minimize delays, while simultaneously freeing up additional airspace and increasing capacity. Figure 2-3 summarizes the benefits of the new CNS systems to the ATM.

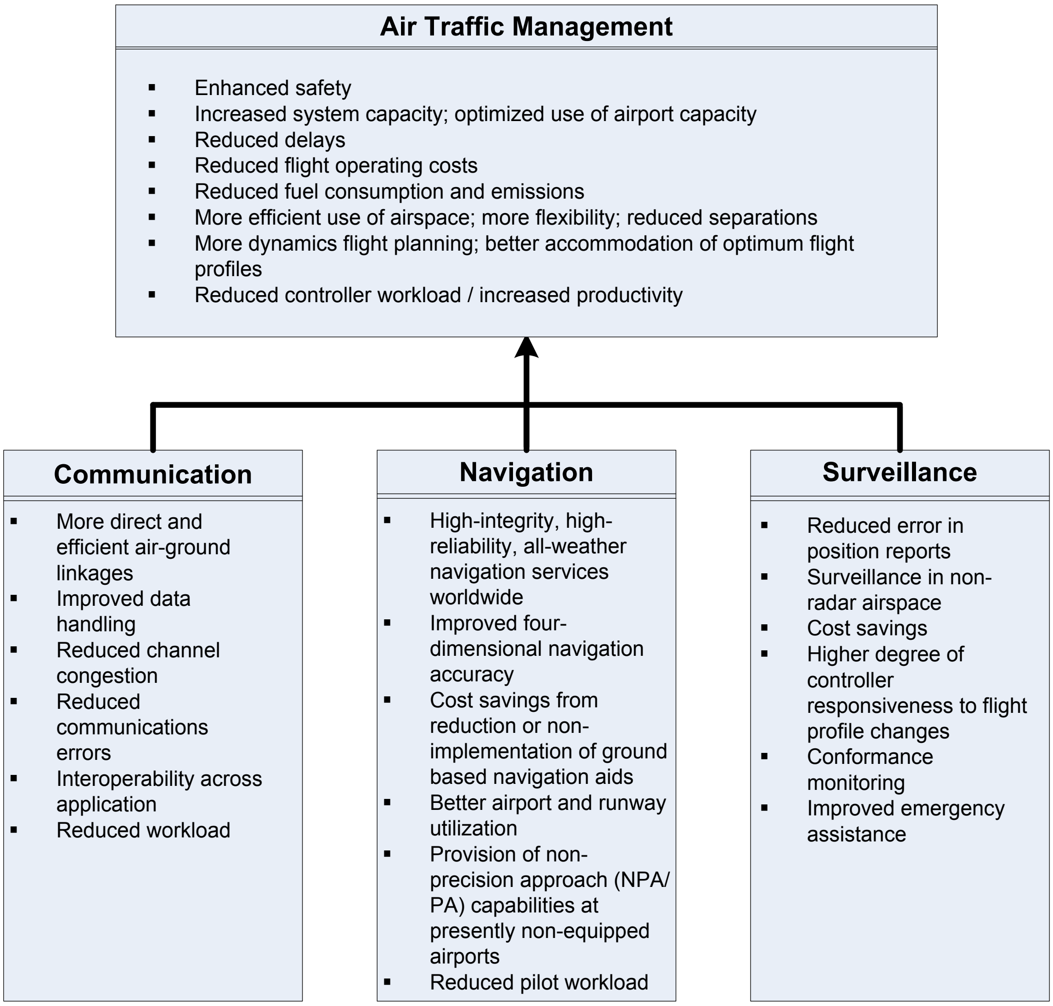


Figure 2-3: A high-level view of benefits of the new CNS system to ATM (ICAO, 2002a)

2.3 Impacts of evolution in CNS

The paradigm shift in CNS, outlined in Figure 2-1, due to developments in technology, directly impacts the characteristics of ATM. Such impacts include the ATM system's ability to effectively manage the separation between aircraft due to: an increase in the accuracy, integrity and reliability of surveillance data, the larger coverage area, a reduction of congestion in the communication channels and the potential for improvements in the detection and resolution of conflicts. The impacts of CNS will in turn change the aspects of the provision of air traffic control services, such as reduction in control instructions from the controllers as pilots will also be involved in a separation situation due to the same level of situational awareness. The evolution in CNS is also seen as a means to eliminate the constraints on the safe growth of air transportation. Despite the positive impacts, the evolution of CNS/ATM can also lead to unforeseen problems. Oliveira et al (2009), state that the main challenge in CNS is the complexity of the technologies which can potentially introduce an unknown number of new failure modes. Therefore, it is crucial to assess and validate the safety of these technologies prior to their implementation to support safety-critical applications. The current relevant methods for safety assessment include evaluation of risk against threshold value (Absolute Method) (ICAO, 1998c), comparison with a reference system (Relative Method) (ICAO, 1998c) and safety assessment method based on Fluid Stochastic Petri Nets (FSPN) (Vismari, 2008). However, these methods have limitations in terms of quantification of risks and are thus sub-optimal. These methods are described and their advantages and drawbacks analysed in Chapter 5.

2.4 Air Traffic Control (ATC) Surveillance Environment

Air Traffic Control (ATC) Surveillance aims at identifying an aircraft's or vehicle's three dimensional position in space; which (identification), where (position) and when (time), in addition to providing other essential data (e.g. intent, velocity) to various ATM systems.

2.4.1 The Need for ATC Surveillance

Surveillance acts as the "eyes" of Air Traffic Control (ATC). The capability to accurately and reliably determine the position of an aircraft at a specific time has a direct influence on the separation distances required between aircraft (i.e. separation standards), and therefore, on how efficiently a given airspace may be utilized.

In areas without surveillance coverage, where ATC is reliant on pilots to verbally report their position, aircraft have to be separated by relatively large distances to account for the uncertainty in the estimated position of aircraft and the timeliness of the information. Separation requirements between aircraft are discussed further in the subsequent chapters. Conversely in terminal areas where accurate and reliable surveillance systems are available and aircraft positions are updated more frequently, the airspace can be used more efficiently to safely accommodate a higher density of aircraft. It also allows aircraft vectoring for efficiency, capacity and safety purposes.

ATC surveillance serves to close the gap between ATC expectations of aircraft movements based on clearances or instructions issued to pilots, and the actual trajectories of these aircraft (ICAO, 2007f). In this way it indicates to ATC when expectations are not matched, providing an important safety function. Surveillance therefore provides "blunder" (false position) detection.

The demand for increased flexibility to airspace users by reducing restrictions associated with flying along fixed routes requires high performance (accuracy, integrity, reliability) navigation capability on board the aircraft. Equally, accurate surveillance is required to assist in the detection and resolution of any potential conflicts associated with the flexible use of the airspace, which is likely to result in a more dynamic environment. This concept will be applied to enable In-Trail Procedure (ITP) (EUROCONTROL, 2009a), which allows a pilot to navigate flexibly in en-route and oceanic areas by having complete situational awareness. The ITP concept is explained in detail in Chapter 8.

Surveillance is required to support automated alerting systems such as Short Term Conflict Alert (STCA) for the ATC function. Automated alerting systems are based on the principle that the ability to accurately track aircraft enables ATC to be alerted when an aircraft is detected to:

I. deviate from its assigned altitude or route, or
II. the predicted future positions of two or more aircraft conflict.

Surveillance also supports minimum safe altitude warnings, danger area warnings and other similar alerts (ICAO, 2007f).

Finally, surveillance is also used to update flight plans and improve estimates of future waypoints, thereby reducing the workload for pilots in providing voice reports on reaching waypoints to the ATC. Therefore, surveillance is a crucial element of air traffic control.

2.4.2 Current ATC Surveillance

Conventional ATC Surveillance is based on voice position reporting by the pilot to the controllers on the ground via radio communication. While manoeuvering in the oceanic area, the pilot has to report every 20 – 30 minutes to the controller within the control area via VHF or HF frequency, and then the controller has to repeat it for verification purposes.

A generic ATC Surveillance system includes sensors (technology), communication links, a surveillance data distribution system, a surveillance data processing system, a surveillance data analysis tool, display, surveillance applications and users. Such a generic system is illustrated in Figure 2-4.

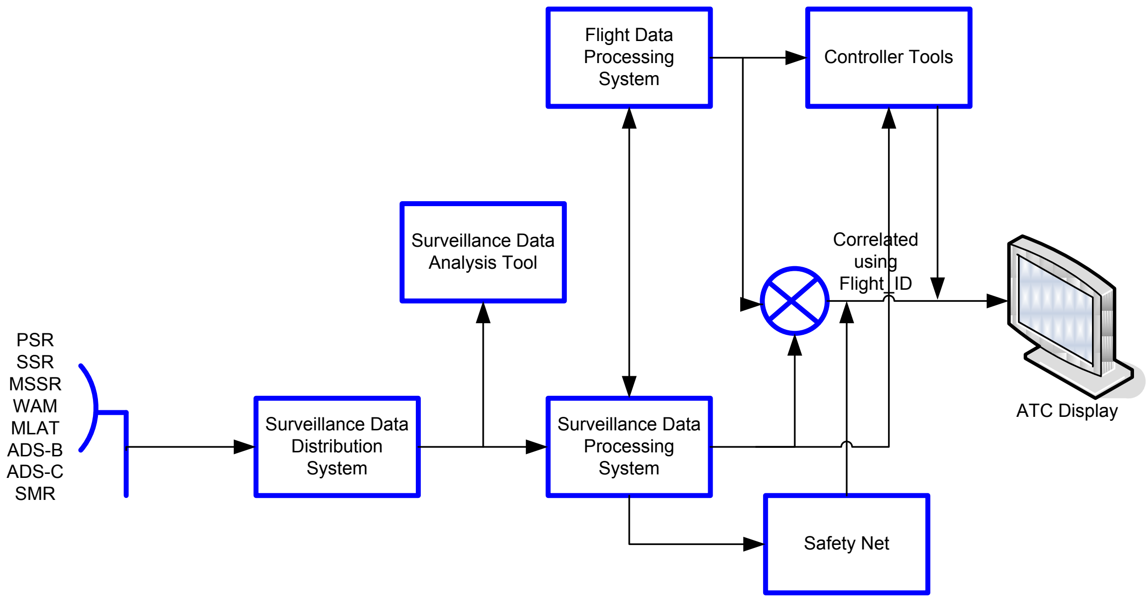


Figure 2-4: Generic ATC Surveillance System

The main components in Figure 2-4 are:

- Surveillance Data Distribution System – converts the data into a standardized format (e.g. ASTERIX) and then transmits the data to other equipment;
- Surveillance Data Processing System – extrapolates plots to generate track state vector;
- Surveillance Data Analysis Tool- analyses data performance;
- Safety Net – tools meant to prevent imminent or actual hazardous situations from developing into major incidents or even accidents;
- Flight Data Processing System – stores, displays and updates flight plan.

Currently, surveillance systems provide controllers with the surveillance picture for their control area (sector). In the future, pilots will also have a similar surveillance picture on-board. Therefore, this advance will impact the current ATC operations.

2.4.3 Surveillance Sensor Categories

Surveillance sensor technologies can be placed in three categories; Non-Cooperative Independent, Cooperative Independent and Cooperative Dependent.

The term 'Non-Cooperative' refers to the ability to detect the position of a target without relying on the response from the target to the transmitted signal by the sensor. On the other hand, the term 'Cooperative' refers to reliance of the sensor on the target's reply to the transmitted signal (interrogation) to derive the target position. A piece of equipment (i.e. a transponder) attached to the target responds to the sensor interrogation. The transponder is a radio signal receiver and transmitter that receives at a frequency 1030 MHz and transmits on 1090MHz.

The term 'Independent' refers to the ability of the surveillance system to derive a target's position on its own, while the term 'Dependent' refers to reliance of the surveillance system on an external system to obtain the target's position, e.g. dependency on a navigation system such as the Global Positioning System (GPS).

Table 2-1 shows the categories of the existing surveillance technologies. Manual position reporting by the pilot to the ATC via radio communication is categorized as Cooperative Dependent, due to the fact that ATC on the ground is required to respond to the call in order to report the aircraft's position. The pilot is dependent on the on-board navigational system such as GPS or Inertial Navigation System (INS) to obtain the aircraft position. In this case the pilot/aircraft acts as the surveillance system to transmit the aircraft position to the ATC.

Table 2-1: Categories of existing surveillance technologies

Surveillance Category	Surveillance Technology
Non-Cooperative Independent	▪ Primary Surveillance Radar (PSR)
Cooperative Independent	▪ Secondary Surveillance Radar (SSR) Mode A/C ▪ Secondary Surveillance Radar (SSR) Mode S ▪ Multilateration (MLAT)
Cooperative Dependent	▪ Manual Position Reporting (voice) ▪ Automatic Dependent Surveillance Contract (ADS-C) ▪ Automatic Dependent Surveillance Broadcast (ADS-B) IN/OUT

2.4.4 Surveillance System Performance Parameter and Characteristics

A surveillance system may be characterized in terms of the following parameters (ICAO, 2007f):

- Coverage volume – the volume of airspace in which the system operates to specification;
- Accuracy – a measure of the difference between the estimated and true position of an aircraft;
- Integrity – an indication that the aircraft's estimated position is within a stated containment volume of its true position. Integrity includes the concept of an alarm being generated if this

ceases to be the case, within a defined time to alarm. Integrity can be used to indicate whether the system is operating normally;

- Update rate – the rate at which the aircraft's position is updated to users;
- Reliability – the probability that the system will continue operating to specification within a defined period. This is also called continuity;
- Availability – the percentage of the total operating time during which the system is performing to specification.

The parameter values may differ for the various surveillance applications supported by the surveillance system during the different phases of flight. For example, more stringent values for the update rate and accuracy are required to enable enhanced separation in terminal areas compared to en-route oceanic areas. The performance characteristics of each surveillance sensor discussed in the previous section is given in Table 2-2.

The same performance parameters can be used to assess different surveillance technologies. However, when applied to different technologies, the definition of the parameters may change slightly. The performance parameters for ADS-B system are defined in Chapter 3.

Table 2-2: Surveillance Sensor Performance Characteristics (ICAO, 2007f)

Surveillance Technology	Coverage	Accuracy	Integrity	Update period
Primary Surveillance Radar (PSR)	S-band 60-80 NM L-band 160-220 NM	In range : 0.1 NM RMS or 0.2 NM 2 σ In azimuth : 0.15 degrees RMS or 0.3 degrees 2 σ	No integrity report provided.	4 - 15 seconds
Secondary Surveillance Radar (SSR) (Mode A/C)	200 NM-250 NM	In range : 0.03 NM RMS In azimuth : 0.07 degrees RMS or 0.14 degrees 2 σ for random errors.	No integrity report provided.	4 - 15 seconds
Secondary Surveillance Radar (SSR) (Mode S)	200 NM-250 NM	Same as SSR(Mode A/C)	No integrity report provided.	4 - 12 seconds
Multilateration (MLAT)	200 NM	10-500 meters	No integrity report provided	1 - 5 seconds
ADS-B	200 NM-250 NM	Determined by the aircraft avionics and independent of range from sensor. For GPS, 95% less than 0.1NM	Position integrity guaranteed to 1*10-7 due to RAIM algorithm in avionics. Integrity value is downlinked in the ADS-B message.	0.5 - 2 seconds

2.4.5 Required Surveillance Applications

Surveillance technologies are meant to make possible various ground and airborne surveillance applications (RTCA, 2002) to support air traffic control, airspace management and aircraft navigation in en-route, terminal and airport surface areas. Surveillance data from different surveillance technologies have different levels of quality and performance (i.e. accuracy, integrity, update rate). The capabilities of the surveillance sources are used as a baseline to develop surveillance tools to support the ground and airborne surveillance applications required. The surveillance applications in three categories are shown in Table 2-3.

Another essential surveillance application to aid pilots and controllers to prevent imminent or actual hazardous situations from developing into major incidents or even accidents is called the safety net (shown in Figure 2-4 as part of ATC surveillance system). Safety net tools for preventing collision between aircraft or collision with terrain/obstacles are available for the controllers in the ground and for the pilot in the cockpit (Skybrary, 2011), including:

- Ground-based safety net that uses surveillance data to provide warning times of up to two minutes. Upon receiving the warning alert, controllers are expected to immediately assess the situation and take appropriate action.
- Ground-based safety net tools include:
    - Short Term Conflict Alert (STCA);
    - Area Proximity Warning (APW);
    - Minimum Safe Altitude Warning (MSAW);
    - Approach Path Monitor (APM).

- Airborne safety nets provide alerts and resolution advisories directly to the pilots. Warning times are generally shorter, up to 40 seconds. Pilots are expected to immediately take appropriate avoiding action.
- Airborne safety net tools include:
    - Airborne Collision Avoidance System (ACAS);
    - Ground Proximity Warning System (GPWS).

The radar supports ground surveillance application tools (e.g. STCA, MSAW, etc.) for the air traffic controllers to manage the airspace and aircraft separation. The emergence of new surveillance technology with higher performance in comparison to the radar system enables the possibility to implement new airborne surveillance application tools. These include the Cockpit Display of Traffic Information (CDTI), In-Trail Procedure (ITP) and Aircraft Separation Assurance System (ASAS) for improved aircraft navigation operations and self separation. In addition, new enhanced communication technologies (e.g. Mode-S Extended Squitter, UAT, and VDL-Mode 4) have also enabled other airborne applications such as Traffic Information Service Broadcast (TIS-B) and Flight Information Service Broadcast (FIS-B) for enhanced situational awareness.

Table 2-3: Surveillance application categories

Category	Application
Ground-based surveillance	a) ATC surveillance in airspace with radar coverage b) ATC surveillance in airspace without radar coverage c) Airport surface surveillance d) Aircraft derived data for ground-based ATM tools.
Airborne-based surveillance	a) Situational awareness ▪ Enhanced traffic situational awareness on the airport surface ▪ Enhanced traffic situational awareness during flight operations ▪ Enhanced visual acquisition ▪ Enhanced successive visual approaches b) Airborne spacing and separation ▪ Enhanced sequencing and merging operations ▪ In-trail procedure ▪ Enhanced crossing and passing operations
Other	a) Ramp control/gate management b) Noise monitoring c) Remote airport charges issuing d) Enhanced situational awareness of obstacles e) Search & Rescue (SAR), emergency response

2.4.6 The Current Surveillance System

The current surveillance system consists of the following: Primary Surveillance Radar (PSR), Secondary Surveillance Radar (SSR), Monopulse Secondary Surveillance Radar and Multilateration. Each country or region implements the surveillance systems required by taking into account the technical performance, geographical structure, contextual environment and cost. For example, it is much more cost effective to implement Multilateration instead of SSR as both have a similar requirement on the aircraft to have a Mode-S transponder onboard, a mandatory requirement by ICAO. The Multilateration sensors are more flexible and cheap as they can be installed on existing infrastructures while the SSR has to be installed on a piece of land and with the associated high cost. In the case of unavailability of surveillance sources, the Air Traffic Control Services are delivered using Procedural Control via radio communication.

2.4.6.1 Primary Surveillance Radar (PSR)

The Primary Surveillance Radar (PSR) involves a beam of energy that is transmitted through an aerial and reflected back from any aircraft in its path to provide information on bearing (azimuth) and distance (range) of the aircraft (Wassan, 1994). Unfortunately, the reflections may also be from fixed objects (e.g. buildings), which tends to create clutter (Aeronautical Surveillance Panel (ASP), 2007) causing uncertainty on the target display. The PSR ground station consists of a transmitter, receiver and rotating antenna. According to ICAO, the future use of PSR in en-route airspace is expected to reduce due to its high cost and the mandatory requirement for aircraft to be equipped with a transponder to support the SSR that has the capability to supersede the PSR. However, PSR is still an important technology for security purposes in both civil and military airspace, despite its inability to uniquely identify targets, their altitude and the need for the transmission of high power pulses that limit its range. PSR remains crucial in high traffic density terminal areas to provide surveillance of aircraft not equipped with a transponder and objects on the runways or taxiways. Figure 2-5 illustrates PSR system operation.

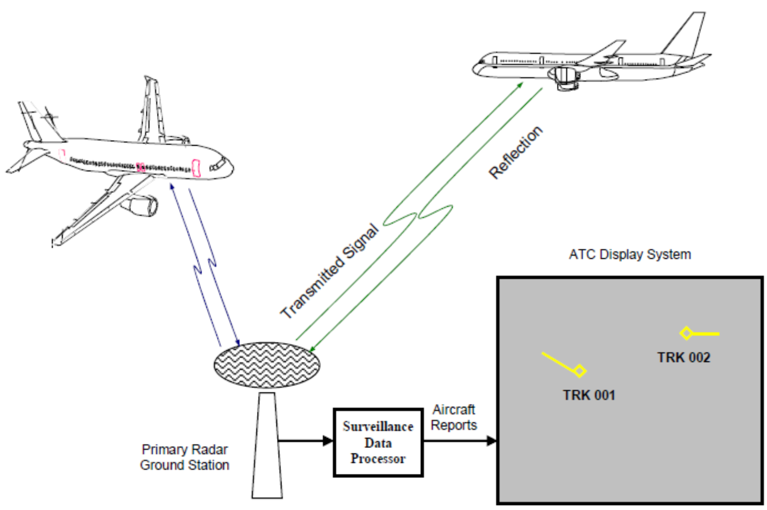


Figure 2-5: Primary Surveillance Radar (ICAO, 2007f)

2.4.6.2 Secondary Surveillance Radar (SSR)

The Secondary Surveillance Radar (SSR) sends out interrogation signals at 1030MHz from the ground station to each aircraft within its range (200- 250 NM) and then awaits a reply at 1090MHz from the aircraft transponder. The aircraft's transponder responds to interrogations, enabling the aircraft's range and bearing from the ground station to be calculated independently by the SSR (ICAO, 2004c), see Figure 2-6. The system provides an update rate of (4-12) seconds. The SSR requests two types of data from an aircraft transponder: Mode A/C or Mode S. Mode A data represents a four digit aircraft identity while mode C data represents aircraft altitude (Wassan, 1994). Mode S is an enhancement of mode A/C by the addition of the selective addressing of targets by the use of unique 24-bit address. It also provides a two-way data link between the ground stations and the aircraft for information exchange (ICAO, 2007f). The SSR overcomes all the drawbacks identified for PSR. However, it is unsuitable for aerodrome surface surveillance due to the accuracy limitations imposed by the transponder delay tolerance. An important achievement with SSR is the Mode S technology that will enable many new surveillance technologies to evolve in the future. For example, Multilateration technology was developed as a result of the Mode-S technology evolution.

There are two classes of SSR in use currently (ICAO, 2007f):

- **Classical SSR** - This SSR system relies on the presence or absence of the SSR transponder replies within the beam-width. Performance can be quite poor, particularly for azimuth accuracy and resolution. This type of system is also subject to significant multipath anomalies due to the poor antenna pattern. Range accuracy depends on the variability of the fixed delay in the aircraft transponder.
- **Monopulse SSR** - The system measures the azimuth position of an aircraft within the horizontal antenna pattern using diffraction techniques. These techniques improve azimuth accuracy and resolution. In addition, these radars typically have large vertical aperture antennas and hence, are less subject to multipath effects.

2.4.6.2.1 Transponder

EUROCONTROL defines a transponder as the airborne radar beacon receiver/transmitter portion of the Air Traffic Control Radar Beacon System (ATCRBS) which automatically receives radio signals from interrogators on the ground. It then selectively replies with a specific reply pulse or pulse group only to those interrogations being received on the mode to which it is set to respond (EUROCONTROL, 2011e). The transponder is mandatory equipment for the SSR operation.

2.4.6.2.2 Interrogation Modes

The SSR has four modes of interrogation/reply: Mode A, Mode C, Mode S and intermode. Ground stations can either be Mode A/C ground stations, which can interrogate and receive replies only on Mode A/C, or Mode S ground stations, which can interrogate and receive replies on all modes. There are two classes of transponders: Mode A/C transponders and Mode S transponder. The former can respond to Mode A, Mode C and intermode interrogations only, whilst the latter can respond to all modes.

- **Mode A**

  Mode A interrogation generates a Mode A reply from the aircraft transponder which is the individual aircraft identification (also known as callsign or squawk). This identification is used by the ATC for operational purposes.

- **Mode C**

  Mode C interrogation generates a Mode C reply from the aircraft transponder, which is the encoded pressure-altitude (known as barometric altitude). Pressure-altitude is the reference for vertical separation in ICAO airspace.

- **Intermode**

  Operational compatibility between Mode S and Mode A/C aircraft and ground elements is achieved by the use of intermode (all-call communication) and by the use of the lockout protocols. Intermode transactions allow Mode S ground stations to simultaneously interrogate both Mode S and Mode A/C transponders in order to determine the Mode S aircraft. Intermode interrogations also allow the ground station to ensure that it receives replies exclusively from either Mode A/C aircraft or Mode S aircraft but not both simultaneously. The lockout protocols permit a Mode S ground station to control a Mode S transponder after its address has been determined so that it replies only to particular subsets of the possible intermode interrogations (ICAO, 2004c).

- **Mode S**

  A Mode S reply contains a 24bit aircraft address, altitude or other data depending on the request by the ground station and aircraft capability. Mode S interrogation and replies are protected by a robust error correction scheme to ensure high reliability information is transmitted to the ground. The Mode S transponder also has the capability to report pressure-altitude in either 100ft or 25ft increments depending on the aircraft altimeter capability.

Mode S SSR can be categorized into two levels; Mode S "Elementary Surveillance" (ELS) and Mode S "Enhanced Surveillance" (EHS). The difference between these two levels is the amount of information given to the ATC by the SSR with the respective capabilities. Europe has issued a Mode S mandate requiring all aircraft in certain airspace to be Mode S equipped (ICAO, 2007f). The European mandate also requires Mode S ELS or Mode S EHS, to be supported.

Mode S Elementary Surveillance (ELS) provides:

- Unique 24 bit aircraft address
- SSR Mode A
- Special Position Indicator (SPI)
- Aircraft Identification (Callsign or Registration)
- Altitude with 25ft resolution
- Flight Status (airborne or ground)
- Transponder Capability Report
- Common-Usage Ground-Initiated Comm B (GICB) Capability Report;
- ACAS Resolution Advisory

In addition to that of the ELS, the Mode S Enhanced Surveillance (EHS) provides:

- Indicated Air speed (or Mach Number)
- Magnetic Heading
- Vertical Rate (climb, descend)
- Selected Altitude
- Ground Speed
- Roll Angle
- Track Angle Rate
- True Track Angle

The Mode S capability provides more aircraft state information to the ATC on the ground, thereby reducing radio communication with the pilot. However, not all the information is displayed on the controller's working position. The controllers can choose the information required on the display to perform their tasks. Apart from that, the transponder technology evolution (specifically Mode S) has encouraged the emergence of new surveillance technologies such as Multilateration and ADS-B. In addition, the safety net tool on-board, ACAS, also emerged as a result of this technology.

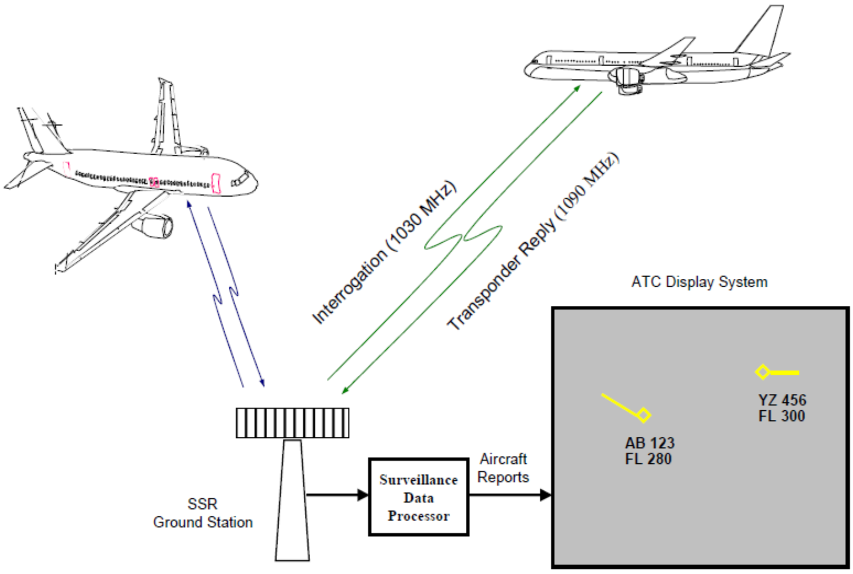


Figure 2-6: Secondary Surveillance Radar (ICAO, 2007f)

2.4.6.3 Surface Movement Radar (SMR)

The Surface Movement Radar (SMR), also known as Airport Surface Detection Equipment (ASDE), is primary radar intended for aerodrome surface surveillance. Similar to the PSR technology concept, the SMR technology detects all objects within its range without uniquely identifying a target. The system provides a one-second update rate and raw digitized video to the surveillance data processor (ICAO, 2004a). The raw video is processed and displayed on an ATC screen for monitoring purposes. The system also faces signal attenuation problems during heavy rain or snow, which causes displayed targets to fade on the ATC screen.

2.4.6.4 Multilateration (MLAT)

The Multilateration (MLAT) technology relies on signals from an aircraft being detected by four or more MLAT ground stations to locate the aircraft. It uses the Time Difference of Arrival (TDOA) technique to establish surfaces which represent constant differences between the target and pairs of receiving stations and determines the position of the aircraft by the intersection of these surfaces (Owusu, 2003).The MLAT system is used as a surveillance tool for airport surface and terminal areas.

The MLAT system requires the aircraft to be equipped with a mode-S transponder. Fortunately, this is facilitated by the mandatory requirements of ICAO for aircraft to be equipped with a transponder to support the SSR technology. The MLAT sensor has coverage of 200 NM with accuracy between 10 to 500 meters. The system accuracy depends on the geometry of the target in relation to the receiving stations and also the relative time of signal receipt. The system provides an update rate of (1-5) seconds. The only disadvantage identified with this technology is the need for a minimum of four ground stations to detect the signals from an aircraft to determine its location.

2.4.6.5 Procedural Control

Currently, most flights are planned via intermediate way-points rather than direct routes, hence limiting the opportunity to obtain changes to cleared flight profiles. This has an adverse effect on aircraft operating costs. Flights operating outside radar and VHF coverage at present are monitored on the basis of the current flight plan (air traffic control clearance) and the pilot-reported position (air-report). The flight plan describes the assigned route along which the aircraft is expected to fly. The position reports, transmitted via HF at relatively infrequent intervals, enable the controller to monitor the aircraft's progress for conformance to its air traffic control clearance (ICAO, 1990). The application of procedural ATC ensures an adequate level of safety, at the expense of optimal flight profiles and system capacity. However, the ATC services to aircraft operating in non-radar environments employ varying degrees of automation and use different procedures for controlling traffic. As a result, pilots are required to be familiar with the individual control aspects of all flight information regions (FIRs) their flights traverse.

In order to maintain the required level of safety in the provision of ATC services, any surveillance systems deployed should co-exist with either voice or data communication service between pilot and ATC with at least similar levels of reliability (i.e. continuity) as assigned to the surveillance system. The two systems should be designed carefully so that no single point of failure can occur in both systems simultaneously. A single point of failure may occur by having a single power source for the ground remote stations or single links from the ground remote stations to the ATC Centre (ICAO, 2010). In order to achieve the required level of reliability, redundant links on separate circuits need to be implemented.

Based on the review of the current surveillance technologies in this Chapter, a number of advantages and disadvantages are identified and verified (based on safety data analysis and input from Subject Matter Experts (SMEs)) in Chapter 4 .These disadvantages are a major obstacle to ensuring that the increasing air travel demand can be met.

2.4.7 Limitations of Current Surveillance Systems

Based on the review of current surveillance systems in the previous sections, the limitations of the systems are summarized:

- The PSR is unable to uniquely identify targets and their altitudes. The system requires transmission of high power pulses to detect the target, which results in low coverage.
- The Classical SSR has low azimuth accuracy and resolution. It is also prone to multipath effects.
- The SMR is prone to signal attenuation which causes the target display to fade during extreme weather conditions.
- The MLAT system accuracy is dependent on the geometry of the target in relation to the receiving stations and also the relative time of signal receipt.
- All of the current surveillance systems are not suitable for remote and oceanic airspace due to difficulty in siting the sensors.

2.5 Choice of Surveillance Technologies by Air Navigation Service Providers (ANSPs)

The need to have surveillance system is explained in section 2.4.1. However, in addition to the limitations identified in section 2.4.7, a number of factors and constraints impinge on the choices of surveillance technologies implemented by an ANSP in a particular State. This can be a single surveillance technology or combination of more than one technology. The factors and constraints are outlined below (ICAO, 2007f).

2.5.1 Cost

The cost of surveillance system is a major factor in the choice of surveillance technology due to the emergence of new surveillance technologies with significantly lower cost compared to the radar system. In many States, the availability of the lower cost systems has enabled surveillance in areas where it was previously uneconomical e.g. the implementation of ADS-B system in non-radar or oceanic airspace whereby it is very costly to have radar system installed and maintained. However, when the chosen surveillance technology is of a cooperative nature, the system deployment also involves airline operators and the ANSP. Therefore, the issue of who bears the cost and who benefits also needs to be considered.

2.5.2 Mixed aircraft equipage

The level of equipage for aircraft that must navigate under particular airspace constraints limits the type of surveillance technology to be deployed. Non-cooperative aircraft can only be detected by primary radar while cooperative aircraft equipped with Mode S or ADS-B capable transponders, can be detected by SSR, MLAT or ADS-B ground receivers. Consideration should also be given to general aviation and military aircraft equipage flying over the airspace.

A temporary solution for this environment is airspace segregation. The ANSP in a particular state can segregate their airspace such that equipped aircraft can operate in defined airspace whilst non-equipped aircraft operate in a different airspace.

2.5.3 Geography

Implementation of surveillance technologies should also take into account the obstacles to radio propagation for any particular surveillance technology in the operational area. SSR Mode-S radar has a long-range capability due to its high gain antenna. It can support surveillance of upper airspace up to 250 NM if the geographical location is free from close obstacles (line of sight). Multilateration is particularly effective in areas with line of sight problems due to its ability and scalability to fill a smaller specific area of surveillance, where long-range radar is ineffective. The choice of ADS-B is not affected by geographic constraints and it fills the gaps identified in either radar or multilateration systems to provide surveillance coverage.

2.5.4 Existing Ground Networking Infrastructure

Availability of complete ground networking infrastructure in a particular ATC operational area makes it easier and cheaper to install ADS-B and multilateration ground stations. This provides an advantage when considering the implementation of these two surveillance technologies. However, in the case of ADS-B, aircraft equipage also needs to be taken into account.

2.5.5 Homogeneous Surveillance Infrastructure

Despite the factors above, it is wise to choose a technology (from the same vendor of the current equipment of the existing system similar vendor) that can easily integrate with the existing ATC system. This allows savings in engineering support, training, documentation management and system planning. In addition, there will be no upgrading cost of the current ATC system. For example, the Surveillance Data Processing System (SDPS) that supports multiple surveillance technologies results in both operational and cost benefits.

2.5.6 Required Functionality

Different surveillance technologies may be chosen depending on the functional needs. Each technology has different functional capabilities beyond the provision of aircraft position and altitude data. Mode S radar is able to provide information of selected altitude; a multilateration system is able to provide a precise position report independent of GPS; while ADS-B is able to provide a high update rate of a high accuracy velocity vector. In the case of ATC surveillance in dense traffic airspace, high update rate and high accuracy surveillance data are required to perform reduced separation. To support military surveillance needs, the use of primary surveillance radar is required to track unidentified aircraft in the airspace.

2.5.7 Equipage Mandate

The choice of ADS-B as a surveillance system depends on a particular State's ability to mandate that for aircraft to operate in their airspace, they must be equipped with an ADS-B capable transponder or ADS-B emitter. The State's ability to issue a mandate may depend on several factors such as cost as well as on political considerations. However, the choice of SSR, Mode S radar and multilateration systems has no constraint of mandate, as ICAO has made it mandatory for commercial aircraft to be equipped with Mode S capable transponders (ICAO, 2007f).

2.5.8 Airspace Capacity Requirement

As a result of increasing air travel demand (see Chapter1), airspace capacity needs to be increased. One method by which this can be achieved is by applying reduced separation standards and this requires high performance (accuracy, integrity, update rate) surveillance technology. At present, the separation standards are stipulated in ICAO Doc 4444 (ICAO, 2007c) . However, these separation standards (3 nautical miles and 5 nautical miles) are based upon the utilization of PSR, SSR and Mode-S radar. Hence, the choice of surveillance technology should also be based on the new surveillance technologies; ADS-B and multilateration, which are envisioned for higher performance to support reduced separation.

2.6 Surveillance Integration

When more than one surveillance system is implemented in an operational area, the surveillance data from the different sensors need to be incorporated into an ATC system for both situational awareness and any ATC separation functions. According to ICAO, these can be done in three ways (ICAO, 2007f):

- A separate ATC display for each surveillance system. However this approach is impractical for the air traffic controllers in performing their tasks.
- A priority system is displayed and other sources discarded, with the priority source provides useable data.
- A fully fused position calculation whereby data from different surveillance sensors are used to calculate the best estimate of aircraft position.

The third approach, 'data fusion', is effective for airspace with redundant surveillance coverage and envisions generating higher accuracy position data. However the integrity of each position plot from each sensor has to be carefully checked to perform the data fusion process.

Air Services Australia performed surveillance integration for airspace with MSSR and ADS-B coverage by providing different symbols on the ATC display for data from each sensor. Priority (rank) is given in this case to the sensors depending on its integrity level and availability in the surveillance area.

2.7 Separation Management

Aircraft separation is performed primarily to prevent collisions and also can assist to optimize the safe use of airspace. Currently the surveillance and the communication systems play an important role in aiding air traffic controllers perform separation management on the surface and in the air. In areas without surveillance coverage, for example, in oceanic areas and remote areas, ATC is dependent on the pilots reporting their position verbally via radio frequencies. Due to uncertainty in the reported position and the low position update rate, the aircraft are separated by relatively large distances (Aeronautical Surveillance Panel (ASP), 2007). On the other hand, in the terminal area, where the surveillance systems are available, reduced separation can be performed. However, with the increasing demand for air travel, the current surveillance systems are unable to improve the separation in order to optimize the airspace capacity. Based on analysis (Joint Planning and Development Office (JPDO)-Air Navigation Services Working Group (ANSWG), 2008) of NextGen capabilities, implementation of ADS-B across the United States National Airspace System could provide 30% of capacity growth to achieve future traffic levels (three times the 2004 traffic levels). Table 2-4 shows the current separation management procedures in comparison to the future separation procedures with ADS-B in place.

Table 2-4: Current and Future Separation Management

Current Separation Procedures	Future Separation Procedures (ADS-B)
▪ Use single sensor reported position and correlation with primary data	▪ Position information from Global Navigation Satellite System (GNSS) via ADS-B
▪ Update rate 4.5s-12s	▪ Update rate 1s-2s
▪ Aircraft velocity is estimated from the history of reported position	▪ Real time aircraft velocity from modern Positioning, Navigation and Timing (PNT) system via ADS-B
	▪ Trajectory based operation and delegated separation procedures introduced.

2.7.1 Use of ATC Surveillance System for Separation

Surveillance systems such as PSR, SSR and ADS-B may be used either alone or in combination in the provision of air traffic control services, including provision of separation between aircraft, provided that (ICAO, 2007c):

- reliable coverage exists in the area;
- probability of detection, accuracy and integrity of the surveillance systems are satisfactory; and
- in the case of ADS-B, the availability of the data from participating aircraft is adequate.

In addition to this, safety assessment of the surveillance systems is crucial before it can be used to provide separation. Since the focus of this thesis is the ADS-B system, further requirements of the system to aid aircraft separation are discussed in Chapter 3. These requirements are tested and validated using real time ADS-B data in Chapter 6.

2.7.2 Constraints to Separation Minima Management

In order to manage separation, a number of constraints need to be considered.

- Human factors e.g. limitation on controller workload
- Technologies (Communication, Navigation, Surveillance) e.g. availability of the technologies
- Operational procedures e.g. approved reduced separation minima
- Contextual environment e.g. extreme weather conditions
- Ability of the Air Navigation Service Providers (ANSPs) e.g. to provide required resources

Hence in this thesis, the constraints caused by the limitations of the current surveillance technologies are discussed further, analyzed and a solution presented, in Chapter 4 based on the findings in Chapter 3.

2.8 Summary

The ability to meet increasing air travel demand is determined by a number of capacity drivers; the controller's capacity, tools to aid the controller's task, the extent of pilot's situational awareness, aircraft capability and contextual environment including the weather conditions and airport capacity. In a structural interview with Harry Daily from the Civil Aviation Authority (CAA), he argued that the ability of the ANSP to provide the appropriate level of air navigation services is also one of the critical factors in meeting the future air travel demand. The controller's workload and task time directly impacts the number of aircraft that can be managed by them in their airspace. Hence, airspace capacity utilization depends on the capacity of the controllers to manage the airspace safely. Majumdar and Polak (2001) developed an approach to estimate the capacity of European airspace by simulating the air traffic controller's workload. However, the controller's workload can be improved by having reliable and accurate tools to assist the controller's tasks.

In addition, shared surveillance information between the controllers and pilots can enhance the situational awareness and reduce the procedural control. As a result there will be less communication between the pilot and controller. The enhanced situational awareness of the pilot also enables more flexible flight routings especially in oceanic airspace. This will reduce the flight time and enable a more economical flight by saving fuel. In addition, a more complete situational awareness onboard will also eliminate difficulties in navigation during extreme weather conditions.

The ability of the surveillance and navigation tools to provide accurate aircraft position information, intent data, speed and the higher update rates will permit to set reduced separation minima. Consequently, airspace utilization can be optimized. In order to support the advanced tools and technologies, aircraft and airports have to be equipped with necessary equipment and infrastructure. As a result, a safe and efficient gate-to-gate operation can be achieved and the increasing air travel demand can be met.

Therefore, in order to achieve these, the next chapter will introduce, discuss and analyze in detail a new surveillance technology (Automatic Dependant Surveillance Broadcast) recognized as the key to resolve most of the problems encountered in the current surveillance systems.

Chapter 3

Automatic Dependent Surveillance Broadcast (ADS-B)

This Chapter introduces the Automatic Dependent Surveillance Broadcast (ADS-B) system. It identifies the role of ADS-B in the global CNS/ATM, and reviews the requirement, system design, functionalities, implementation, as well as supported airborne and ground applications. Furthermore, it analyses the system's strengths and drawbacks to support ATC surveillance. This chapter is the backbone of this thesis and feeds into the analyses conducted in Chapters 4, 6 and 7.

3.1 Background

As discussed in Chapter 2, ICAO endorsed the Future Air Navigation System (FANS) CNS/ATM concept, which is largely based on the satellite technologies in 1992. ADS-B is one of the enablers of this concept, aimed to improve airspace capacity. It is envisioned to overcome the limitations of the radar system (discussed in Chapter 2 and verified in Chapter 4) and to modernize the ATM system. It is the key driver of the Single European Sky (SES) ATM Research (SESAR) and the USA Next Generation Air Transportation System (NextGEN) programs.

3.2 Principle of ADS-B Operation

RTCA (2002) defines ADS-B as a function on an aircraft or a surface vehicle operating within the surface movement area that periodically broadcasts its position and other information without knowing the recipients and without expecting acknowledgements as the system only supports one-way broadcasts. The system is automatic in the sense that it does not require external intervention to transmit the information. It is characterized as dependent due to its dependence on aircraft navigation avionics to obtain the surveillance information. ADS-B is a cooperative system, because it requires common equipage for aircraft, or vehicles on the airport surface to exchange information. It provides aircraft state information such as horizontal position, altitude, vector, velocity and trajectory intent information. The latter is critical for trajectory prediction which is the basis of the trajectory-based operations concept of SESAR and NextGen.

The ADS-B system architecture is divided into two subsystems, “ADS-B Out” and “ADS-B In”. ICAO (2003b) defines the term “ADS-B Out” as the broadcast of ADS-B transmissions from the aircraft, without the installation of complementary receiving equipment to process and display ADS-B data on the cockpit displays. The complementary subsystem is “ADS-B In”, which provides air-to-air situational awareness to the pilots. ADS-B Out has the capability to operate independently to provide air-ground surveillance services to the ATC. On the other hand, implementation of ADS-B In requires fully operational ADS-B Out as a pre-requisite, certification of cockpit displays, consideration of pilot human factors and other activities which have a longer deployment schedule.

An ADS-B equipped aircraft uses an on-board navigation system to obtain the aircraft position from GNSS. The system then broadcasts periodically the position, velocity and intent data to other ADS-B equipped aircraft and ADS-B ground stations within its range via a data link service. The ground stations transmit the received ADS-B reports to a surveillance data processing system to process the data for ATC use. Figure 3-1 illustrates the ADS-B system.

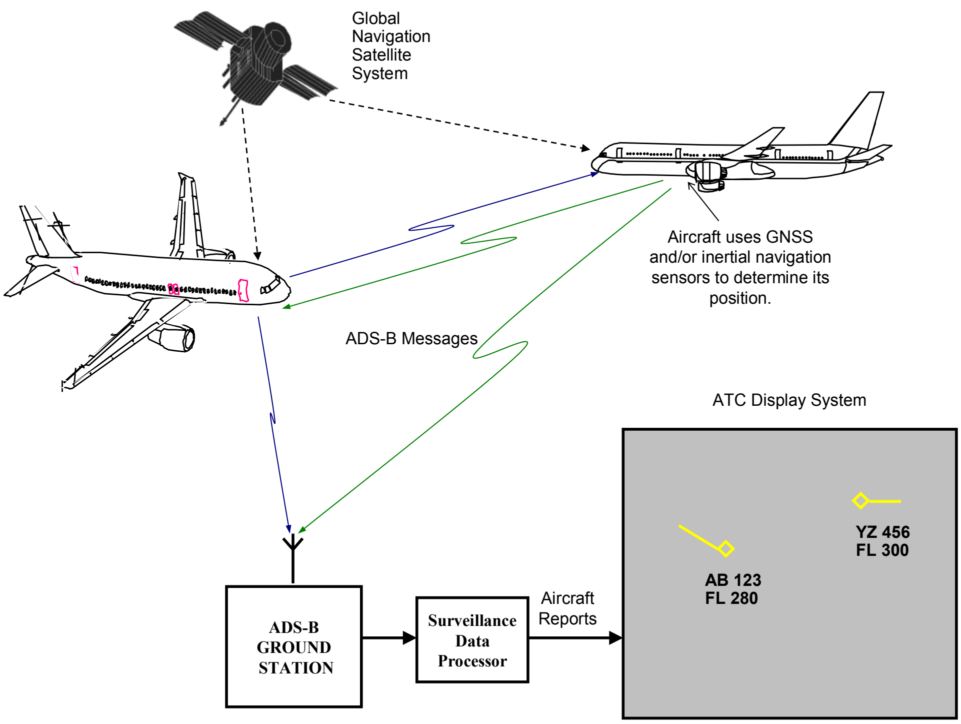


Figure 3-1: Automatic Dependant Surveillance Broadcast (ADS-B) (Owusu, 2003)

3.3 Key differences between Radar and ADS-B

The main difference between radar and ADS-B surveillance is the means of determining the aircraft position and state vector information. As discussed in Chapter 2, radar determines the position from the travel time of a ground-emitted beam reflected by the aircraft and detected by the ground-based station, independent of any aircraft systems. Aircraft speed, direction, turn rate and other state vector information are estimated from consecutive position reports. ADS-B uses position information and state-vectors computed onboard by the aircraft navigation system and broadcast this information via data link. The altitude information is obtained in both cases from an air data computer or barometric altimeter onboard the aircraft. The advantages and disadvantages (Aeronautical Surveillance Panel (ASP), 2007, ICAO, 2007f, Comsoft GmbH, 2007) of the ADS-B system are summarized in Table 3-1.

Table 3-1: Advantages and disadvantages of ADS-B system

Advantages	Disadvantages
Provides the same real-time information to both pilots in aircraft cockpits and ATC in the ground.	As with any secondary surveillance technology, successful surveillance requires the cooperation of the targets. However, ADS-B not only relies on a functional transponder, but also on the integrity of the aircraft navigation system. If this fails, the aircraft will not be able to broadcast its position, or worse, it may broadcast invalid positions.
Enables efficient airspace usage.	It is relatively easy to broadcast fake ADS-B messages simulating non-existent aircraft. Both of these cases are broader, but not substantially different in risk from a classical secondary radar transponder reporting a wrong Mode-C altitude.
ADS-B can be implemented rapidly for a relatively low cost compared to radar.	For complete coverage, all potential targets have to be equipped with ADS-B capable transponders.
Provides a much greater margin in which to implement conflict detection and resolution than is available with any other system.	Since ADS-B messages are broadcast, they are available to all aircraft with the right equipment. Except for regulatory action, there is no way to restrict the availability of aircraft positions. This may lead to security issues.
Enhance aviation safety through features such as automatic traffic call-outs or warnings of imminent runway incursion.	It is totally dependent on aircraft avionics.
ADS-B technology can be scaled and adapted	The service outages are expected due to

Advantages	Disadvantages
for use in general aviation, ground vehicles and in airspace where radar is ineffective or unavailable.	poor GPS geometry when satellites out of service.
General aviation (GA) aircraft can use ADS-B datalinks to receive flight information services such as graphical weather depiction and textual flight advisories. In the past, these services have been unavailable or too expensive for widespread use in GA.	The ground receiver sensors require optimum site with unobstructed view to aircraft.
Reduced cost for ground station maintenance. According to the FAA (FirebirdV8, 2006) the maintenance cost for a radar station costs as much to maintain 20 Ground Based Transceivers (GBT) for ADS-B.	Signal jamming due to the use of same frequency (Mode S) by many systems such as SSR, TCAS, MLAT and ADS-B, particularly in dense airspace.
Enables pilot to receive traffic information with aircraft identification, direction and relative altitude.	
Provides ability to change observation area along with option to take closer look on individual aircrafts.	
Reduces ATC workload.	
Increases situational awareness of the pilot.	

The disadvantages identified in Table 3-1 may contribute to failures of the ADS-B system. The failures may lead to either corruption or loss of ADS-B data. For example, signal spoofing may cause the onboard navigation receiver to estimate the aircraft position to be somewhere other than where it actually is or to be located where it is but at a different time. The corrupted navigation data will be transmitted to the ADS-B transponder, which will subsequently be broadcast to the users. This may impose a safety threat to the ATC and other aircraft navigation operations which rely on the ADS-B system. In addition, failure of the onboard navigation system may lead to loss of ADS-B position information to the users. Apart from that, security issue is also foreseen due to the nature of the ADS-B system, which broadcast aircraft information to all equipped recipients. This allows tapping of the surveillance information with harmful intention to the aircraft.

3.4 ADS-B Infrastructures

The system infrastructure includes ground and airborne infrastructures, that must be certified based on the ICAO/RTCA standards. Figure 3-2 and Figure 3-3 illustrate the avionics for ADS-B Out and ADS-

B In. Table 3-2 and Table 3-3 show the ground and airborne components, their functionalities and the required standards. The aircraft equipage requirement for ADS-B differs according to the implementation of ADS-B Out and ADS-B In. The operational ADS-B Out is a pre-requisite for the ADS-B In implementation. Table 3-4 presents the requirements for both ADS-B Out and ADS-B In.

To enable ADS-B equipped aircraft to operate in non-radar airspace, it has to be certified to Acceptable Means of Compliance (AMC) 20-24 standard (EASA, 2008) (airworthiness and operational approval of the "Enhanced Air Traffic Services in Non-Radar Areas using ADS-B Surveillance"). According to (Rekkas, 2013) the EU Regulation 1207/2011 applies to enable aircraft to operate in radar airspace. However, this regulation is not adopted globally. The aircraft included in this thesis are certified to AMC 20-24 (EASA, 2008) and operate in the London Terminal Area, one of the most dense radar airspaces in the world.

According to the Surveillance Performance and Interoperability Implementing Rule (SPI-IR) (EUROCONTROL, 2011d), aircraft with airworthiness certification on or after 8 January 2015 are to be equipped with secondary surveillance radar transponders with the capabilities specified in Annex IV of the SPI-IR (*forward-fit*). While aircraft with airworthiness certification before 8 January 2015, are to be equipped with the same by 7 December 2017 (*retrofit*). The requirements stipulated in Annex IV of the SPI-IR enable full implementation of ADS-B Out by the aircraft operators. However, to date no regulation has been placed on the Air Navigation Service Providers (ANSPs) to implement ADS-B ground infrastructures. It is expected that this rule will follow in the near future due to the need to implement ADS-B globally.

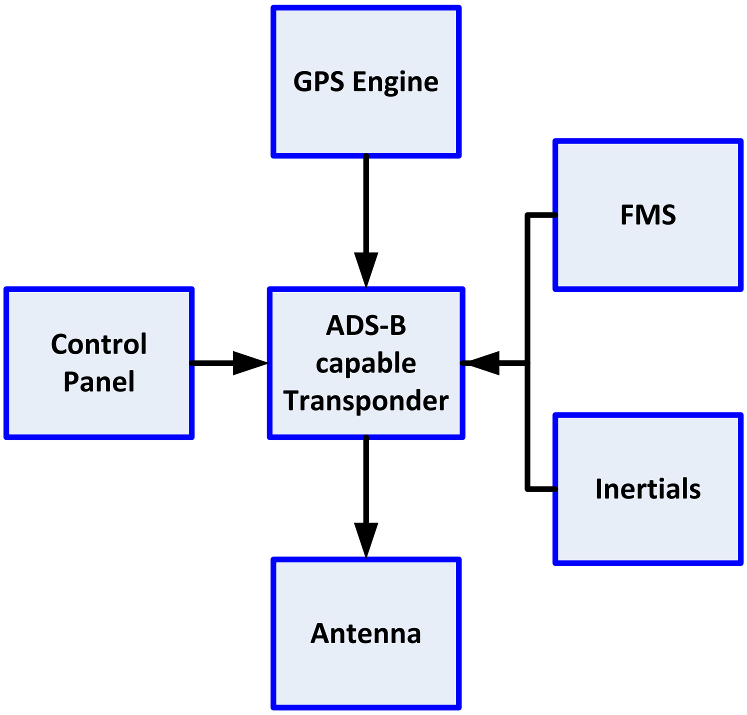


Figure 3-2: ADS-B Out avionics

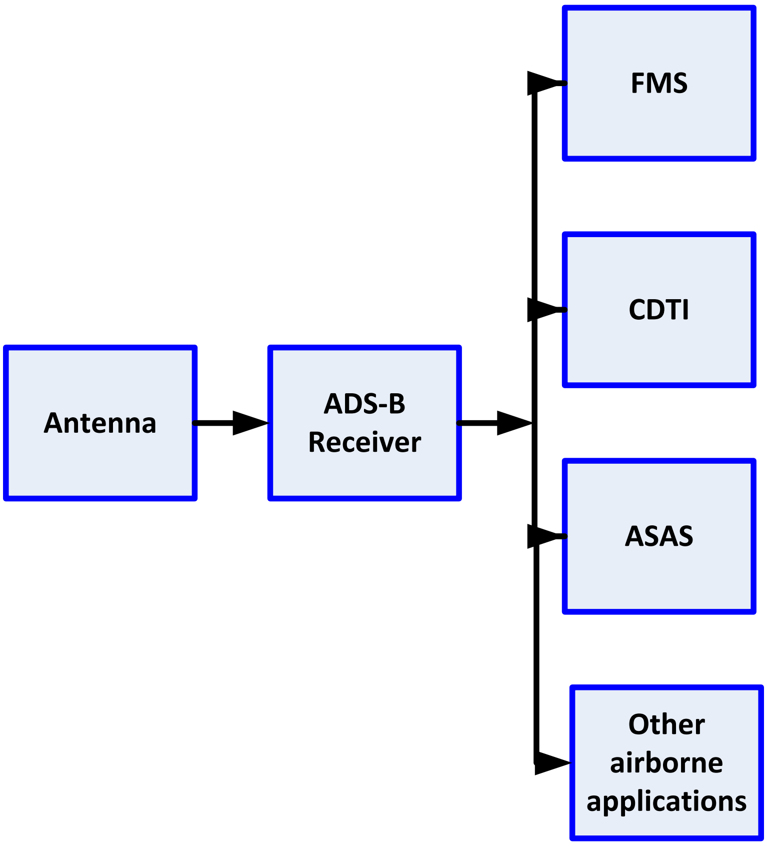


Figure 3-3: ADS-B In avionics

Table 3-2: ADS-B Ground infrastructure components

Components	Function	Standard
ADS-B receiver and antenna	Receive ADS-B messages broadcast from aircraft	ED-129 Technical Specification for 1090MHz Extended Squitter ADS-B Ground Station
GPS Clock	Time stamp received ADS-B messages	ICAO Annex 10
Communication Link	Transmit message from ground station to ATC surveillance data processing unit	Any form of secured dedicated private network connection such as lease line, fiber optic.
ADS-B situational display	Display aircraft position and state vector in a similar manner as radar	Controller Working Position (CWP) standard similar to radar displays

Table 3-3: ADS-B Airborne infrastructure components

Component	Function	Standard
Navigation Source (e.g. GPS)	Derive and transmit aircraft position and state vector information to ADS-B emitter	• TSO C-129A, TSO C-129 or TSO C-129A; or • TSO C-145/C-146 or TSO C-145A/C-146A
ADS-B Avionics (standalone box for UAT) *For 1090ES ADS-B, this function will be performed by the transponder (MODE-S ES transponder)	Encode and broadcast ADS-B message	TSO-154c (UAT) TSO-166b(1090ES)
Antenna for ADS-B , Transponder, GPS	To support ADS-B OUT, a single antenna at the bottom of the aircraft is required. To support ADS-B IN, antenna diversity is required, whereby two antennas; one at the top and one at the bottom of the aircraft is required.	TSO-154c (UAT) TSO-166b(1090ES)
Antenna Duplexer	To enable one antenna sharing between transponder and ADS-B unit.	
Barometric Altimeter	Generate aircraft altitude	
Altitude Encoding Altimeter	Synchronize altitude information transmitted in the ADS-B message and altitude transmitted by the transponder	
Control Panel	To enable pilot to key in or select aircraft identification, SPI, emergency pulse	
Flight Management System (FMS)	To manage flight plan and connected to other avionics	

Table 3-4: Aircraft equipage requirements for ADS-B Out and ADS-B In

ADS-B Out	ADS-B In
Precision GPS Source- Standards vary worldwide but enhanced standards such as TSO-C145 or TSO-C146 will work anywhere.	ADS-B Out system
A transmitting radio- e.g. ADS-B qualified Mode-S transponder (1090ES) or dedicated ADS-B data radio (978 MHz), only used below 18K feet in the US airspace	TIS-B data transmission at both 1090ES and 978 MHz
Simple Controls -Module to enter a squawk code and verify that ADS-B is working	FIS-B graphical weather data is transmitted only at 978 MHz. The system is smart enough to know the exact location and provides a total weather map with prioritization around the current position.
Data link - 1090ES data link is commonly referred to as "Mode S-Extended Squitter" or 978 MHz data link is commonly referred to as "UAT (Universal Access Transceiver)".	Receiver or transceiver for ADS-B In function.

It is noted that ADS-B is highly dependent on navigation and communication systems. At present GPS is widely used and supported as the navigation source for ADS-B. Three types of data links are used in States; Mode S-Extended Squitter (1090ES), Universal Access Transceiver (UAT), and VDL-Mode 4 of which 1090ES is the most widely deployed.

3.4.1 On-board navigation source for ADS-B

This section will focus on the GPS, at present the most widely used navigation source for ADS-B. However, it should be noted that there is no mandate on using GPS as the navigation source. Any on-board navigation system which satisfies the required standards is acceptable.

3.4.1.1 Requirements

The minimum requirements for the navigation source for ADS-B are specified in the Technical Standard Orders TSO-C129, TSO-C145, TSO-C146 and TSO-C196. According to the RTCA, all GPS equipment compliant with the 'Minimum Operational Performance Standards for Global Positioning System / Wide Area Augmentation System Airborne Equipment' are expected to satisfy the requirements for U.S. ADS-B applications.

The navigation source should have the capabilities to provide position accuracy (e.g. Horizontal Figure of Merit – HFOM) and integrity (e.g. Horizontal Protection Level (HPL) (Federal Aviation Administration, 2010). In addition, the integrity level should be equal to or less than 10^{-7} per flight-hour with integrity time to alert equal to or less than 10 seconds. The system is also required to be at least compatible with GNSS receivers that perform receiver autonomous integrity monitoring (RAIM) and fault detection and exclusion (FDE), along with the output of corresponding measurement status information, as well as integrity containment bound and 95% accuracy bound indications (EUROCONTROL, 2011d).

3.4.1.2 Architecture

GPS can be divided into three elements: ground, space and user segments (Royal Academy of Engineering, 2011) :

- The ground or control segment is used to upload data to the satellites, to synchronize time across the constellation and to track the satellites to enable orbit and clock information.
- The space segment consists of the GPS satellites in six orbital planes. 24 satellites make a full constellation, although as of November 2013 there are 31 in active service (US Air Force, 2013).
- The user segment consists of the receivers and associated antennae, to receive and decode the signal and compute Position, Navigation and Time (PNT) and related information.

3.4.1.3 Measurements

GPS is a ranging system with three carrier frequencies, all multiples of a fundamental frequency (Table 3-5). The distance is derived primarily by measuring the time difference between the transmission of a coded signal from the satellite and reception at the receiver. This range is known as the pseudorange rather than range since it includes a number of system unknowns such as clock biases and propagation delays which must be solved for or estimated. The carrier phase of the signals can also be used to derive the range, providing a more accurate position, but with inherent ambiguity. Ranges to at least four satellites are required to determine position and time.

Table 3-5: GNSS RF Carrier Frequencies (Royal Academy of Engineering, 2011)

GPS Frequencies	
L1	1575.42 MHz
L2	1227.6 MHz
L5	1176.45 MHz

The navigation message is transmitted from the satellite to the user and gives the satellite identifier together with information on satellite health, predicted range accuracy, ionosphere and clock correction coefficients as well as orbital ephemeris to allow the receiver to calculate the satellite position. The message also contains an almanac which gives status, location and identifier information for all satellites in the constellation.

3.4.1.4 Backup

In the case of unavailability of GPS, Inertial Navigation Systems (INS) can be used as a backup positioning source for ADS-B. INS, also known as Inertial Reference Unit (IRU), is an independent system comprised of gyros and accelerometers that provide aircraft state, position and velocity information in response to signals resulting from inertial effects on the system components. Once initialized with a known position and heading, INS continuously calculates the aircraft position and velocity. However, there is currently no requirement to provide a backup navigation source for the ADS-B system.

3.4.2 Data link technologies for ADS-B

Data link technologies enable uplink and downlink of data between aircraft and ground-based ATC. Three types of potential ADS-B data links are proposed (ICAO, 2003c): the Mode-S Extended Squitter (1090ES), the Universal Access Transceiver (UAT) and the VHF Digital Link (VDL) Mode 4. The data link characteristics are discussed in the following sub-sections and their differences summarized in Table 3-6. Mode-S 1090ES is explained in greater detail in Section 3.5, given its mandate by ICAO as the global datalink for ADS-B. Furthermore, its importance is underlined by the fact that all aircraft analyzed in Chapter 6 are equipped with 1090ES.

3.4.2.1 Universal Access Transceiver (UAT)

The Universal Access Transceiver is a bi-directional data link developed to support ADS-B. It also supports the Flight Information Service Broadcast (FIS-B) such as weather and flight service information for aircraft. In addition UAT is capable of supporting transmission of radar information via the Traffic Information Service Broadcast (TIS-B) to ADS-B equipped aircraft. This enables to provide situational awareness of unequipped aircraft. The datalink utilizes the 978MHz frequency. UAT data link networks are being installed as part of the FAA’s NextGen, typically for general aviation users.

3.4.2.2 VHF Digital Link (VDL) Mode 4

VHF Digital Link Mode 4 (VDL4) is a digital datalink designed to operate in the VHF frequency band using one or more standard 25 KHz VHF communications channels. It is capable of providing digital communications and surveillance services between aircraft and ground vehicles, as well as ground stations (EUROCONTROL, 2001-2013b). VDL4 is based on the Self Organizing Time Division Multiple Access (STDMA) technology. This concept allows VDL4 to operate without a centralized co-coordinating station, thus eliminating the need for ground infrastructure. However, ground stations serve an important role in providing other services that enhance VDL4 operations. VDL4 supports broadcast and point-to-point communication with a minimum of overhead information, essential for time critical data exchange and low-end users.

3.4.2.3 Mode-S Extended Squitter (1090ES)

The Mode-S Extended Squitter (1090ES) has been developed as an extension to the Mode S technology (described in Chapter 2) for Secondary Surveillance Radar (SSR). It supports Mode A/C radar, Mode S radar, MLAT, TCAS and ADS-B. The data link transmits at 1090MHz. It is used widely in the United States and Australia for ADS-B Out service for commercial aircraft in non-radar airspace. European countries and China are using the data link for ADS-B trial operations in radar and non-radar airspace. It suffers from multipath (e.g. reflections from buildings, aircraft etc.), also making it unsuitable for airport applications. There are also concerns about overloading at this frequency, which is, for example, also occupied by TCAS.

Table 3-6: Comparison between 1090ES, VDL4 and UAT

1090ES	VDL4	UAT
Single channel	Multi channel	Single channel
Frequency 1090MHz	Frequency 108 – 137MHz	Frequency 978MHz
Random access	Time slot access	Time slot access
Fixed and limited channel data bandwidth	Bandwidth 19.2kbps	Bandwidth 2-3 MHz
Fixed ADS-B reporting rate	Variable ADS-B reporting rate	Fixed ADS-B reporting rate
Extension to Mode S	New system	New system
Support air-air broadcast, uplink, downlink	Support air-air broadcast, uplink, downlink	Support air-air broadcast, uplink, downlink
ICAO standard exist	ICAO standard exist	ICAO standard exist
Mandatory equipment	Test equipment	Test equipment

3.4.2.4 Data link performance

Data link performances is assessed in terms of the transmission range (air-to-air and air-to-ground), bandwidth (BW) and the vulnerability of the data link to external factors (interference, multipath, FRUIT, signal jamming). NATS and the EUROCONTROL Experimental Centre have conducted trials to compare the link performance of Mode-S 1090ES, UAT and VDL4 on the Heathrow airport surface for a selected set of trajectories and receiving ground station positions. The trial results (NATS, 2002) indicate that:

- During the static trial, messages were lost from the 1090ES when aircraft equipped with the same data link (1090ES) passed close to the test vehicle. The likely cause assumed is co-channel interference from the passing aircraft transponder rather than a temporary obstruction by the aircraft structure. The messages from UAT were not affected.
- 1090ES and UAT showed a reduction in the reception probability when the test vehicles were close to the Distance Measuring Equipment (DME). This is assumed due to:
  - Corruption from the DME;
  - Signal blocked by the obstruction; or
  - Reflection or multipath due to the obstruction.

  However, VDL4 did not suffer from performance degradation.
- 1090ES and UAT were not available in certain sectors of the airport, where there was an obstruction between the ground stations and the test vehicle. VDL4 on the other hand was unaffected by the obstructions. This shows that the 1090ES and UAT signals were blocked due to the obstruction.
- 1090ES showed a lower performance with reception probability of 94.7% compared to UAT at 99.9% and VDL4 at 100%. This is assumed due to other users of the same frequency (1090ES) on the airport surface. Further studies are required to confirm this hypothesis.
- UAT had better link reliability than 1090ES but suffered from line of sight problems. VDL4 had the highest link reliability.

The performance of 1090ES is assessed in Chapter 6 for air-to-ground broadcast service for various ADS-B installations and aircraft make-models.

3.5 ADS-B using Mode S 1090MHz Extended Squitter (1090ES)

Mode S technology has two types of squitter, a short (56 bit) DF11 acquisition squitter and the extended (112 bit) DF17 squitter. The squitter is a reply format transmission without being interrogated by another means such as radar. The downlink format (DF) and uplink format (UF) are the two functional components of Mode S. UF is a specific interrogation originating from SSR or other aircraft requesting specific information from the aircraft. DF is the reply from the aircraft to the UF interrogation. The DF17 extended squitter is similar to elementary and enhanced surveillance (explained in Chapter 2) except that it does not need interrogation, i.e. it simply 'broadcasts'. The DF17 extended squitter includes the airborne position (BDS 0, 5), surface position (BDS 0, 6), extended squitter status (BDS 0, 7), identity and category (BDS 0, 8) as well as airborne velocity (BDS 0, 9). Binary Data Store (BDS) is a register within the transponder maintaining avionics data in 256 different 56 bit wide registers. It can be loaded with information and read-out by the ground system. Each register contains the data payload of a particular Mode S reply or extended squittter. The BDS registers are also known as Ground Initiated Comm B (GICB) registers (ICAO, 2004d). The registers which are not updated within a fixed period are cleared by the transponder. Registers are identified by a two digit hex number. For example, BDS 05h (or also represented as BDS 0, 5) is the position squitter (SELEX System Integration, 2013). In addition to the 56 bits, the Mode S short acquisition squitter includes:

- 8 bit CONTROL;
- 24 bit ICAO aircraft address; and
- 24 bit PARITY,

1090ES includes an additional 56 bits data field used to carry ADS-B information. Table 3-7 presents the 1090ES ADS-B message type DF17, register and broadcast rate of each register. Figure 3-4 presents the data format.

Table 3-7: 1090ES Extended Squitter ADS-B message, register and broadcast rates (RTCA, 2011)

			Broadcast Rate		
Transponder Register	**Event-Driven Message Priority**	**1090ES ADS-B Message**	**On-the-Ground, not moving**	**On-the Ground and moving**	**Airborne**
BDS 0,5	N/A	Airborne Position	N/A	N/A	2/1 second (0.4-0.6 sec)
BDS 0,6	N/A	Surface Position	LOW RATE 1/5 seconds (4.8 -5.2 sec)	HIGH RATE 2/1 second (0.4-06 sec)	N/A
BDS 0,8	N/A	Aircraft Identification and Category	LOW RATE 1/10 seconds (9.8- 10.2 sec)	HIGH RATE 2/1 second (4.8-5.2 sec)	HIGH RATE 2/1 second (4.8-5.2 sec)
BDS 0,9	N/A	Airborne Velocity	N/A	N/A	2/1 second (0.4 - 0.6 sec)
BDS 6,1	TCAS RA = 1 Emergency = 2	Aircraft Status (Emergency/Priority Status, Subtype=1) (TCAS RA Broadcast,	TCAS RA or Mode A Change 0.7 – 0.9 seconds		
			No TCAS RA, No Mode A Change		

			Broadcast Rate		
Transponder Register	**Event-Driven Message Priority**	**1090ES ADS-B Message**	**On-the-Ground, not moving**	**On-the Ground and moving**	**Airborne**
		Subtype=2)	4.8 – 5.2 seconds		
BDS 6,2	N/A	Target State and Status (TSS)	N/A	N/A	1.2 – 1.3 seconds
BDS 6,5	N/A	Aircraft Operational Status	4.8 – 5.2 seconds	No change NIC_{SUPP}/NAC/SIL 2.4 - 2.6 seconds	TSS being broadcast or not No change TCAS/NAC/SIL/NIC_{SUPP} 2.4 – 2.6 seconds
				Change in NIC_{SUPP}/NAC/SIL 0.7 - 0.9 seconds	TSS being broadcast Change in TCAS/NAC/SIL/NIC_{SUPP} 2.4 – 2.6 seconds
					TSS not broadcast Change in TCAS/NAC/SIL/NIC_{SUPP} 0.7 – 0.9 seconds

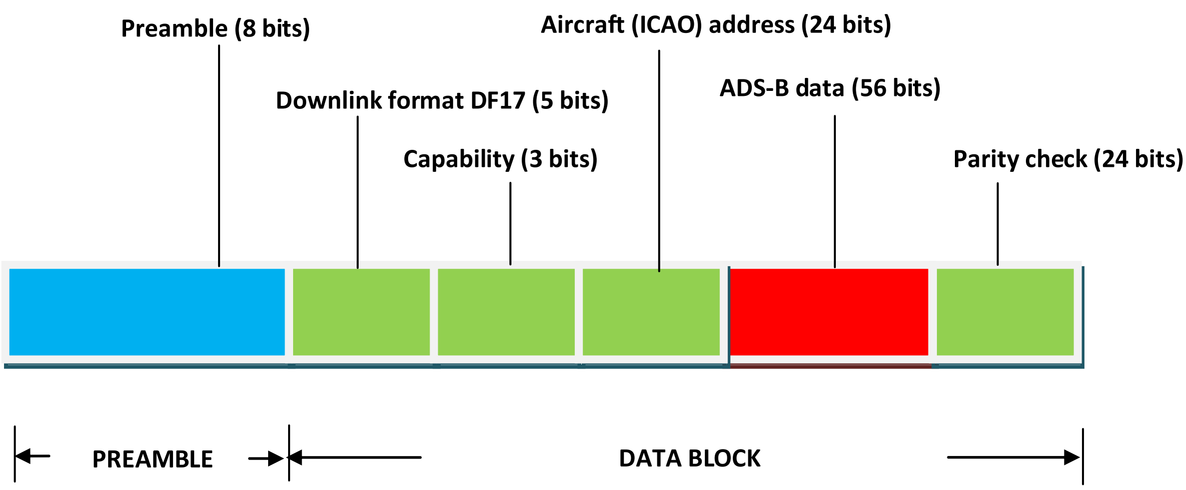


Figure 3-4: ADS-B Extended Squitter Data Format (modified from (EUROCONTROL, 2007))

The extended squitter illustrated in Figure 3-4 is composed of a preamble (8 bits) or also known as control bit, aircraft ICAO address (24 bits), parity check (24 bits), capability (3 bits), downlink format (5 bits) and ADS-B message (56 bits). The preamble bit is required to allow synchronization on reception. The parity check represents the error detection code with the capability bit indicating the capability of the Mode S transponder. The downlink format value is 17, representing the message type – ADS-B. The ADS-B message is defined in Table 3-6. It is also defined in Mode S Extended Squitter Standards and Recommended Practises (SARP) (Annex 10 Am. 77) (ICAO, 2002b) and Mode S Specific Services (ICAO, 2004d). The total duration of the extended squitter message is 120 µs (8µs preamble and 112µs data block). The data block is transmitted using Pulse Position Modulation

(PPM). PPM is a relatively simple modulation scheme for a 1090MHz receiver to decode in the presence of non-overlapping (in time) replies (Institute of Air Navigation Services, 2003).

The minimum content of an ADS-B message is composed of the following (De Oliveira et al., 2009) :

- Emitter Category – defining characteristics of the end users, for example light, medium or heavy aircraft, helicopters, UAV (Uninhabited Aerial Vehicle), land vehicles and obstacles.
- Emitter Identifier - corresponding to the 24 bit network address in ATN
- Latitude, Longitude, Flight Level – corresponding to the 3D position of emitter end user.
- Aircraft Identification – corresponding to the aircraft identification code (Squawk code)
- Data quality indicators – describing the integrity and accuracy of the data.

In addition to the above parameters, the ADS-B message also contains velocity, time stamp and intent information (in the latest version based on DO-260B (RTCA, 2011)).

3.5.1 ADS-B position encoding and decoding – Compact Position Reporting (CPR) algorithm

ADS-B position data are provided in the World Geodetic System (WGS-84) format, latitude and longitude. Compact Position Reporting (CPR) was developed for ADS-B messages broadcast on the 1090ES Extended Squitter (ES) datalink to reduce the number of bits required to transmit the latitude and longitude information. Position resolution for ES messages is approximately 5.1 meters for an airborne target and 1.3 meters for a surface target (Sensis Corporation, 2009). The circumference of the earth is approximately 40 000 kilometers so 40 000 000 m/5.1 m = ~7 800 000 discrete position values. 7 800 000 position values would require 23 bits in a message. Longitude is expressed over a range of 360° so longitude would require the full 23 bits. Latitude is expressed over a range of 180° so only 3 900 000 discrete position values or 22 bits would be required. Similarly, surface position would require 25 bits for longitude and 24 bits for latitude. CPR transmits position with 17 bits each for latitude and longitude plus 1 “CPR format” bit. Table 3-8 tabulates the message bits required for ADS-B position encoding with and without CPR for airborne and surface targets.

Table 3-8: Message bits required for position encoding with and without CPR (Sensis Corporation, 2009)

		Without CPR	With CPR	Bits saved with CPR
Airborne Position	Latitude	22	17	
	Longitude	23	17	
	CPR Format	0	1	
	Total	45	35	10
Surface Position	Latitude	24	17	
	Longitude	25	17	
	CPR Format	0	1	
	Total	49	35	14

CPR saves 10 bits per position message for airborne targets and 14 bits per position message for surface targets. Position messages are envisioned to broadcast twice per second under most conditions. Therefore, CPR saves 20 bits/second for airborne targets and 28 bits/second for surface targets (Sensis Corporation, 2009).

3.6 System Architecture

The optimum ADS-B architecture is unknown because it depends on the type of the data links planned to be used by the regions. As discussed in section 3.4.2, ICAO proposes 1090ES as the global data link for ADS-B while UAT and VDL4 will be used at the regional level. The ADS-B system analyzed in this thesis, and hence the architecture is based on 1090ES. ICAO enumerated a number of functional requirements related to various surveillance applications without stipulating those to be supported by ADS-B (ICAO, 2003a). The surveillance applications envisioned to be supported by the ADS-B system are described in section 3.7. Figure 3-5 depicts the high level architecture of a complete ADS-B system.

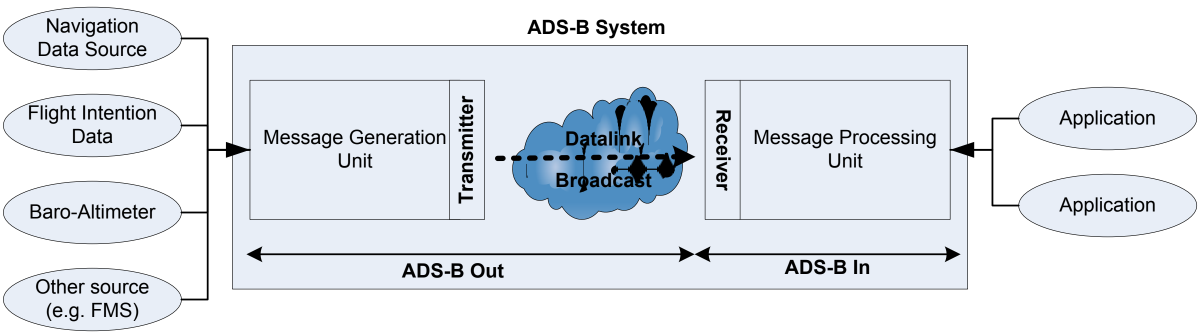


Figure 3-5: High Level Architecture of ADS-B (ICAO, 2003a)

The ADS-B system depicted in Figure 3-5 is composed of a message generation unit (which merges the data coming from aircraft sensors such as the navigation sensor, barometric altimeter and pilot inputs including aircraft identification and flight intent information), a transmitter (for transmission of the message), a data link (which carries out message distribution), a receiver (that receives the message), and a message processing unit (this prepares the ADS-B report for the use of various surveillance applications as described in section 3.6.2). Thus, unlike radar surveillance technology, which does not require a means of communication, ADS-B incorporates communication requirements to deliver the surveillance functions. In addition, ADS-B relies on the on-board navigation equipment to obtain aircraft positioning information. This shows a strong dependency between surveillance, navigation and communication functions in ADS-B technology. Therefore, it is important to apply the Required Communication Performance (RCP), Required Surveillance Performance (RSP) and Performance Based Navigation (PBN) requirements to ADS-B system design and its implementation. The ADS-B system is integrated with many other external systems such as GNSS which provides the navigation data; barometric altimeter that provides the aircraft altitude; a module that allows the pilot to manually key-in message such as flight intent, aircraft identification; and others. The application functions linked to the ADS-B system in Figure 3-5 represents the surveillance applications that utilize the ADS-B data to provide either air-air surveillance such as Cockpit Display of Traffic Information (CDTI), Aircraft Separation Assurance System (ASAS) or air-ground surveillance for the ATC.

3.6.1 System Integration

ADS-B system is a complex system, being highly dependent upon navigation and communication technologies. The ADS-B system is integrated with the following sub-systems to generate the ADS-B report, for broadcast to the ground-based ATC and to other ADS-B equipped aircraft within its configured range:

- Navigation system
- Barometric altimeter
- Pilot input module (FMS/Control Panel)
- Data link medium
- Transmitter
- Receiver

Each of these subsystems is prone to failures, and in order to assure safety, a detailed understanding of failure modes of each is required. Chapter 7 identifies, analyses and quantifies these failures. The data generated by the individual avionic systems listed above are integrated in the ADS-B Emitter/ ADS-B capable transponder into a report which is broadcast to ground stations and other ADS-B equipped aircraft within the coverage area. Figure 3-6 shows a Context Diagram illustrating the data sources, elements and flow for ADS-B.

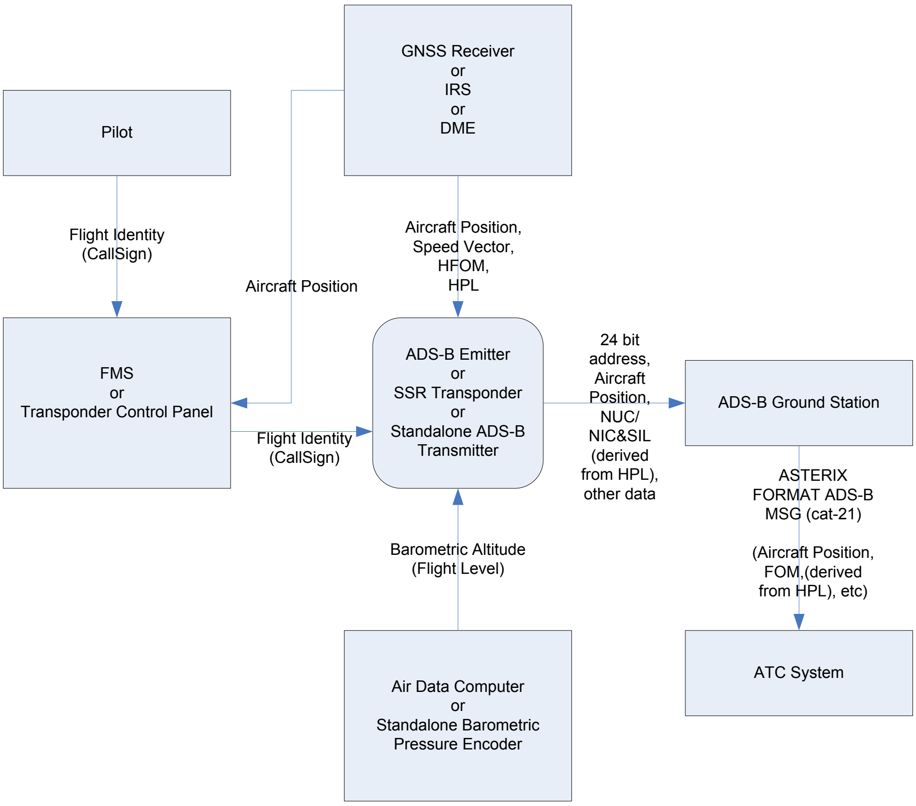


Figure 3-6: Context Diagram for ADS-B data source, element and flow

3.6.2 ADS-B report generation

An ADS-B message is a block of formatted data which composes an ADS-B report in accordance with the properties of the ADS-B data link (RTCA, 2002).The data link determines the size and type of information that can be broadcast. ADS-B reports are specific information provided by the ADS-B Report Assembly Function to external applications supported by ADS-B. The report contains identification, state vector, and status/intent information. The elements of the ADS-B report used and the frequency with which they must be updated vary by application. The portions of an ADS-B report that are provided vary by the capabilities of the transmitting ADS-B system. Figure 3-7 illustrates the report generation process and the corresponding modules.

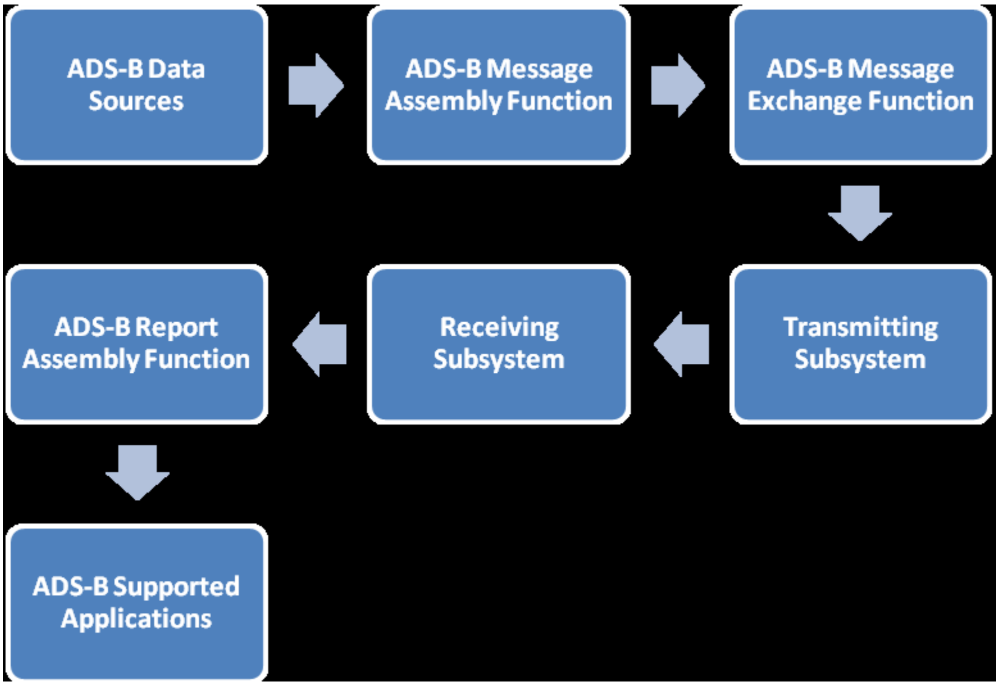


Figure 3-7: ADS-B Report Generation Process

3.7 Supported Applications

ADS-B supports two types of applications:

- Aircraft-to-aircraft applications i.e., applications that transmit data from one aircraft or vehicle to others in the air and on the ground; and
- Aircraft-to-ground applications i.e., applications that require data to be broadcast from an aircraft or vehicle to fixed ground users (RTCA, 2002).

These applications can be categorized into three groups as shown in Table 3-9. The ADS-B data elements required to support enhanced air navigation and surveillance applications are summarized in Table 3-10.

Table 3-9: ADS-B supported applications

Category	Application
Ground-based surveillance applications	1) ATC surveillance in airspace with radar coverage 2) ATC surveillance in airspace without radar coverage 3) Airport surface surveillance 4) Aircraft derived data for ground-based ATM tools
Aircraft-based surveillance applications	1) Situational awareness ▪ Enhanced traffic situational awareness on the airport surface ▪ Enhanced traffic situational awareness during flight operations ▪ Enhanced visual acquisition of traffic ▪ Enhanced successive visual approaches 2) Airborne spacing and separation ▪ Enhanced sequencing and merging operations ▪ In-trail procedure

Category	Application
	▪ Enhanced crossing and passing operations
Other applications	1) Ramp control/gate management 2) Noise monitoring 3) Flight following (for flying schools) 4) Remote airport charges issuing 5) Enhanced situational awareness of obstacles 6) Search and Rescue (SAR)

Table 3-10: ADS-B information required to support ADS-B applications (RTCA, 2002)

Information Element	Aid to Visual Acquisition	Conflict Avoidance and Collision Avoidance	Separation Assurance & Sequencing	Flight Path Deconfliction Planning	Simultaneous Approaches	Airport Surface (A/V to A/V & A/V to ATS)	ATS Surveillance
Identification							
Call Sign			✔	✔	✔	✔	✔
Address	✔	✔	✔	✔	✔	✔	✔
Category			✔	✔	✔	✔	✔
State Vector							
Horizontal Position	✔	✔	✔	✔	✔	✔	✔
Vertical Position	✔	✔	✔	✔	✔		✔
Horizontal Velocity	✔	✔	✔	✔	✔	✔	✔
Vertical Velocity	✔	✔	✔	✔	✔		✔
Heading						✔	
NIC		✔	✔	✔	✔	✔	✔
Mode Status							
Emergency/ Priority Status							✔
Capability Codes		✔	✔	✔	✔	✔	✔
Operational Modes		✔	✔	✔	✔	✔	✔
State Vector Quality		✔	✔	✔	✔	✔	✔
Air-Reference Vector		✔	✔	✔	✔		✔
Intent		✔	✔	✔			✔

3.8 ADS-B performance parameters, indicators, requirements and standards

ADS-B performance is measured in terms of accuracy, availability, integrity, continuity and latency of the surveillance data provided by the system (EUROCONTROL, 2011d). These parameters are defined in the following subsections. The quality indicators representing the surveillance data accuracy and integrity are derived from the onboard navigation source that feed the ADS-B system with aircraft position and velocity. Therefore, the ADS-B surveillance data performance mainly is driven by the onboard navigation system. In addition, the surveillance data performance also relies on the performance of the communication system that broadcasts the ADS-B surveillance data to users. Furthermore, various other factors affect the surveillance data performance. These are investigated in Chapter 6 and 7. ICAO in collaboration with the RTCA, FAA, EUROCONTORL and Air Services Australia has developed various requirements and standards to ensure adequate system performance and interoperability. Chapter 5 addresses how the performance parameters relate to safety. The requirements and standards discussed in this section only apply to ADS-B Out. To date, the complete standards or requirements for ADS-B In are still to be developed.

3.8.1 ADS-B performance parameters

3.8.1.1 ADS-B Accuracy

ADS-B accuracy is defined as a measure of the difference between the aircraft position reported in the ADS-B message field and the true position. It is also defined as noise where the noise is assumed to follow a Gaussian distribution and the RMS value is quoted (ICAO, 2006b). ADS-B accuracy is also analysed based on the quality indicator representing position estimate accuracy included in the ADS-B message. The quality indicator derivation and definition are described in the next sub-section. In this thesis, the ADS-B horizontal position accuracy is assessed (Chapter 6).

Horizontal position accuracy is assessed as the horizontal position measurement error distribution. For ADS-B, horizontal position accuracy is defined as the radius of a circle centred on the reported position of the target such that the probability of the actual position of the target being inside the circle is 95% (ICAO, 2006b). This is illustrated in Figure 3-13.

Vertical accuracy is defined as the vertical position measurement error distribution. For ADS-B, barometric altimeter on the aircraft provides the altitude to the ADS-B emitter and transmitted to the ADS-B ground station (ICAO, 2006b). In addition, ADS-B also provides geometric altitude derived by the onboard navigation system. However, the altitude data from the barometric altimeter is the current standard requirement for ATC operations even though the geometric altitude provides greater accuracy. Therefore, accuracy of the vertical position can be measured with reference to the geometric altitude.

The contributing elements to ADS-B accuracy include accuracy of the onboard navigation function that provides the positioning data to the ADS-B system, onboard latency and delay in the ADS-B communication function. Other factors that influence ADS-B horizontal position accuracy are investigated in Chapter 6.

3.8.1.2 ADS-B Integrity

ADS-B integrity is the level of trust that errors will be correctly detected. Integrity risk is the probability that an error larger than a given threshold in the information is undetected for longer than a predefined time to alert (ICAO, 2006b). ADS-B horizontal position integrity is the level of trust that can be placed in the navigation source to provide the input to the ADS-B reported position. This is represented by the integrity quality indicator derived from the navigation source position integrity indicator. The derivation of the integrity quality indicator included in the ADS-B message is explained in section 3.8.2. ADS-B position integrity is also analysed based on the quality indicator.

3.8.1.3 ADS-B Continuity

ADS-B continuity is the probability that the system performs its required function without unscheduled interruption, assuming that the system is available when the procedure is initiated (ICAO, 2006b). ADS-B continuity includes:

- the continuity of functions affecting all aircraft (e.g. satellite function, ground data acquisition function): expressed in terms of number of disruptions per year;
- the continuity of system affecting only one aircraft (e.g. transponder function): expressed per flight hour; and
- the continuity of navigation sources (including satellite constellations) of sufficient quality in the region which affects many aircraft.

3.8.1.4 ADS-B Availability

ADS-B availability is the ability of the system to perform its required function at the initiation of the intended operation. Availability is measured by quantifying the proportion of time the system is available with respect to the time the system is planned to be available. Periods of planned maintenance are not included in the availability measure (ICAO, 2006b). ADS-B availability includes:

- the availability of functions affecting all aircraft (e.g. external positioning function, ground data acquisition function) ;

- the availability of system affecting only one aircraft (e.g. transponder function): expressed per flight hour; and
- the availability of navigation sources (including satellite constellations) of sufficient quality in the region will affect many aircraft.

3.8.1.4 ADS-B Latency

ADS-B latency is the delay between the aircraft position determination by the on-board navigation system and the position reception by the ground station. The latency measure directly affects the position accuracy. Latency measures for each aircraft are analysed in Chapter 6. The factors that contribute to ADS-B latency, latency budgeting and latency models are also identified and derived in Chapter 6.

3.8.2 Generation of surveillance data performance indicators

The ADS-B system obtains aircraft horizontal position in the World Geodetic System-84 (WGS-84) coordinates from the onboard GPS. The ADS-B reports delivered to ATC contain indicators of the position accuracy (Navigation Accuracy Category for Position (NACp)) and integrity (Navigation Integrity Category (NIC)). These indicators are based on the GPS integrity monitoring capability (RAIM) which reports the Horizontal Protection Level (HPL) with a 10^{-7}/hr integrity risk (encoded as NIC) and Horizontal Figure of Merit (HFOM) as a 95% horizontal accuracy bound (encoded as NACp). HFOM is also known as Estimated Position Uncertainty (EPU).

The NIC parameter specifies a position integrity containment radius (Rc). NIC is reported such that ATC or other aircraft may determine whether the reported geometric position has an acceptable level of integrity for the intended use (Federal Aviation Administration, 2010). Table 3-11 tabulates the applicable NIC values.

Table 3-11: NIC Values (Federal Aviation Administration, 2010)

NIC	Containment Radius
0	Unknown
1	RC < 37.04 km (20nm)
2	RC < 14.816 km (8nm)
3	RC < 7.408 km (4nm)
4	RC < 3.704 km (2nm)
5	RC < 1852 m (1nm)
6	RC < 1111.2 m (0.6nm)
	RC < 926 m (0.5nm)
	RC < 555.6 m (0.3nm)
7	RC < 370.4 m (0.2nm)
8	RC < 185.2 m (0.1nm)
9	RC < 75 m
10	RC < 25 m
11	RC < 7.5 m

The NACp specifies the accuracy of the aircraft's horizontal position information (latitude and longitude) transmitted from the aircraft's avionics. Table 3-12 provides the applicable NACp values.

Table 3-12: NACp values (Federal Aviation Administration, 2010)

NACp	Horizontal Accuracy Bound
0	EPU ≥ 18.52 km (10nm)
1	EPU < 18.52 km (10nm)
2	EPU < 7.408 km (4nm)
3	EPU < 3.704 km (2nm)
4	EPU < 1852 m (1nm)
5	EPU < 926 m (0.5nm)
6	EPU < 555.6 m (0.3nm)
7	EPU < 185.2 m (0.1nm)
8	EPU < 92.6 m (.05nm)
9	EPU < 30 m
10	EPU < 10 m
11	EPU < 3 m

The block diagram in Figure 3-8 illustrates the interface and data flow between a GPS receiver and ADS-B system on-board.

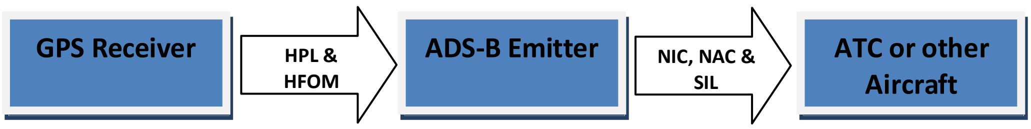


Figure 3-8: Data flow between navigation source and ADS-B equipment

In addition to the NACp and NIC, ADS-B system performance is determined by the Source Integrity Level (SIL) parameter (Smith et al., 2006). SIL is defined as the probability of the integrity containment radius used in the NIC parameter being exceeded without detection (ICAO, 2006b). The GPS HPL is encoded as the NIC at a SIL corresponding to 10^{-7}per hour, which is equivalent to SIL=3. ADS-B surveillance safety is assured by the NIC/SIL integrity parameters (ICAO, 2006b). Figure 3-9 illustrates the coded performance parameter for ADS-B based on GPS as a navigation source.

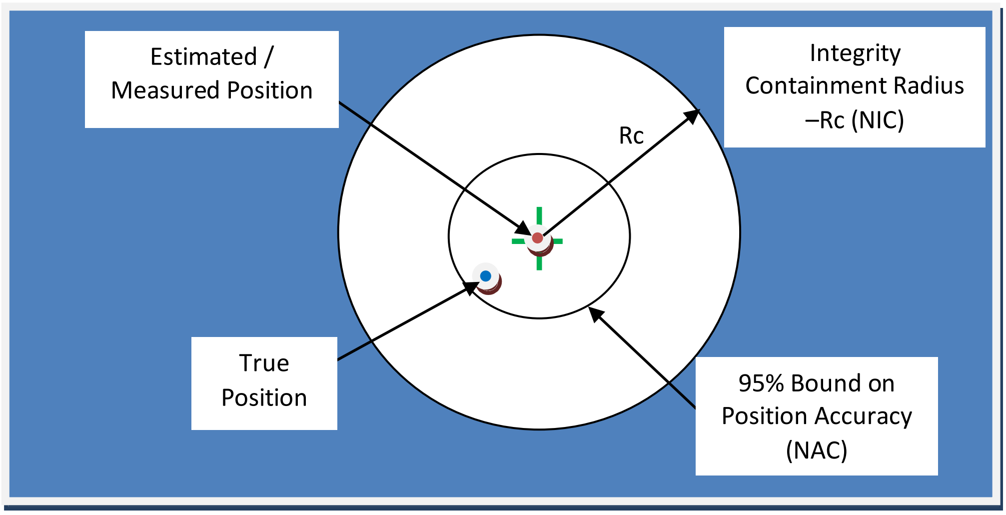


Figure 3-9: Coded performance parameters for ADS-B (modified from (ICAO, 2006b))

3.8.3 ADS-B Performance Requirements

Performance requirements for surveillance are determined by the application, including the airspace in which the aircraft operates. For example, reduced separation minima for the terminal area require better performance than in the en-route sector. The general requirements for the performance stipulated in the SPI-IR (EUROCONTROL, 2011d) and ED-142 (EUROCAE, 2010) are summarized in Table 3-13.

Table 3-13: Summary of ADS-B surveillance performance requirements

Item	Integrity	Accuracy	Continuity	Latency
Overall ADS-B system	$\leq 10^{-5}$ per flight hour (with respect to NIC) with time to alert ≤10 seconds	<150 meters for 3NM separation	Update rate of ≤ 2 seconds	Total Latency ≤ 1.5 second in 95% of transmissions. Uncompensated Latency ≤ 0.6 second in 95% of transmissions. Uncompensated Latency ≤ 1.0 second in 99% of transmissions.

3.8.4 ADS-B Performance Standards

ADS-B standards for avionic and ground station equipment are discussed in Section 3.4. In this section, ADS-B performance standards are discussed. The main standards are developed by the RTCA and used globally by Regulators, ANSPs, airline operators and aviation equipment manufacturers. The standards relevant to the work in this thesis include ADS-B performance standards for operations, system and safety and interoperability. These standards are described as below:

3.8.4.1 Operational Performance Standard

The operational performance standard is provided in the 'Minimum Operational Performance Standards (MOPS) for the 1090 MHz Extended Squitter Automatic Dependent Surveillance Broadcast (ADS-B) and Traffic Information Services Broadcast (TIS-B) 'or also known as RTCA DO-260B. This revision supersedes DO-260 and DO-260A. This document contains the minimum operational performance for airborne equipment for Automatic Dependent Surveillance-Broadcast (ADS-B) and Traffic Information Service-Broadcast (TIS-B) utilizing the 1090 MHz Mode-S Extended Squitter (1090ES). Compliance with these standards by manufacturers, installers and users is recommended as one means of assuring that the equipment will satisfactorily perform its intended functions under conditions encountered in routine aeronautical operations. To date most of the operational aircraft flying were certified under the DO-260 standard. The equipage upgrade specifically for aircraft will only take place at the beginning of 2015. This is discussed in section 3.4. All the aircraft included in this thesis are certified under DO-260. The technical differences between DO-260, DO-260A and DO-260B were analysed by the ADS-B Study and Implementation Task Force (ICAO, 2012a). The findings are summarized in Table 3-14.

The improvements made from RTCA DO-260 to DO-260B results in additional information. This information is meant to increase the user confidence on the ADS-B information and as a door to enable the development of further ATM automation application for enhanced surveillance functions. However, it is important to note that these improvements in the standards do not improve the individual performance parameters. The only improvement noted will be due to the change in SDA (proposing direct connection between onboard navigation system and ADS-B transponder) which will reduce latency of the ADS-B message, contrary to the system architecture proposed in the earlier standard.

Table 3-14: Differences between DO-260, DO-260A and DO-260B

	DO-260	DO-260A	DO-260B	Availability of data in Asterix CAT 21
Introduction of Navigation Integrity Category (NIC) to replace Navigation Uncertainty Category (NUC_P)	NUC_P is used	NIC is used to replace NUC_P	More level of NIC available. Vertical component removed	NIC is shown in v1.0 and above. More level of NIC (shown as PIC) is available in v2.1
Quality Indicator for Velocity (NUC_R and NAC_V)	NUC_R is used	Replaced with NAC_V. Definition remains the same	Vertical component removed	Available in v0.23 and above
Surveillance Integrity Level and Source Integrity Level (SIL)	Not available	Surveillance Integrity Level is used	Renamed as Source Integrity Level. Definition is changed to exclude avionics fault.	Available in v1.0 and above
System Design Assurance (SDA)	Not available	Not available	To address probability of avionics fault	Available in v2.1
Navigation Accuracy Category (NAC_P)	Not available	Derived from HFOM and VFOM	Relies only on HFOM	Available in v1.0 and above
Geometric Vertical Accuracy (GVA)	Not available	Not available	Derived from VFOM	Available in v2.1
Barometric Altitude Integrity Code (NIC_{BARO})	Not available	To indicate integrity of Barometric altitude	Same as DO-260A	Available in v1.0 and above
Length / Width of Aircraft	Not available	Provide an indication of aircraft size	Same as DO-260A	Available in v1.0 and above
Indication of capabilities	Only show status of TCAS and CDTI	More information available including capability to send Air Reference Velocity, Target State and Trajectory Change reports	Additional information on type of ADS-B in (i.e. 1090ES in or UAT in)	Available in v1.0 and above, except availability of 1090ES/UAT in and information on GPS antenna offset
Status of Resolution Advisory		Information on whether Resolution Advisory is active	Same as DO-260A	Available in v1.0 and above
GPS offset		Indication on whether GPS offset is applied	Information on GPS antenna offset is provided	GPS offset status is available in v1.0 and above. Information on GPS offset is not available in ASTERIX
Intention	Not available	Able to indicate intended altitude and heading	Same as DO-260A	Intended altitude is available in v0.23. Intended heading is not available in ASTERIX
Target Status	Not available	Not available	Indication of Autopilot mode,	

	DO-260	DO-260A	DO-260B	Availability of data in Asterix CAT 21
			Vertical Navigation mode, Altitude Hold mode, Approach Mode and LNAV Mode	
Resolution Advisory	Not available	Not available	Availability of Active Resolution Advisories; Resolution Advisory complement record, Resolution Terminated; Multiple Threat encounter; Threat Type indicator; and Threat Identity data	Available in v1.0 and above
Mode A	Broadcasted using test message in USA only	Broadcasted using test message in USA only	Broadcasted worldwide as a regular message	Available in v0.26 and above

The new information available under DO-260A/B would benefit the users in terms of operational decisions as follows (ICAO, 2012a):

- The additional quantum levels of NIC would provide the ANSPs more flexibility in deciding whether the NIC is considered as 'good'. For example, if it is decided that Rc<0.6NM can be used for radar separation, instead of Rc<0.5NM, more aircraft could benefit from the ADS-B services. Instead in DO-260, the level immediately after HPL<0.5NM is HPL<1.0NM.
- The SIL will allow the user to further assess the integrity of the reported position.
- The SDA will indicate the robustness of the system, and allowing the ANSPs to decide on a minimum SDA for ADS-B services.
- The NIC_{BARO} which indicates the integrity of the barometric height may potentially be used to develop new ATM tools in this feature.
- The width / length which indicate the size of the aircraft may be used as an input for generating alerts on airport surface movement control.
- Indication on GPS offset may be one of the inputs for generating alerts on airport surface movement control. Indication on the availability of 1090ES/UAT will allow the controller to anticipate a potential request for in-trail procedure clearance. Indication of the resolution advisory status allows the controller to know whether the pilots were alerted about the potential conflict.
- The intent heading and flight level can be used as an input to the trajectory prediction algorithm in the Short-Term Conflict Alert.
- The target status allows the controller to know the mode that the aircraft is in.
- The Resolution Advisory will help the controller know the advisories that are provided to the pilots by the ACAS. This will prevent the controller from giving instructions that are in conflict with the ACAS.
- The Mode A allows flight plans to be coupled with the ADS-B tracks.

3.8.4.2 System Performance Standard

The system performance standard is provided in the 'Minimum Aviation System Performance Standards (MASPS) for Automatic Dependant Surveillance Broadcast (ADS-B)' or also called RTCA DO-242A. This document supersedes DO-242 and provides an up-to date view of the system-wide operational use of ADS-B. This revised ADS-B MASPS concentrates on four major areas of development:

- Separating the accuracy and integrity components of the Navigation Uncertainty Category (NUC) into the new fields Navigation Accuracy (NAC) and Navigation Integrity Category (NIC);
- Reorganization of the State Vector, Mode-Status, and On-condition reports;
- Restructuring the content and manner in which intent information is broadcast; and
- Clarification that system requirements at the MASPS level are based on operational ranges and not particular applications.

3.4.8.3 Safety & Interoperability Performance Standard

The safety and interoperability performance standard is provided separately for non-radar and radar airspace in Safety, Performance and Interoperability Requirements for the ADS-B Non-Radar-Airspace (NRA) Application (RTCA DO-303) and Safety, Performance and Interoperability Requirements for Enhanced Air Traffic Services in Radar-Controlled Areas Using ADS-B Surveillance (ADS-B-RAD) (RTCA DO-318). These documents provide the requirements for ADS-B Out safety and interoperability in non-radar and radar airspace respectively.

It is important to understand that the requirements stipulated in the various standards by RTCA, EUROCAE or ICAO are meant to affirm the required functions and performance level. However the standards do not provide the methods/mechanisms to implement those requirements. They are totally dependent on the equipment manufacturers. Hence, there is no standardized method available on how to develop the mechanism to enable the required functions within the system. The willingness of the equipment manufacturers to invest in the research and development of the system functionalities are also influenced by the mandate of the ADS-B system. Various versions of the equipment may induce different problems due to the different methods developed by the different manufacturers.

3.9 Implementation

A fully operational ADS-B system (ADS-B Out and ADS-B In) requires all aircraft to be equipped with certified ADS-B avionics, certified ADS-B ground stations with complete airspace coverage, globally agreed operational procedures and most importantly a mandate. These in turn depend on the airline operators to equip aircraft, ANSP to provide the ground infrastructures and Regulators (ICAO, FAA, and EUROCONTROL) to provide the operational procedures and mandate to the stakeholders. In addition, the willingness of equipment manufacturers to develop the required functionalities to support the required ADS-B application is crucial. Before the system can be made fully operational, collaborative effort from both the ANSP and airline operators must made compulsory. This is vital to assess and ensure the required system performance including safety to support the intended surveillance applications.

According to the FAA and EUROCONTROL, ADS-B is envisioned to modernize the air transportation system with improved safety, capacity and efficiency. Despite the anticipated benefits of ADS-B, its adoption rate is tied to each operator's own cost/benefit analysis. The higher the benefit over the cost, the greater the likelihood of early adoption. In addition, political interference also plays a major role in the adoption and implementation of ADS-B. ADS-B component costs vary from several thousand to several tens of thousands of dollars depending on overall system capability. According to "FreeFlight Systems", an ADS-B component provider in the United States, the component cost for smaller aircraft can be as little as $10,000 while for larger aircraft, the cost can go up to more than $100,000. According to (Esler, 2007) two key ingredients for optimizing the cost/benefit are to:

- buy the right technical standard order (TSO) which is approved by the regulators and includes pre-testing which minimizes short term costs; and
- get double-duty out of the ADS-B components.

Due to the involvement of various parties and costs, the implementation processes are carried out in phases. The progress of ADS-B implementation in recent years has been driven by voluntary effort of the various parties and in some cases a regional mandate (e.g. in Australia). Without a global mandate, it will not be possible to provide a complete ADS-B service. Instead, ATC will have to operate in mixed mode operational environment (radar and ADS-B), which will disable the ADS-B In function. However, full mandate will be achieved following the SPI-IR forward-fit and retrofit rule as discussed in section 3.4. Figure 3-10 illustrates the global plan for the deployment of ADS-B services. Table 3-15 summarizes the progress made by the main players.

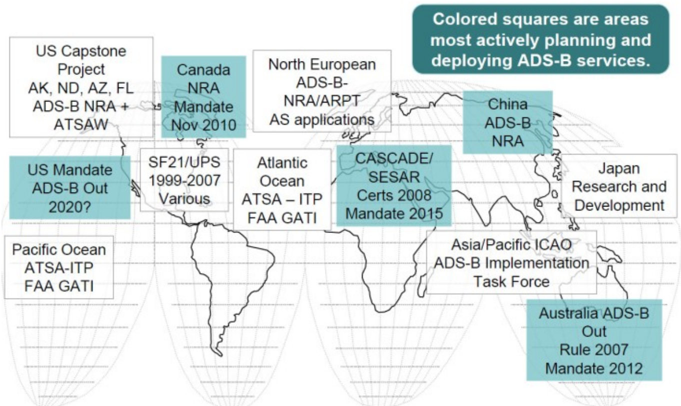


Figure 3-10: ADS-B Worldwide Planning and Deployment (Boeing, 2009)

Table 3-15: Summary of current ADS-B implementation progress

Country	Project	Progress & Mandate
USA	NextGen	2010 – FAA publishes an ADS-B out rule; 2013 – Ground infrastructure in place; 2015 - 2020 – Mandate will be for 100% equipage of ADS-B out
Australia		2003 – Instrumental in forming APANPIRG ADS-B Implementation Task Force; 2007 – Installed 28 sets of ground equipment providing high altitude coverage; Ground surveillance trial at Bundaberg complete; 2008 – Existing equipage being certified for use in Non-radar airspace and radar upper airspace (voluntary); Low altitude program delayed; 2012 – Mandate of ADS-B Out equipage in Jun 2012
Europe	SESAR, CASCADE	2009 – Proposed Notice of Proposed Rulemaking (ENRPM) activity October 2008 through February 2009; 2012 – Potential mandate for production aircraft; 2015 – Mandate for all aircraft (full retrofit) for entry into airspace
Canada		Nov 2008 – Tactical use of surveillance separation within coverage volume; Aug 2008 – AIC to be issued stating this plan and the requirements for tactical surveillance -Transport Canada approval required -Enter correct ICAO Flight ID from field 7 on the flight plan -Include "ADS-B" in field 18 of the filed ICAO flight plan; Mid 2009 – Airspace segregation FL350 to FL400 inclusive in Hudson and Minto Sectors; Nov 2010 – Later ADS-B implementation in other remote areas where there is no radar coverage

3.9.1 ADS-B Out Deployment

Based on the summary in Table 3-15 and Figure 3-14, it is clear that the first stage of ADS-B implementation focuses on ADS-B Out in non-radar airspace. Australia is leading in this initiative. This is due to Australia's difficult topography which causes difficulties to site radars to provide complete surveillance coverage in the region's airspace. In December 2009, Airservices Australia commissioned the ADS-B Upper Airspace Project (UAP), providing ADS-B coverage across the whole continent. Since then, 29 ADS-B sites have been added, in addition to 14 sites in Tasmania which are now fully operational. Aircraft avionics are being assessed and approved for operational use. ADS-B data from non-approved aircraft is filtered out at each site. Currently, over 1200 aircraft are approved and receiving the operational and safety benefits of ADS-B services in Australia. Australia has also made ADS-B equipage mandatory for all aircraft (domestic and foreign) operating at or above FL290 as of December 2013 (SKYbrary, 2013).

ADS-B deployment in Canada is focusing on non-radar airspace. To date, ADS-B has enabled surveillance coverage for 250,000 square nautical miles of airspace over Hudson Bay in Northern Canada. The majority of the flights in this airspace link Europe and North America, while many transit to Asia, including those using polar tracks. The service commenced in January 2009. The controllers are currently using ADS-B tactically by applying reduced separation between equipped aircraft on an opportunity basis. This means each aircraft will have the appropriate protected airspace around it applied based on its capability (SKYbrary, 2013). The next step for NAV CANADA is to segregate airspace vertically and deploy ADS-B in other remote areas without radar coverage.

ADS-B deployment is also ongoing in the United States (U.S.) as the key enabler of the NextGen project. In the U.S., ADS-B service is provided via two type of datalinks; 1090 MHz Extended Squitter (1090ES) and UAT. The U.S. ADS-B Final Rule requires aircraft operating above FL180 to broadcast on the 1090ES link. While for aircraft flying below FL180; both links are supported. Depending on aircraft equipage, both ADS-B Out and In are supported. However, no mandate is in place yet for ADS-B In. In May 2010, the U.S. ADS-B Final Rule was published, requiring ADS-B Out equipage in U.S. airspace where a transponder is currently required with compliance by 1 January 2020 (SKYbrary, 2013).

Twenty integrated ADS-B and WAM systems including more than 200 stations are deployed for operational use at various sites in Europe. According to (Rekkas, 2013), this number is expected to increase significantly over the next few years based on the existing contracts and firm commitment by the ANSPs. ADS-B is deployed as mean of surveillance in non-radar airspace in Europe including Iceland and Italy. WAM/ADS-B systems are deployed in Armenia, Austria, Czech Republic, Germany, Latvia, Netherlands (North Sea), Portugal (Azores), Romania, Spain, Sweden and UK (East Midlands, Edinburgh and North Sea). Other ANSPs have implementation plans from 2013 onwards: Bulgaria, Cyprus, Denmark (ADS-B only in Faroe island, Greenland; WAM/ADS-B in mainland and North Sea) Finland, France (ADS-B only in overseas territory), Greece, Norway (North Sea), Portugal (Madeira, Porto, Lisbon), Sweden (country-wide). The deployment of WAM/ADS-B ground systems by the CRISTAL Projects of CASCADE is close to completion. The projects cover both non-radar and radar airspace. The ANSPs involved in this project are:

- AVINOR, Norway
- BULATSA, Bulgaria
- DCA, Cyprus
- DFS, Germany
- HCAA, Greece
- ISAVIA, Iceland

The projects are anticipated to be completed in 2014.

3.9.2 ADS-B In Deployment

The deployment of ADS-B Out by the airlines has been on-going for the past few years. Airborne deployment includes aircraft equipage and certification. In non-radar airspace, several hundreds of aircraft are already certified based on the AMC 20-24 (EASA, 2008). On a global scale, the EASA ADS-B NRA Airworthiness approval was applied by Australia and Canada. More than 1300 aircraft are approved for operations and more than 5500 are monitored over Europe to be compliant with the requirements of the AMC 20-24 (EASA, 2008). In radar airspace, the aircraft are required to be certified with the EU Regulation 1207/2011. ADS-B is certified to complement radar in high density airspace, airport surface and the ADS-B Out requirements of ATSAW and initial spacing applications. To date, 70 aircraft monitored in Europe are compliant with the EU Regulation 1207/2011. The number will increase in the next few years driven by the relevant mandate dates.

ATSAW or ADS-B In has been operational in Europe since February 2012 under the ATSAW Pioneer project of CASCADE in cooperation with airlines, ANSPs and avionics manufacturers to provide an airborne traffic situation to the flight crew. The objective of the ATSAW project is to assist airlines to equip the aircraft with certified ATSAW equipment and use it in their operations. The ATSAW equipage is voluntary and no mandate is envisaged in Europe. The project is conducting two operational applications; ATSAW during flight operations (ATSAW AIRB) and the ATSAW In Trail Procedure (ITP) over the North sea (Shanwick FIR and Reykjavik FIR). The project is anticipated to be completed by end of 2013. Six airlines equipped 28 aircraft with the ATSAW equipment:

- British Airways
- Delta
- Lufthansa
- Swiss International Airlines
- US Airways
- Virgin Atlantic

The ATSAW Pioneer project marked the first operational use of surveillance in the cockpit in Europe and paves the way for the deployment of other “ADS-B In” applications.

According to Rekkas (2013), internationally harmonized standardization work plan involves co-ordination between EUROCONTROL, FAA, EUROCAE, RTCA, Australia, Canada, Japan, ICAO and also civil-military interoperability. These should enable global interoperability and ensure that equipped aircraft can use their installations worldwide.

3.9.3 ADS-B Performance Monitoring

ADS-B monitoring is being undertaken by Airservices Australia, EUROCONTROL and the FAA to assess the equipage rate and ADS-B performance. Airservices Australia is monitoring ADS-B performance at a number of levels. In the first level, site monitoring is conducted to check the receiver sensitivity and antenna cable in real time. This is conducted by injecting an ADS-B signal into the antenna and then checking if the signal is received at the correct signal strength and whether the message is received reliably by the ATC system (Airservices Australia, 2013). At the second level, a significant number of ground station parameters (Airservices Australia, 2013) are monitored remotely and if the parameter performance exceeds predefined thresholds, alerts are generated. At the third level, all failures, service outages and repair/return to service times for each ADS-B site are recorded. The last level is currently under development. Airservices Australia is developing a tool to capture and report the avionics performance for each airframe. The report will contain the following information:

- 24 bit code
- Associated flight ID

- Minimum and maximum FOM (NUC / NIC)
- Number of position “jumps”
- Number of zero integrity reports
- Registered operator and aircraft type (for Australian aircraft)
- ADS-B data version

The reports are recorded in the Airservices System Issue Database (ASID). Finally the anomalies identified are sent as a feedback to the relevant airlines, operators or manufacturers for further analysis and mitigation.

In Europe, EUROCONTROL monitors ADS-B performance based on the traffic identified for the 13000 aircraft participating in the monitoring project. The data for the aircraft is obtained from the following ADS-B ground stations:

- Athen (HCAA), Greece
- EUROCONTROL Experimental Centre (EEC), Bretigny, France
- Langen (DFS), Germany
- Schiphol (LVNL), Netherlands
- Toulouse (DSNA), France
- Warlingham (NATS), UK
- Charles de Gaulle airport (DSNA), France
- Schiphol airport (LVNL), Netherlands

To date, 20 billion reports have been analyzed to monitor the ADS-B data accuracy against multiradar data accuracy for all the participating aircraft. Aircraft compliance with the EASA AMC 20-24 is also monitored. Anomalies identified in the participating aircraft are resolved in co-operation with the related airlines, operators and avionics manufacturers (Rekkas, 2013).

The FAA has developed an active monitoring system called the Surveillance and Broadcast (SBS) monitor to ensure the ground equipment at each ADS-B site delivers the required services to the FAA (Office of Inspector General, 2011). However, the FAA has not developed automated means and procedures to analyze the large amount of performance data recorded by the SBS monitor or assigned sufficient human resources to carry out analysis (Office of Inspector General, 2011). In addition, the FAA has not ensured the network design for the SBS monitor works as intended and is a reliable tool that can help it to avoid and resolve outages (Office of Inspector General, 2011). A recent update by the FAA (2013) indicates that the SBS monitor is planning to include avionics compliance monitoring in the future.

The review shows that, Airservices Australia's approach is the most advanced for monitoring the deployment of ground and airborne equipment deployment for all aircraft in the airspace. EUROCONTROL and the FAA have still to improve the current monitoring approach to ensure ADS-B safety for ATC operations. Significantly, the Airservices Australia's approach can be enhanced to enable safety monitoring and mitigation by adopting the methods proposed in this thesis, including the ADS-B position integrity validation in Chapter 6 and ADS-B failure mode analysis in Chapter 7.

Further information on ADS-B implementation and operation guidance are provided in (ICAO, 2007a), though it does not detail the implementation and validation processes for ADS-B. In summary, the following factors should be considered and developed for ADS-B implementation:

- New surveillance procedures;
- A study on specific operational requirements for each region;
- Ground infrastructures implementation;
- Mandatory aircraft equipage; and
- Training for pilots and controllers to operate in the new operational environment, as their functional roles may change with full ADS-B implementation. This is discussed in section 3.9.5.2.

3.9.4 Challenges for ADS-B Implementation

According to Boeing (2009), a number of crucial challenges have been identified in ADS-B implementation efforts. The first is to have international interoperability by implementing an optimal single ADS-B link for traffic surveillance of all aircraft. Next, in order to globally implement ADS-B, the current surveillance standards need to be revised and extended. In addition, a transition strategy for surveillance has to be carefully designed. Another known challenge is the cost to equip the aircraft and deploy the ground infrastructure borne by airlines and ANSPs respectively. Finally, a global mandate is crucial to provide complete ADS-B Out and ADS-B In services.

3.9.5 How can ADS-B fit into the ATC System?

The objective of ATM is "to enable aircraft operation to meet their planned times of departure and arrival and adhere to their preferred flight profiles with minimum constraints, without compromising the agreed levels of safety" (EUROCONTROL, 2006a). The current ATM system (ICAO, 2000) is illustrated in Figure 3-11. Due to the technological advancements, the ATM system has incorporated airborne components; airborne CNS and Aircraft Collision Avoidance System (ACAS). This section focuses on ATC and airborne ATM components. These components are inter-reliant to ensure the safe control, monitoring and management of the air traffic. Figure 3-12 shows the functional components in a new ATC paradigm (proposed in this thesis) combining ATC and Airborne Communication, Navigation and Surveillance (CNS), as depicted in Figure 3-11.

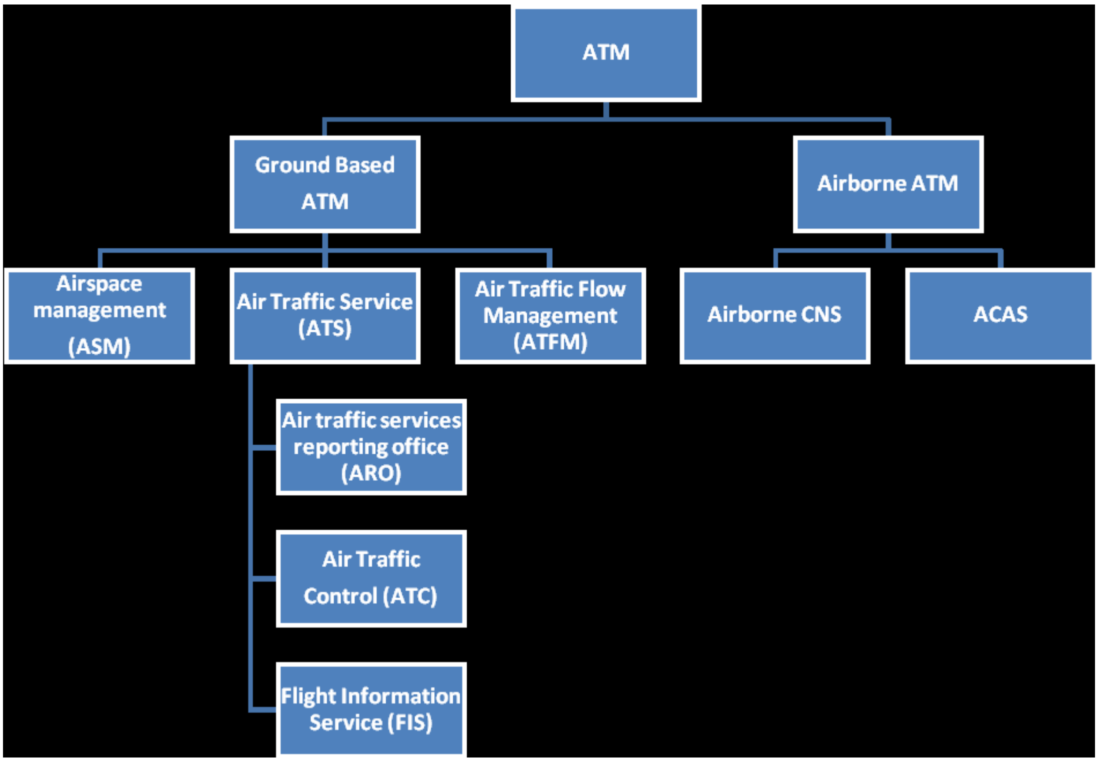


Figure 3-11: Air Traffic Management (ICAO, 2000)

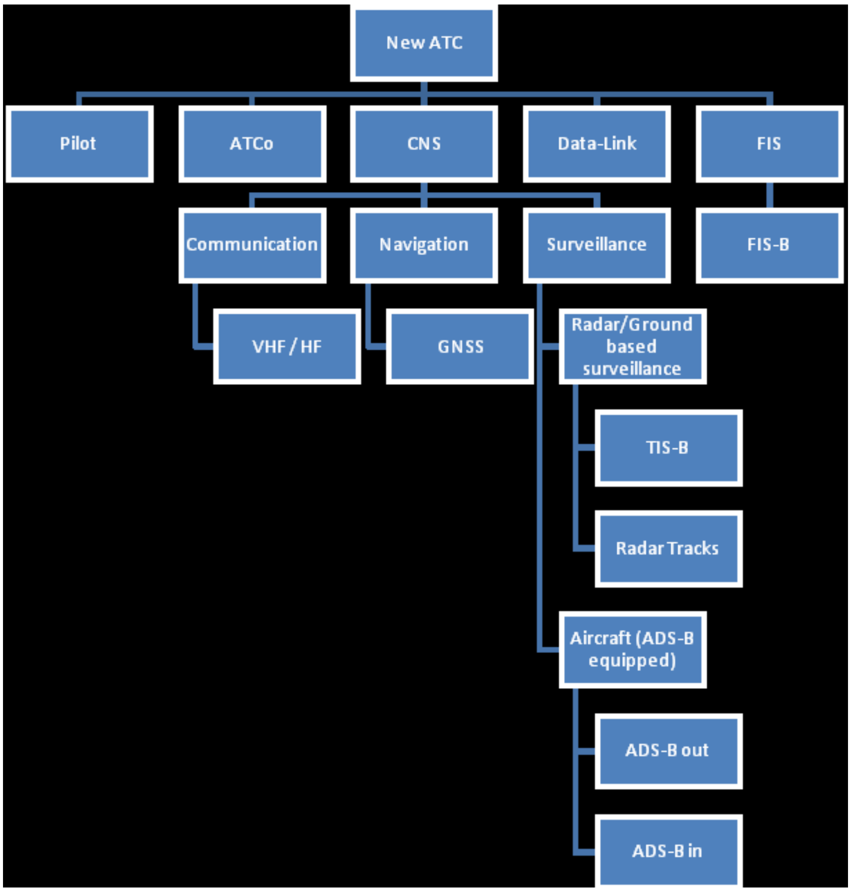


Figure 3-12: New ATC System Component (proposed in this thesis)

3.9.5.1 New ATC System Loop Model

Hansman (1997) states that in the current ATC operation, the role separation between controllers and pilots is functional and ambiguous. Controllers have the responsibility for traffic separation while the pilot is responsible for the safety of the flight. The pilot will defer to controllers on the traffic issues as the controllers have more information on it. Likewise, controllers will often defer to pilots on weather information. Hence it is obvious that the functional role of pilots and controllers is directly determined by the availability of reliable information in hand. Bearing this in mind, the implementation of new surveillance technology such as ADS-B and TIS-B, and datalink technologies, will enable both pilots and controllers to have access to the same situational information. Therefore, this may create conflict in the role separation between pilots and controllers. Emergence of the new technologies is expected to support new surveillance applications envisaged to balance both controller and pilot workload, optimize capacity, increase efficiency and improve safety. It is envisioned that the ADS-B system will be the primary surveillance source in the future. This will create controller dependency on the aircraft to obtain the surveillance data. Conversely, pilots will have less dependency on the controllers due to enhanced situational awareness. Radar surveillance and procedural control via communication aids will act as a backup system. Therefore, the ATC role structure has to be carefully designed and clearly enforced upon the implementation of the new technologies.

A new ATC loop model is proposed in this thesis as a result of the emergence of ADS-B technology, which has resulted in the emergence of many new application tools such as ASAS and CDTI. The model combines the ground and airborne ATC functional components. The components are interdependent. The model illustrates interaction between ATC components, tools and users. In addition the model also introduces data fusion component to fuse the current ground surveillance data with the ADS-B data. Data fusion is foreseen to enhance the data integrity and retain the data flow continuity in the air and on the ground. Figure 3-13 depicts the new ATC loop model for the future operation.

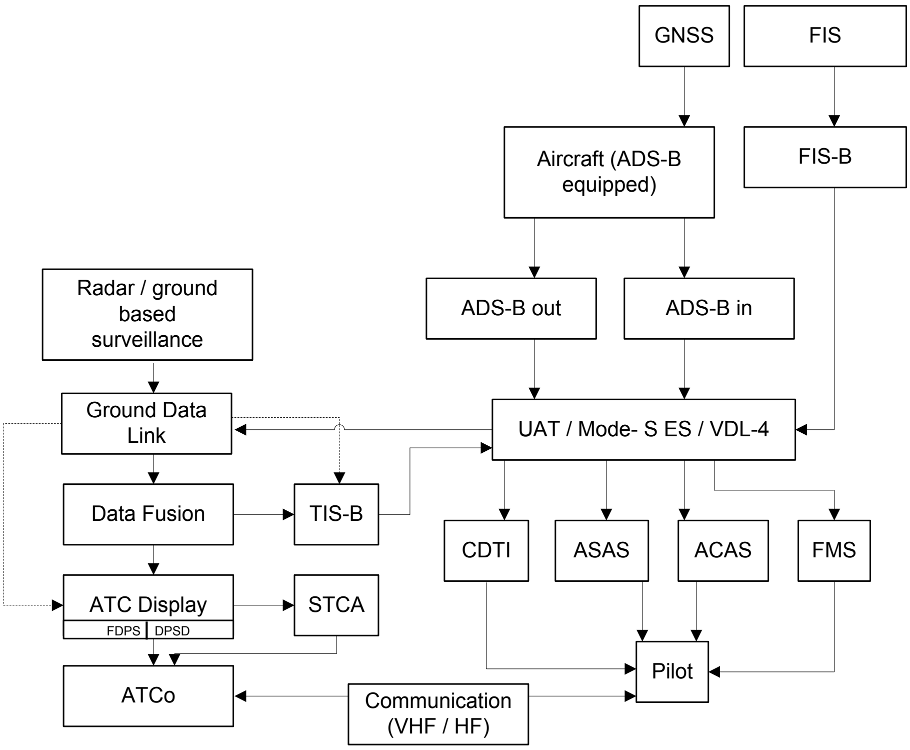


Figure 3-13: New ATC Loop Model

3.9.5.2 Potential change in the role of controller and pilot

The components of the model are mapped to the ATC functions, controller (ATCo) role and pilot role in Table 3-16. The potential change in the role of the ATCo and pilot are analysed and mapped based on the new ATC loop model in Figure 3-13 for all phases of flight. Based on the mapping, with the existence of ADS-B and its applications, the role of ATCo will be more focused on monitoring rather than controlling in the future, while pilots will be able to self navigate. Based on the mapping, further analysis is made using a widely used approach for functional modelling, Structured Analysis and Design Technique (SADT). The approach was introduced by Ross of Soft Tech Inc. in 1973 and is further described by Lissandre (1990)and Lambert (1999). In the SADT diagram, each functional block is modelled with five main elements; functions, input, control, mechanism and output. Figure 3-14 illustrates the ATC functional blocks analyses with the new applications and technologies as input. The role shift in Table 3-15 and ATC functional blocks in Figure 3-14 provide an insight and paves the way to the future ATC operations with enhanced ground surveillance applications and airborne surveillance applications in place. The application input to each function in Figure 3-14 could be expanded as new applications emerge as a result of complete ADS-B implementation worldwide.

Table 3-16: ATC paradigm shift based on phases of flight

ATC Functions	Current Role | Support Technologies								New Role | Support Technologies							
Conformance monitoring	ATCo	DPSD , FDPS	ATCo	DPSD , FDPS	ATCo	DPSD , FDPS	ATCo	COMMS	ATCo	DPSD , FDPS	ATCo	DPSD , FDPS	ATCo	DPSD , FDPS	ATCo	DPSD , FDPS
Hazard Monitoring	ATCo	DPSD	ATCo	DPSD	ATCo	DPSD			ATCo	DPSD	ATCo	DPSD	ATCo	DPSD	ATCo	DPSD
Sequencing	ATCo	DPSD , FDPS, COMMS	ATCo	DPSD , FDPS COMMS	ATCo	DPSD , FDPS, COMMS	ATCo	FDPS, COMMS	ATCo	DPSD , FDPS, COMMS	ATCo	DPSD , FDPS COMMS	Pilot	ASAS,CDTI, ADS-B, TIS-B	Pilot	ASAS,CDTI, ADS-B, TIS-B
Spacing	ATCo	DPSD , FDPS, COMMS	ATCo	DPSD , FDPS COMMS	ATCo	DPSD , FDPS, COMMS	ATCo	FDPS, COMMS	ATCo	DPSD , FDPS, COMMS	ATCo	DPSD , FDPS COMMS	Pilot	ASAS,CDTI, ADS-B, TIS-B	Pilot	ASAS,CDTI, ADS-B, TIS-B
Merging	ATCo	DPSD , FDPS, COMMS	ATCo	DPSD , FDPS COMMS	ATCo	DPSD , FDPS, COMMS	ATCo	FDPS, COMMS	ATCo	DPSD , FDPS, COMMS	ATCo	DPSD , FDPS COMMS	Pilot	ASAS,CDTI, ADS-B, TIS-B	Pilot	ASAS,CDTI, ADS-B, TIS-B
Conflict Detection	ATCo	DPSD, FDPS	ATCo	DPSD , FDPS	ATCo	DPSD , FDPS	Pilot	ACAS	ATCo	DPSD, FDPS	Pilot	ACAS, CDTI	Pilot	ACAS, CDTI	Pilot	ACAS, CDTI
Short-term conflict detection	ATCo	DPSD,STCA	ATCo	DPSD,STCA	ATCo	DPSD,STCA	Pilot	ACAS, visual	ATCo	DPSD, STCA	Pilot	ACAS, CDTI	Pilot	ACAS, CDTI	Pilot	ACAS, CDTI
Conflict Resolution & Intervention	ATCo	COMMS	ATCo	COMMS	ATCo	COMMS	ATCo	COMMS	ATCo	COMMS	ATCo	COMMS	ATCo	COMMS	ATCo	COMMS
Flight-Replanning	ATCo	FDPS, COMMS	Pilot	FMS,COMMS	Pilot	FMS,COMMS	Pilot	FMS,COMMS	ATCo	FDPS, COMMS	Pilot	FMS,COMMS	Pilot	FMS,COMMS	Pilot	FMS,COMMS
Conformance to ATC vector	Pilot	COMMS	Pilot	COMMS	Pilot	COMMS	Pilot	COMMS	Pilot	COMMS, ASAS	Pilot	COMMS, ASAS	Pilot	COMMS, ASAS	Pilot	COMMS, ASAS
Onboard collision avoidance	Pilot	ACAS	Pilot	ACAS	Pilot	ACAS	Pilot	ACAS	Pilot	ACAS, CDTI	Pilot	ACAS, CDTI	Pilot	ACAS, CDTI	Pilot	ACAS, CDTI
Information feed & support	ATCo	COMMS	ATCo	COMMS	ATCo	COMMS	ATCo	COMMS	ATCo	FIS-B	ATCo	FIS-B	ATCo	FIS-B	ATCo	FIS-B
	Airport Surface		**En-route Terminal**		**En-route Domestic**		**Oceanic / remote area**		**Airport Surface**		**En-route Terminal**		**En-route Domestic**		**Oceanic / remote area**	

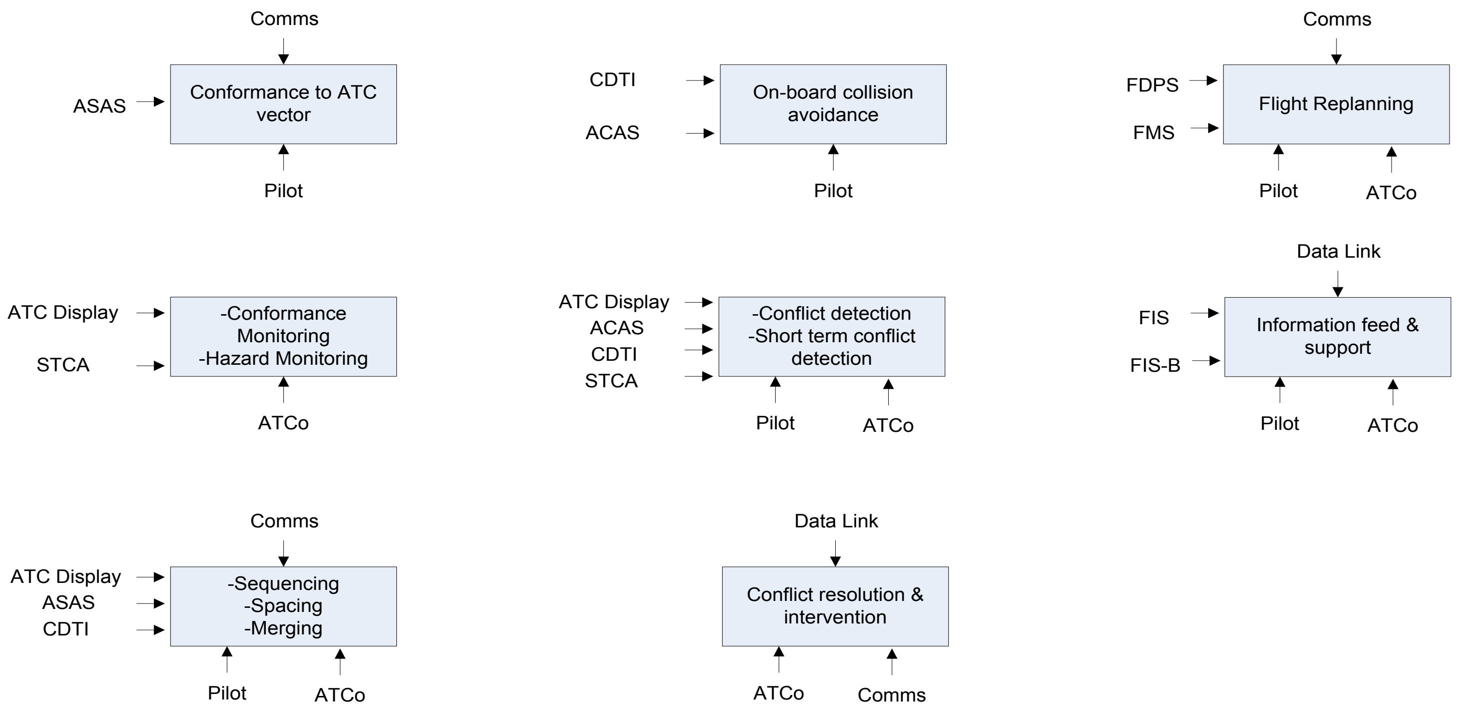


Figure 3-14: ATC Functional blocks

3.10 Summary

This Chapter has introduced the ADS-B system along with detailed description of the requirements, system architecture including functions and how they are supported. The Chapter also discussed the progress of system implementation worldwide and proposed a new ATC loop model with the implementation of ADS-B. The model is important for ATC operations during the transition period and complete implementation of ADS-B. Finally the Chapter proposes a paradigm shift in the ATC operational tasks between the pilots and controllers, envisaged upon complete ADS-B implementation in the future. The next chapter will provide a theoretical solution for the limitations in the current surveillance system (Chapter 2) based on the potential capabilities of ADS-B identified in this Chapter.

Chapter 4

Current limitations and potential of ADS-B

This Chapter identifies the limitations of the current surveillance systems and the associated potential incidents, and presents a theoretical case for the potential of ADS-B to overcome the current limitations.

From the findings in Chapter 2 and discussions with Air Navigation Service Providers (ANSPs) personnel, a set of causal factors is derived that lead to incidents due to the limitations in the current surveillance systems. The causal factors are validated by Subject Matter Experts (SMEs) and safety data from ANSPs. This is followed by an assessment of the capabilities of the ADS-B system (reviewed in Chapter 3) to address the limitations of the current surveillance systems, and to provide the necessary support to Air Traffic Control (ATC) services in achieving the required level of safety.

4.1 Background

Chapter 2 has reviewed the current Air Traffic Management (ATM) surveillance systems, including Primary Surveillance Radar (PSR), Secondary Surveillance Radar (SSR), Monopulse Secondary Surveillance Radar (MSSR) and Multilateration (MLAT). Surveillance systems provide Air Traffic Control Operators (ATCOs) with aircraft position in order to perform separation and airspace management, underpinned by situational awareness and functions such as trajectory prediction and conflict detection. Currently, the primary surveillance system that supports ATM, and in particular ATC, is radar. Brooker (2004) discusses radar inaccuracies and the impacts on mid-air collision risks. His work is supported by a review of quantitative en-route safety assessment methods (Brooker, 2002) and safety assessment methodology for Communication, Navigation, Surveillance / Air Traffic Management (CNS/ATM) systems based ATC (Vismari, 2011) and (ICAO, 1998c). It is clear from this assessment that radar system performance is insufficient to meet the anticipated increase in air traffic (underpinned by a reduction in separation minima) and to cater for new ATC applications (such as enhanced situational awareness for pilots and controllers, trajectory prediction and conflict detection). The current surveillance system is thus fundamentally limited and cannot accommodate any further increase in air traffic. The limitations in the current surveillance systems are particularly acute in the provision of ATC services in low altitude, remote and oceanic areas and include unavailability of service in oceanic and remote areas; limited service during extreme weather conditions and outdated equipment without spare parts (ICAO, 2000). The impacts of these limitations manifest in the occurrence of incidents and accidents. The ICAO defines these two types of occurrences (ICAO, 2001b) as below:

- An ***accident*** is "an occurrence associated with the operation of an aircraft, which takes place between the times that any persons board the aircraft with the intention of flight and that all such persons have disembarked, in which any person suffers death or serious injury, or in which the aircraft receives substantial damage";
- An ***incident*** is "an occurrence, other than an accident, associated with the operation of an aircraft which affects or could affect the safety of operation. Such incidents and accidents are reported by ANSPs to civil aviation regulators".

Automatic Dependent Surveillance Broadcast (ADS-B) (reviewed in Chapter 3) is expected to address the limitations of the current systems. Both, the FAA's Next Generation Air Transportation System (NextGen) and the European Commission's Single European Sky (SES) and its ATM Research (SESAR) programme recognise ADS-B as the key to the respective goals to modernise ATM operations and address the deficiencies in the current surveillance systems. Unlike the radar system which operates independently, the ADS-B system relies on Global Navigation Satellite Systems (GNSS) such as GPS to determine an aircraft's current state (location, time and related data) and derive aircraft intent information. The ADS-B system has the potential to support surveillance services not only in the terminal and en-route airspace, but also in remote and oceanic areas. Furthermore, it should enable many new surveillance applications such as synchronised situational awareness (crew-crew, crew-air traffic controller, ATC-ATC, etc). These benefits have the potential to enhance the current operational paradigm of ATM in non-radar and remote areas without jeopardising the required level of safety.

4.2 Methodology

Currently, there is no evidence in the public domain research literature on the analysis of the limitations of the current surveillance systems and the capability of the ADS-B system to overcome them. The literature provides the limitations in the current surveillance systems without proposing any potential solutions. Therefore, a comprehensive methodology in Figure 4-1 is developed to facilitate the resolution of the current limitations. The following sections explain the methodology in detail.

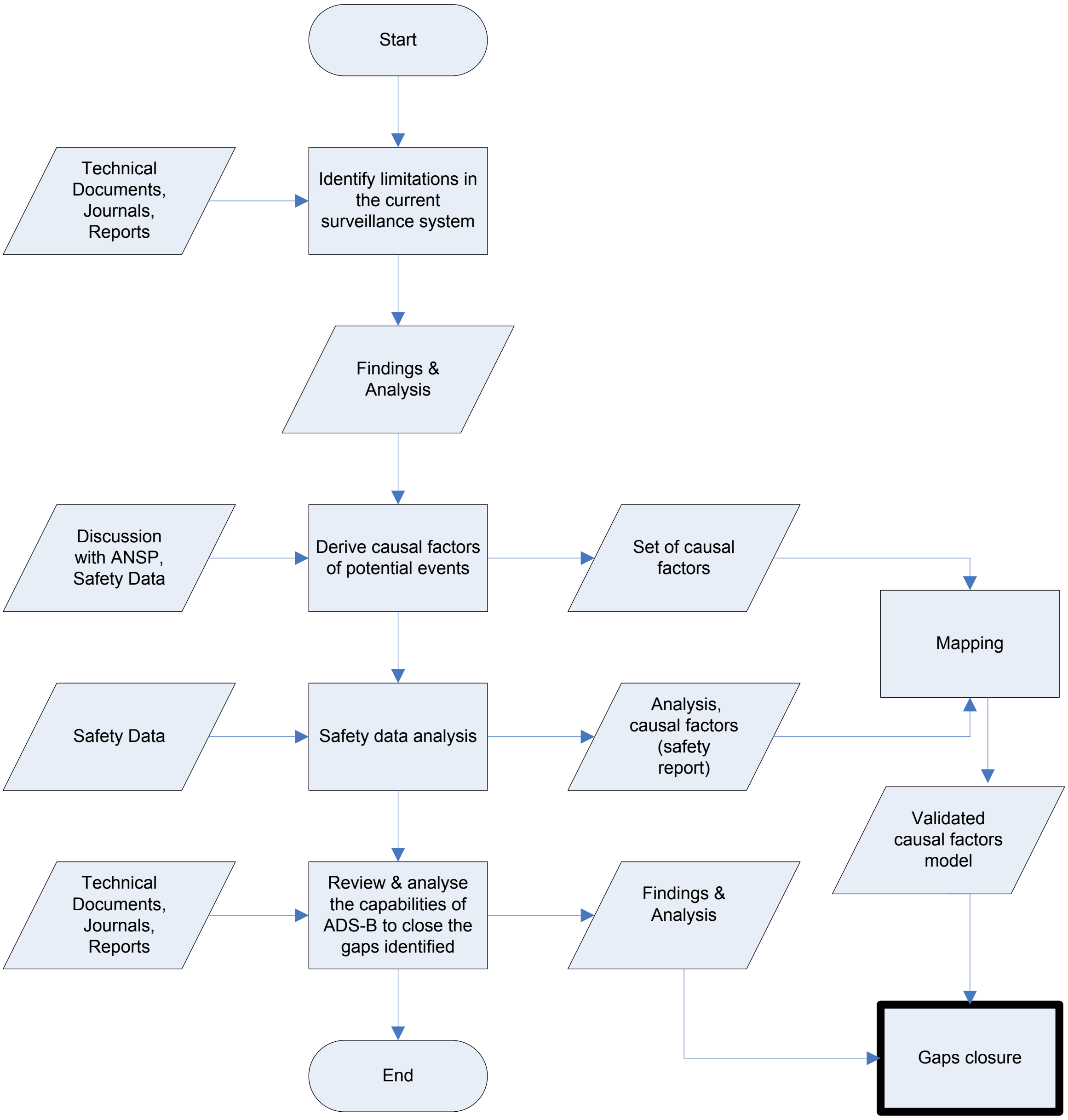


Figure 4-1: Methodology to derive, validate and resolve limitations in the current surveillance systems

4.3 Analysis of the current limitations

As discussed in Chapter 2, the current surveillance systems in use consist of Primary Surveillance Radar (PSR) (Wassan, 1994, Aeronautical Surveillance Panel (ASP), 2007), Secondary Surveillance Radar (SSR) (Wassan, 1994, Dawson, 2004), Monopulse Secondary Surveillance Radar (MSSR) (Dawson, 2004), Surface Movement Radar (ICAO, 2004a) and Multilateration (MLAT) (Owusu, 2003). Each country or region implements surveillance systems taking into account of technical performance, geographical structure, contextual environment and cost. For example, MLAT sensors are more flexible and relatively inexpensive as they can be installed on existing infrastructures such as high rise buildings or communication towers while the SSR has to be sited on dedicated land which incurs space rental and higher maintenance costs. No additional is incurred by the airline operators as both systems have the same requirement to have a Mode-S transponder onboard, a mandatory requirement by ICAO (Surveillance and Conflict Resolution Systsms Panel, 2004).

Based on the review of the current surveillance technologies in Chapter 2, a number of advantages and disadvantages are identified (Table 4-1). These disadvantages are a major obstacle to ensuring that the increasing air travel demand can be met.

Table 4-1: Advantages and disadvantages of the current surveillance technologies

Technology	Advantages	Disadvantages
PSR	Provides surveillance of aircraft or vehicles not equipped with transponder.	▪ Disability to uniquely identify targets and their altitudes ▪ Need for transmission of high power pulses that limit its range ▪ Signal clutter ▪ Signal attenuation ▪ Not suitable for oceanic and remote airspace
SSR	SSR overcome all the drawbacks identified in PSR.	▪ False Replies Unsynchronised with Interrogator Transmissions (FRUIT) in multi-radar environments ▪ Garbling in dense airspace ▪ Not suitable for aerodrome surface surveillance due to the accuracy limitations imposed by the transponder delay tolerance ▪ Dependency on transponder and on the need to have it switched on – i.e. not suitable to identify non-equipped aircraft. ▪ Not suitable for oceanic and remote airspace
SMR	Provide surveillance of vehicles not equipped with transponder and objects on the runways or taxiways	▪ Signal attenuation ▪ Target not uniquely identified
MSSR	-Reduce garbling and FRUIT -Its accuracy provided for a reduction of separation minima in en-route ATC from 10 nm to 5 nm	▪ Dependency on transponder ▪ Not suitable for oceanic and remote airspace
MLAT	Ability to support mode S elementary	▪ System accuracy depends on the geometry of the target in relation to the receiving stations and also the relative time of signal receipt ▪ Dependency on transponder ▪ Not suitable for oceanic airspace

One way to minimize the drawbacks identified in each of the current surveillance systems is to combine these technologies in a sophisticated manner (Olivier et al., 2009, Bloem et al., 2002) taking advantage of the strengths of each system. For example, in an area with a line-of-sight problem or limited radar coverage, integration of the radar and MLAT systems is a potential solution, taking advantage of the flexibility of installing MLAT sensors on existing infrastructure. On the other hand, in an area with multiple radar coverage, their combined usage should also enable a more reliable coverage within the radar airspace. However, the relative high cost of radar is a major barrier to the realisation of this approach. In summary, although integration is useful to some limitations, others remain, including unavailability of coverage in oceanic areas and remote regions.

4.4 Taxonomy and Causal Factor Model for Incidents/Accidents

The term ***system limitation*** in this thesis refers to insufficient capability or inadequacy of a system to perform in the different phases of operation with the required performance in terms of accuracy, integrity, continuity and availability (Surveillance and Conflict Resolution Systems Panel, 2004) which could lead to incidents or accidents. The limitations identified in the current surveillance systems, might be due to particular functional requirements overlooked during the system design phase, e.g. extreme cases such as coverage in remote areas, the need for high-performance situational awareness for flight crew and controllers, degraded visual conditions during extreme weather (Herrera et al., 2009), especially for Visual Flight Rules (VFR) flights and requirements to meet future air traffic volumes. Today there is no single surveillance system that satisfies the Required Surveillance Performance (RSP) (Surveillance and Conflict Resolution Systems Panel, 2004) required for the future traffic volumes, without jeopardising safety.

4.4.1 Taxonomy: Causal Factors for Incidents/Accidents due to Limitations in the Current Surveillance Systems

Definitions of ‘taxonomy ‘are inconsistent in the literature (Wilke and Majumdar, 2012). However, ‘scheme of classification’ (Wilke and Majumdar, 2012) is adopted as the definition of taxonomy for the purpose of this thesis. The scheme in the context of this thesis refers to a set of causal factors, while the classification refers to incidents or accidents due to the limitations in the current surveillance systems. In this thesis, the term ‘causal factor’ refers to the factors that contribute to the causes of an incident or accident. The new taxonomy is derived and validated using the research methods based on literature review, structured communication with Subject Matter Experts (SMEs), on the job experiences, review of existing taxonomies and safety report analysis. Figure 4-2 illustrates the processes applied to derive and validate the taxonomy.

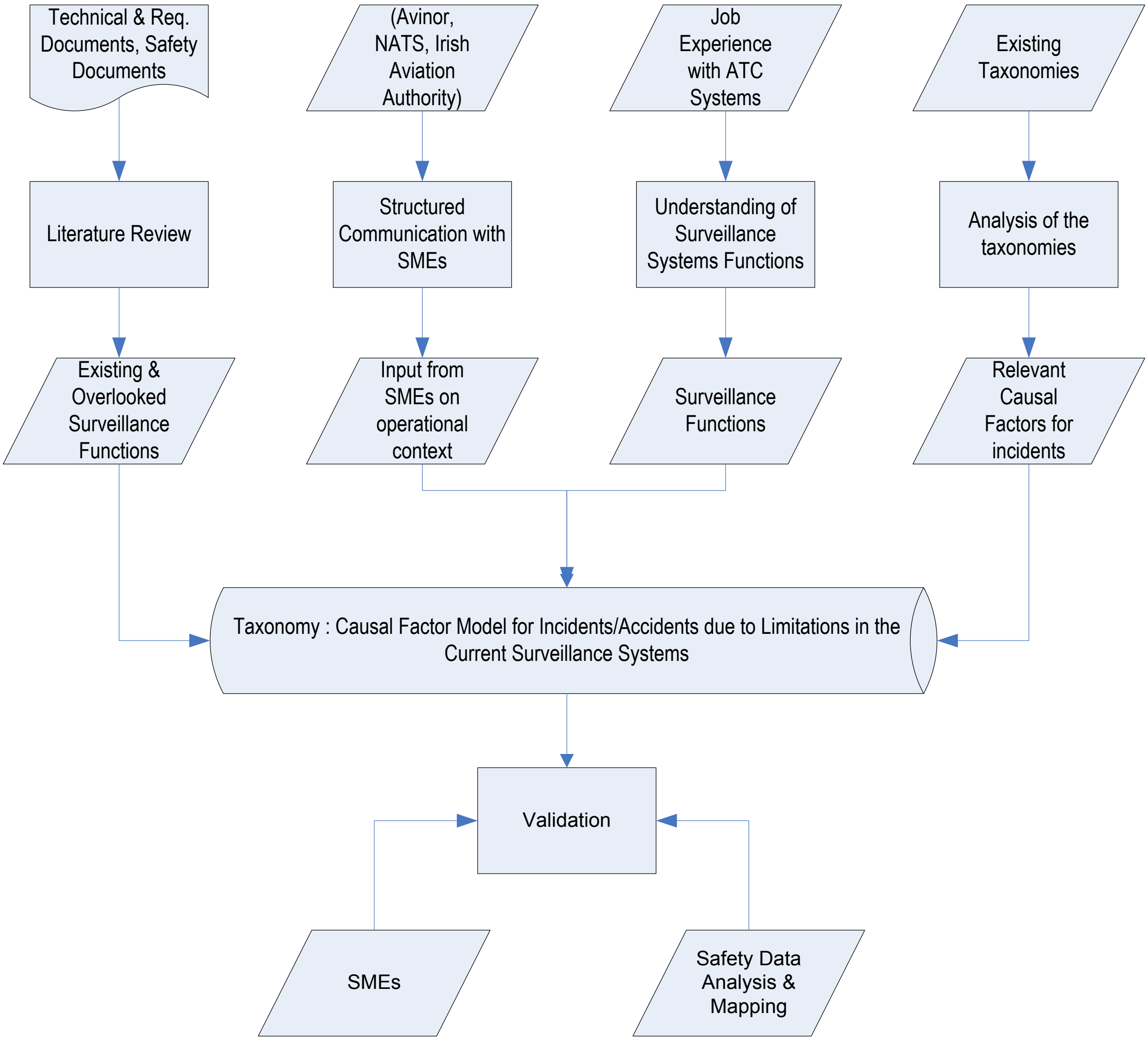


Figure 4-2: Methodology for derivation and validation of the new taxonomy

In the first part of the process, an extensive literature review on the current surveillance systems functions and their limitations to support increasing air traffic is conducted and summarized in Table 4-1. The inputs used include documents on technology, system requirements and safety, from ICAO, EUROCONTROL and RTCA. The findings from the literatures comprise of existing required surveillance functions and those overlooked during system design and implementation to provide complete ATC services for the users in all operational contexts. Secondly, structured communication with a number of aviation safety personnel from ANSPs (i.e. Irish Aviation Authority, Avinor Norway and NATS UK), were surveyed to identify any limitations of the current surveillance system (e.g. limited surveillance coverage in oceanic and remote areas) to provide complete ATC services.

Thirdly, the researcher's five years of working experience with ATC systems enabled greater understanding of the current surveillance system functions and the new functions required to accommodate future air traffic requirements. Finally, ICAO generic aviation taxonomy, Accident/Incident Data Reporting (ADREP) (ICAO, 2006a) and ESARR2 (EUROCONTROL, 2009b) safety reporting requirements are reviewed for relevance to this thesis. ADREP provides a step-by-step guidance to generate an incident / accident report. For example, for a loss of separation incident, the following information is required to complete the ADREP reporting template:

- Minimum horizontal separation estimated. (Est minimum horiz sep)
- Minimum horizontal separation prescribed. (Req minimum horiz sep)
- Minimum horizontal separation recorded. (Min horiz sep recorded)
- Minimum vertical separation estimated. (Est vert separation)
- Minimum vertical separation prescribed. (Req vert separation)
- Minimum vertical separation recorded. (Vertical sep recorded)

It is widely accepted that ADREP is a comprehensive safety reporting aid. However, it does not provide comprehensive guidance to the investigator on the analysis process. ADREP defines ATM specific occurrences as ATM or CNS service issues, including failure or degradation of all the facilities, equipment, personnel, procedures, policy, and standards involved in the provision of State approved Air Traffic Services. This classification scheme is too general for the investigator to make any conclusion on the potential factors of a particular ATM related occurrence. However, based on the ESARR 2 reporting requirements, the ATM specific occurrence reporting has improved through breaking down the category into Occurrence Related to the ATM Support Functions; Communication, Surveillance, Data Processing, Navigation or Information. ESARR 2 further provides severity classification to indicate the severity of the ATM Support Functions that limits or disables the ATM services to the users. Even though this is seen as a good improvement, the categorization still does not help the investigators to narrow down the analysis to identify the causal factors of the ATM Support Functions. EUROCONTROL states that safety reports produced by ANSPs in ECAC are not always categorized into the different types of occurrences required (e.g. failure of communication, navigation, surveillance functions etc.) (EUROCONTROL, 2010a). Therefore, the new taxonomy provides the potential causal factors due to the limitations in the current surveillance functions that may lead to occurrences.

The outputs from the four processes explained above, feeds to the derivation of the new taxonomy as below:

- C1- Lack of situational awareness
- C2- Limited surveillance coverage
- C3- Inaccurate positioning information
- C4- Low update rate (position data)
- C5- Loss of communication
- C6- Unsynchronised surveillance information between flight crew and ATC
- C7- Visual deficiencies in extreme weather conditions

The taxonomy developed in this thesis only focuses on the surveillance function. Figure 4-3 shows how the new taxonomy improves the taxonomies stipulated by ADREP and ESARR2 for ATM Specific Occurrence Category. It is important to note that, mitigation efforts can only be proposed upon identification of specific causal factors of an event to avoid repeating the safety occurrences.

In the last step of the process, the new set of taxonomy in Figure 4-3 and the causal model developed based on the taxonomy in Figure 4-4 are validated by surveillance and ATM safety experts from Avinor, Norway and also using safety data analysis in section 4.5. The experts' profiles are tabulated in Table 4-2.

Table 4-2: New taxonomy validation by Aviation Experts from Avinor Norway

Name	Job Title	Years of Experience in ATM	Area of Expertise
Bjørn Hovland	Project Manager	17 years	Surveillance systems
Trude Myhre	Senior Safety analyst	3 years	Safety Engineering
Tommy Kjelsrud	Senior Safety analyst	7 years	Safety Engineering
Kjersti Disen	Senior Safety advisor	22 years	SMS,QMS
Anne Chavez	Safety manager	30 years	SMS,QMS

Safety reports from ANSP are analysed to identify occurrence due to the limitations in the current surveillance systems. The causes of the identified occurrences are further analysed to identify the contributing causal factors. Then the causal factors identified from the safety reports are grouped and mapped to validate the new taxonomy (see Table 4-7).

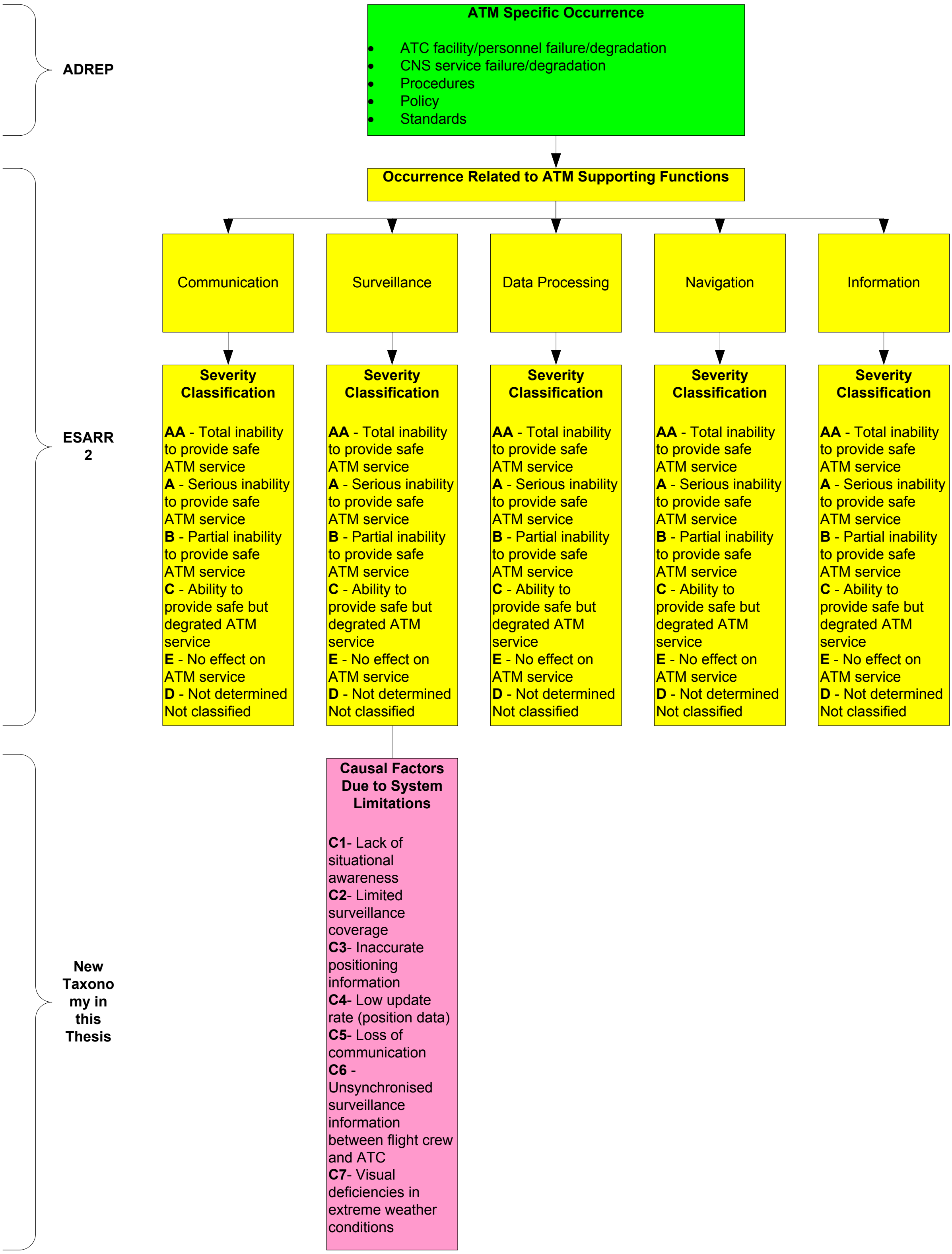


Figure 4-3: Improvement of ADREP and ESARR2 for ATM specific occurrence category with the new taxonomy

4.4.2 Causal Factor Model for Incidents/Accidents due to Limitations in the Current Surveillance Systems

Credible incident/accident analysis requires a comprehensive taxonomy together with historical occurrences analysis information or experience, and a causal or risk model. In order to transform the taxonomy derived in this thesis into an applied analytical and investigation methodology, a new causal factor model for incidents/accidents resulting from the limitations in the current surveillance systems is developed. The new model is developed using a modified Ishikawa or fishbone diagram (Stolzer et al., 2008) in Figure 4-4.

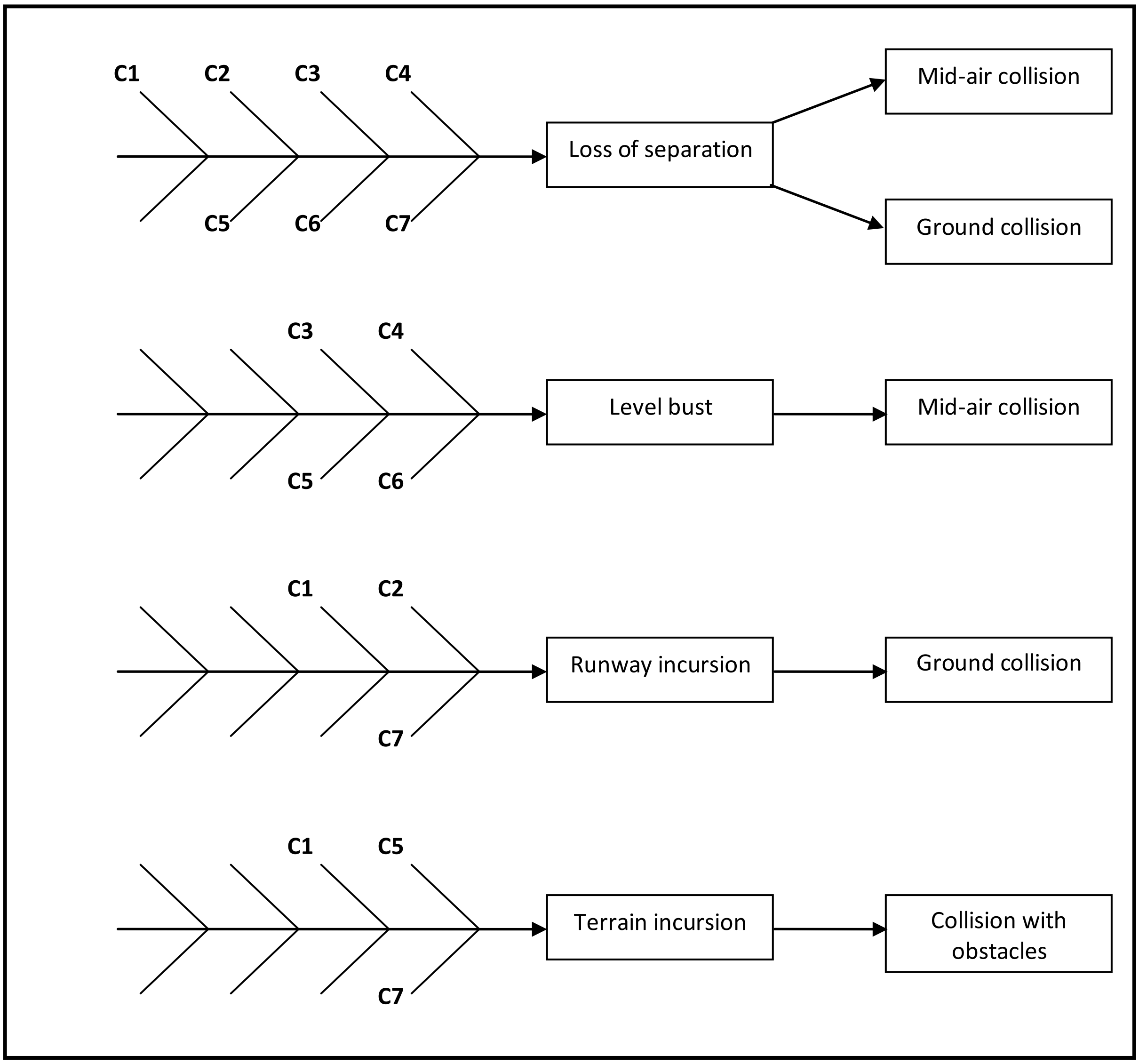


Figure 4- 4: Causal Factor Model for Incidents/Accidents due to Limitations in the Current Surveillance Systems

From the literature (EUROCONTROL, 2005), four main aviation incident categories; loss of separation, level bust, runway incursion and terrain incursion are identified as the main effects of the causal factors derived. The incidents are then mapped to potential accidents; mid-air collision, ground collision and collision with obstacles. The derived causal factors are mapped to identify their potential relevance to the incidents and accidents. The method used to develop the model is reverse engineering, whereby in the Ishikawa method, the causes of an encountered effect/problem are identified. In this thesis, the causal factors are derived earlier and then their potential effects are identified. The structure of the model is a fishbone. The incident and accidents are placed to the right of the spine respectively and the related causal factors are placed on the main bones extending from the spine of the diagram. Occurrence of a potential incident/accident can be due to individual existence of any causal factor on the main bones. The model is flexible as more causal factors may be added as the subject matter evolves in the future with the emergence of new surveillance technologies.

Amongst others, the two main models for aviation accident-incident investigation are the Integrated Risk Picture (IRP) Risk Model (Perrin and Kirwan, 2000) and the Causal Model for Air Transport Safety (CATS) (Ale, 2009). The IRP Risk Model represents the risk of aviation accidents with a particular emphasis on the contribution of ATM. For each of the five accident categories, it embeds separate causal factors such as technical failure and human error (see Figure 4-5).

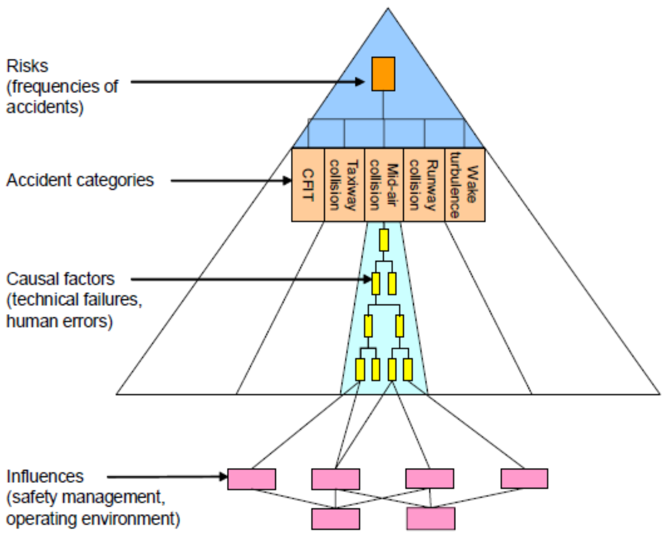


Figure 4- 5: Integrated Risk Picture (IRP) Risk Model (Perrin and Kirwan, 2000)

The model does not clearly mention which ATM component function may have caused the event. The risk of each accident category is quantified by providing a structured breakdown of their causes with their probability of occurrence. Although the model focuses on ATM contribution to accidents; it only considers events involving interaction with ATC.

The CATS model, models causal factors (human error, technical failures, environmental and management influences) in certain characteristic accident categories including loss of control, collision and fire. The causes and consequences of such accidents differ according to the phases of flight in which they occur. In contrast to the IRP model, CATS attempts to quantify the risks of all possible aviation accidents by taking into account all possible causal factors. It considers aviation accident to be the result of complex combination of many different causal factors.

The IRP and CATS models are largely similar, except the scope of CATS model is broader and the risk calculation method more detailed. The causal model proposed in this thesis in Figure 4-5 represents specific causal factors for accidents/incidents due to the existing limitations in the current surveillance systems. The model differs from the IRP Risk and CATS models as these only consider technical failures of the CNS/ATM systems that may contribute to accidents, while the model proposed in this thesis specifically considers the limitations of the surveillance systems that may lead to unanticipated incidents. This understanding is crucial in order to avoid unanticipated events that could jeopardise safety. Table 4-3 highlights the differences between the proposed model and the IRP and CATS models.

Table 4-3: New Causal Model, IRP, CATS

Model	Application	Focus	Output	Focus on ATM supporting function limitations
IRP	Accidents with ATM contribution that involves ATC interaction. In particular mid-air collision, runway collision, taxiway collision, CFIT and wake turbulence accident.	Each accident can be explained by either single or combination of causal factors.	Qualitative and quantitative	None
CATS	All accidents	Complex combination of all possible causal factors.	Qualitative and quantitative	None
New Causal Factor Model	Incidents and accidents due to limitations in the surveillance system function	Each incident can be explained by either single or combination of causal factors	Qualitative	Focus on Surveillance function only

4.5 Safety Data Analysis

The aim of the safety data analysis is to validate the taxonomy identified in Section 4.4 based on the analysis of comprehensive safety reports on accidents / incidents involving aircraft from ANSPs.

The key requirements for the data are:

- a detailed explanation of the causal factors of the events;
- sufficient reporting duration (to meet the analysis objective) and
- a consistent quality of reporting.

The possible outcomes of the analysis are:

- all the causal factors can be mapped on one-to-one basis to the safety report;
- only part of the causal factors can be mapped to the safety reports; or
- the causal factors are insufficient to cover all the factors identified in the safety reports.

After reviewing safety reports from various ANSPs and regulators, it was found that data from the Norwegian ANSP, Avinor, was best suited for this analysis due to its completeness and organised structure. In addition, structured communication with SMEs from EUROCONTROL indicated that, based on their working experience with the European countries on safety issues, the Norwegian ANSP, has an excellent reputation for reporting of safety occurrences. All the safety reports are stored in the MESYS database, which contains original reports and the findings of investigations. This reporting system complies with the EUROCONTROL Safety and Regulatory Requirements (ESARR 2) (EUROCONTROL, 2009b). Based on these facts, the organisation was evaluated as a reliable source of reporting and five years (2008 – 2012) of incident data were gathered accordingly.

The Norwegian ANSP operates 46 airports in Norway, with 12 of these in cooperation with the armed forces. Their operations also include air traffic control towers, control centres and technical infrastructure for aircraft navigation and surveillance. Figure 4-6 shows the radar locations maintained by the ANSP. Most of Norway's airspace has redundant radar coverage. Table 4-4 presents Instrument Flight Rules (IFR) and Visual Flight Rules (VFR) aircraft movements for all the 46 airports in Norway for the period 2008 to 2012. The trend indicates a gradual increase from 2009 to 2012 after a significant drop from 2008 to 2009.

Figure 4-6: Radar locations for Norwegian airspace (Avinor, 2011)

Table 4-4: IFR and VFR Traffic for Norwegian airspace (2008-2012)

Year	Traffic
2008	870365
2009	834883
2010	841859
2011	869348
2012	893813

4.5.1 Safety Data Analysis Results

A descriptive statistical analysis (Table 4-5) on the five years of safety data shows that with the exception of 2010 and 2011, with the same level of incidents, the number of incidents has been increasing significantly. However, the number of accidents decreased significantly from 2010 to 2011 (from 9 accidents to 3 accidents) despite the increase in air traffic. The accident figure increased again from 2011 to 2012 by 4 accidents.

Table 4-5: Incident, Serious Incident and Accident for the year 2008-2012 (Norwegian Airspace)

Occurrence Class	2008	2009	2010	2011	2012
Accident	3	4	9	3	7
Incident	882	1391	1506	1505	1775
Serious Incident	10	9	9	10	13
Total	**895**	**1404**	**1524**	**1518**	**1795**

From the analysis of safety reports, three main causes of incidents/accidents (known as occurrence type in the safety report and severity classification in the ESARR2 taxonomy) can be directly associated to occurrence related to the ATM functions (defined in Figure 4-3):

- Insufficient separation- *In the absence of prescribed separation minima, a situation in which aircraft were perceived to pass too close to each other for pilots to ensure safe separation* (EUROCONTROL, 2009b).
- Lack of or reduced ability to provide ATM services- *An event in which elements in the ground ATM system performances are unserviceable, insufficient, unavailable or corrupted so that the safety of traffic, ensured through the provision of air navigation services, is impaired or prevented* (EUROCONTROL, 2009b).
- Inability to provide Air Traffic Services (ATS) - *An event in which elements in the ground ATS system are unavailable* (EUROCONTROL, 2009b).

These categories are defined in detail in ESARR2 (EUROCONTROL, 2009b) and the MESYS database design is in line with the ESARR2 template. Figure 4-7 presents the occurrence type and number for the period 2008-2012.

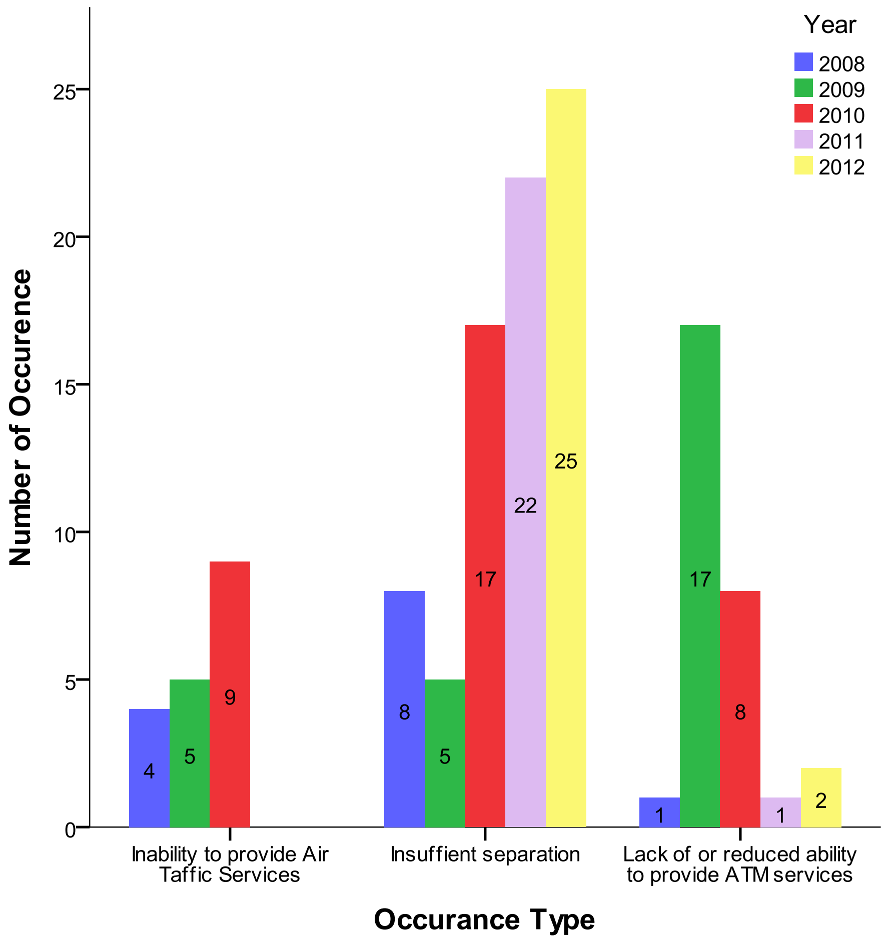


Figure 4-7: Occurrence number and type for 2008-2012

Occurrences caused by 'insufficient separation' were at the lowest level in 2009 (5 incidents) and highest in 2012 (25 incidents). The incidents caused by 'lack of or reduced ability to provide ATM services' were at the highest level in 2009 (17 incidents) and lowest in 2008 and 2011 (1 incident each year). Overall, the 'insufficient separation' category has the highest count over the five years (77 incidents). There is no significant pattern shown in the occurrence of incidents due to 'lack of or reduced ability to provide ATM services'. However, incidents caused by 'inability to provide Air Traffic Services' and 'insufficient separation' show a continuous increase from 2008 to 2010 and 2010 to 2012 respectively. No incidents were recorded in 2011 and 2012 for 'inability to provide Air Traffic Services' category. The statistics in Figure 4-7 include occurrences related to all the ATM supporting functions. However, the occurrences of interest in this thesis are only those related to the surveillance function. A review of the safety reports is used to refine the analysis and identify the occurrences related to surveillance function. Figure 4-8 shows the number of occurrences related to surveillance functions and the other ATM supporting functions. The figure shows that of the 18 occurrences from 'inability to provide Air Traffic Services', 10 are due to the surveillance function. Of the 77 occurrences from 'insufficient separation', 55 are due to the surveillance function and of the 29 from 'lack of or reduced ability to provide ATM services', 11 are due to the surveillance function. The other ATM supporting functions are communication, data processing, navigation and information functions as stated by ESARR2.

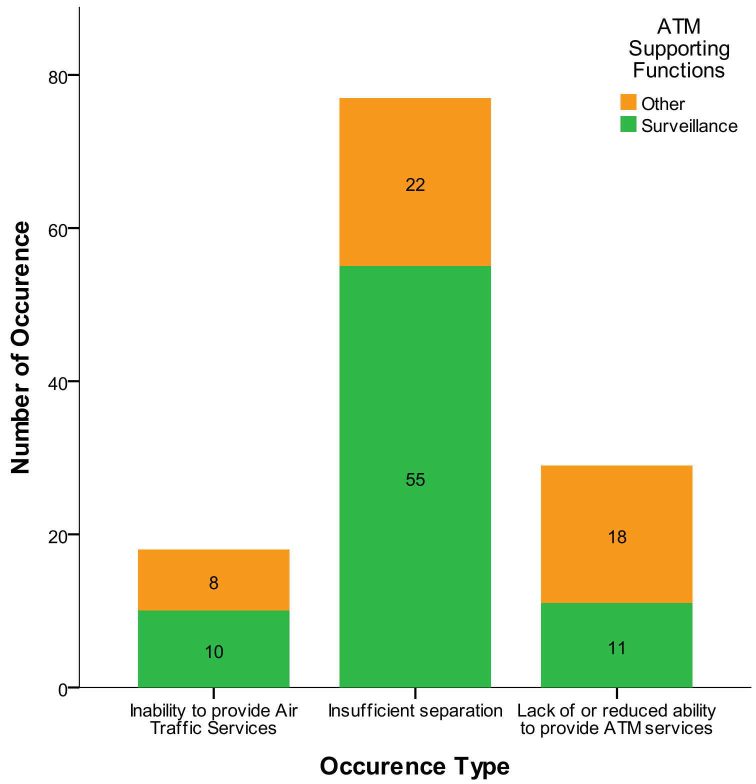


Figure 4-8: Occurrence related to ATM supporting functions

Based on the narratives for the occurrences associated with the surveillance function identified in Figure 4-8, the causal factors for each occurrence type are identified and categorised as follows:

- Contextual Environment- *External air transport environment includes the physical environment outside the immediate work area such as weather (visibility/turbulence), terrain, congested airspace and physical facilities and infrastructure including airports as well as broad organizational, economic, regulatory, political and social factors (ICAO, 1993)*. This definition is adopted in this thesis.
- Human Error- Literature search and structured communication with a safety expert from EUROCONTROL, Peter Stastny, and the ATM Safety researcher Lucio Vismari from Sao Paulo University revealed that ICAO does not have an agreed definition for Human Error. Therefore, the nearest definition relevant to this research is by *Isaac and* Ruitenberg (1999) in which human error in ATM/ATC is defined as *"intended actions which are not correctly executed"*. Hollnagel et al. (1995) refined this definition by adding that, *"human error, can denote a cause, as well as an action".* This refined definition is adopted in this thesis.
- System Limitation- *Defined in Section 4.4*.

Table 4-6 shows the percentage of causal factor categories for each occurrence type related to the surveillance function, over the five years. The results show that 80% of 'Inability to provide Air Traffic Services' occurrences are due to 'system limitation'. For 'insufficient separation', 45.45% of the causal factors are categorised as 'system limitation' with 'human error' being 52.73%. The corresponding figures for 'lack of or reduced ability to provide the ATM services' occurrences are 54.55% and 45.45%. In summary, the results show that 'system limitation' is the highest contributing factor to the occurrences due to 'lack of or reduced ability to provide the ATM services' and 'Inability to provide Air Traffic Services'.

Table 4-6: Categorisation of causal factors for occurrence related to surveillance function

Occurrence Type	**Categorisation of Causal Factors**		
	Contextual Environment	**Human Error**	**System Limitation**
Lack of or reduced ability to provide Air Traffic Services	0%	45.45%	54.55%
Inability to provide Air Traffic Services	10%	10%	80%
Insufficient separation	1.82%	52.73%	45.45%

A set of questions were raised to verify and identify the underlying causes of the findings in Figures 4-7 to 4-8 and Table 4-6 from an operational point of view. Structured communication with five ATM personnel (Table 4-2) was conducted on 24 March 2013 at Avinor, Norway to discuss the questions. The results are presented in Table 4-7.

Table 4-7: Questionnaire to Avinor

Questions	Response from Avinor
The analysis in Figure 4-7 shows continuous increase in occurrence due to 'Inability to provide ATS' (2008-2010). Further analysis in Table 4-6 shows that 80% of the causes for the occurrences are due to 'System Limitation' related to surveillance function. What are the plausible reasons for this? However, this, significantly improved to zero occurrence in the last two consecutive years, 2011 and 2012. What are the plausible reasons for this drastic improvement?	Before 2010, technical issues involving ATC systems where considered as occurrences, hence logged in the MESYS database. However, after 2010, they were no longer recorded in the MESYS. This may have been the justification for the improvements seen in 2011 and 2012. In addition, there was no radar fall out experienced in the two years. Avinor feels it has more stable technical systems in the past few years. A number of occurrences of radar fade out were experienced within the years (2008-2010) particularly in the North of Norway.
Figure 4-7 shows a continuous increase from year 2008 – 2012 except for a small decrease in 2009 for occurrence due to 'Insufficient Separation'. Based on the analysis in Figure 4-8, 70% of the occurrences are related to the Surveillance Function. Further analysis on the 70% of the occurrences, indicated that 52.7% are due to Human Error and 45.45% are due to System Limitation. What is your view on this?	No comments were given on the Human Errors found; instead, Avinor stated that, the figures found should reflect the error. Avinor added that any degradation of a system that supports separation services to aircraft results in larger aircraft separation. Hence, this is also considered as an occurrence.
The number of occurrences due to 'Lack of or reduced ability to provide ATM services' has been decreasing from 2009 -2012. What is the plausible reason for this improvement?	Avinor stated that the following reasons may have contributed to the improvements seen: ▪ More stable systems in the past few years; ▪ Exclusion of technical issues from MESYS; ▪ Under-reporting in some units; and ▪ No automatic comparison of reporting with "actual" incidents.

The safety data analysis and the questionnaire indicate that the incidents identified are mainly related to the limitations in the current surveillance system and that the incident numbers are also partially influenced by the reporting culture.

Therefore the incidents identified under the 'system limitation' category (Table 4-6) from the safety reports, are analysed further to extract their causal factors, and then grouped and mapped to the causal factors identified in Section 4.4 in Table 4-8.

Table 4-8: Mapping of causal factors (safety report) to derive causal factors

Causal factors identified from safety reports (Norwegian ANSP 2008-2010) for 'Occurrences' due to the 'system limitation' category	Number of occurrence	Derived causal factors as the consequences of limitations in the current surveillance systems
1. Short Term Conflict Alert (STCA) not triggered due to high speed of aircraft 2. Lack of ATC awareness on traffic 3. Lack of pilot awareness on surrounding traffic	1 3 3	**C1** - Lack of situational awareness
1. No situational awareness in certain oceanic sectors due to unavailability of radar coverage 2. VFR aircraft not detected 3. No radar for operational use in certain areas due to difficulty to site radar 4. Aircraft not visible on a specific radar display due to a line-of-sight problem between aircraft antenna position and radar station when aircraft is in high altitude 5. No ATC surveillance coverage in uncontrolled airspace 6. No radio communication and track identification on radar display	3 2 3 2 1 2	**C2**- Limited surveillance coverage
1. Inaccurate track display on radar screen 2. Inaccurate information on aircraft speed	1 1	**C3**- Inaccurate positioning information
1. Delay on track update on radar display	3	**C4**- Low update rate (position data)
1. Radio communication problem 2. Unavailability of radio coverage in certain oceanic and remote areas 3. Radio frequency congestion	2 2 1	**C5**- Loss of communication
1. Unsynchronised traffic information between TCAS (aircraft) and ATC 2. Misinterpretation of actual aircraft position - ATC 3. Unsynchronised situational awareness between pilot and ATC	3 2 2	**C6**- Unsynchronised surveillance information between flight crew and ATC
1. Surface Movement Radar (SMR) provides poor visibility of track during extreme weather condition 2. Unavailability of limited radar coverage due to extreme weather condition	1 1	**C7**- Visual deficiencies in extreme weather conditions

Another important finding from this analysis is that some causal factors identified from the safety reports categorised as due to system limitation, have a correlation with human error. In such cases, the effect of system limitation may lead to human error. Table 4-9 and 4-10 show examples of this scenario. It is not possible to show the correlation statistically as the variables of correlation are based on the interpretation of the safety reports.

Table 4-9: Example scenario (Avinor safety report) that shows correlation between system limitation and human error

Occurrence	Occurrence Type	Causal factor identified from safety report	Causal factor categorisation	Analysis based on the report narrative
Incident	Insufficient Separation	Unsynchronised traffic information between TCAS (aircraft) and ATC	System Limitation	Due to the effect of limitation in both systems TCAS and ATC Surveillance system, there is a tendency for the pilot or the controller to make an error. The ATC might give a wrong separation instruction based on the radar estimation or the pilot may navigate at wrong separation due to TCAS alert.

This scenario can be associated with the Ueberlingan accident.

"*On 1 July 2002 at 21:35:32 hrs a collision between a Tupolev TU154M, which was on a flight from Moscow/ Russia to Barcelona/ Spain, and a Boeing B757-200, on a flight from Bergamo/Italy to Brussels/Belgium, occurred north of the city of Ueberlingen (Lake of Constance). Both aircraft flew according to IFR (**I**nstrument **F**light **R**ules) and were under control of ACC Zurich. After the collision both aircraft crashed into an area north of Ueberlingen. There were a total of 71 people on board of the two airplanes, none of which survived the crash" (German Federal Bureau of Aircraft Accidents Investigation, 2004).*

Table 4-10: Analysis of the Ueberlingen Accident

Occurrence	Occurrence Type	Causal factor identified from safety report	Causal factor categorisation	Analysis based on the report narrative
Accident	Insufficient Separation	Unsynchronized traffic information between TCAS (aircraft) and ATC instructions	System Limitation	The imminent separation infringement was not noticed by ATC in time. The instruction for the TU154M to descend was given at a time when the prescribed separation to the B757-200 could not be ensured anymore. The TU154M crew followed the ATC instruction to descend and continued to do so even after TCAS advice them to climb. This manoeuvre was performed contrary to the generated TCAS RA.

The analysis of the Ueberlingen accident in Table 4-10 shows that the unsynchronised surveillance information from ATC with the TCAS system led to the human error which finally caused the catastrophic event. The incident would have been avoided if both the pilot and ATC had the same level of situational awareness of the traffic.

In summary, this analysis shows that the limitations in the current surveillance systems are significant as it is the main contribution to all the occurrences related to the surveillance function. Hence, improved and high performance surveillance systems are required to support increasing air traffic based on the required performance by ICAO. The next section reviews the capabilities of ADS-B system to overcome the limitations in the current surveillance system to support future air traffic.

4.6 Safety improvement potential of ADS-B

High performance ADS-B positioning information (in terms of accuracy, integrity and update rate) in real time is required to enable many ground and airborne applications in the future (Butterworth-Hayes, 2012). The capabilities of ADS-B are outlined in Chapter 3. This can be verified by the functionalities supported by the airborne applications. For example, on the airport surface, a traffic display (CDTI) in the cockpit showing all aircraft taxiing on the maneuvering area and within the terminal area, coupled with a background airport map from Flight Information Service Broadcast (FIS-B) would improve the pilot's situational awareness, reduce the risk of runway incursions and assist the pilot to navigate around an unfamiliar airport (AirservicesAustralia, 2007). Furthermore, it will improve safety during extreme weather and reduced visibility conditions (Herrera et al., 2009). In the case of reduced or unavailability of radio communication between pilots and controllers, availability of traffic display (CDTI) and assistance to perform separation (ASAS) will aid safe aircraft navigation.

The use of In-Trail Procedure (ITP) in a Controller-Pilot Data Link Communication (CPDLC) environment is accepted and positively rated by the flight crew and controllers (EUROCONTROL, 2009a). ADS-B provides safety measure for this application by providing traffic display (CDTI), as a complement to more specific ITP information to improve situational awareness in support of flight level changes. The CRISTAL-ITP Project (EUROCONTROL, 2009a) concluded that the quality of the ADS-B OUT information from the reference aircraft in terms of update rate, accuracy and integrity as received was sufficient to support ITP flight trial. The data recorded from the trial also showed that the received ADS-B OUT information was compliant with Airborne Traffic Situational Awareness—In-

Trail Procedure Safety Performance Requirements (ATSA-ITP SPR) (RTCA, 2008). This will enable aircraft surveillance in oceanic and remote areas (which did not exist with the current surveillance system) resulting in increased safety for aircraft navigation within these areas.

Over the past 20 years, the threat of a mid-air collision occurring on a commercial flight has tremendously decreased and is very rare (Zwegers, 2010). This is primarily due to the implementation of TCAS. However, the TCAS system was not designed for small GA aircraft due to its size and prohibitive cost (Zwegers, 2010). Therefore, mid-air collisions involving General Aviation (GA) still occur, especially with student pilots onboard.

ADS-B data can be used to improve TCAS surveillance and traffic display. This technique is known as hybrid surveillance (RTCA, 2006a). The use of ADS-B data (passive surveillance) enables TCAS traffic displays to more accurately depict the bearing and velocity of surrounding aircraft. In addition, the identity information received through ADS-B allows identification of other aircraft. Furthermore ADS-B enables TCAS to track aircraft at a range of more than 100NM compared with 40NM using TCAS active surveillance (AirservicesAustralia, 2007). Hence ADS-B improves situational awareness and safety for the TCAS application. Despite these advancements, the collision avoidance function within TCAS remains unchanged with Hybrid Surveillance; ADS-B information is not used as input to calculate resolution advisories. It is envisaged that in the future, ADS-B data to be used in the TCAS collision avoidance function taking advantage of its high performance (accuracy and update interval).

This is supported by research conducted by the Embry-Riddle Aeronautical University (ERAU). ERAU conducted a case study with 100 training aircraft fully equipped with ADS-B in a dense airspace. The study (Zwegers, 2010) indicated that ADS-B has dramatically decreased the risk of mid-air collision in a very congested airspace by:

- providing pilots with real-time traffic information with high accuracy, in which to implement conflict detection and resolution, especially below radar coverage (low altitude and ground information), thereby avoiding mid-air collision and runway incursion;
- providing pilots with graphical and textual weather information; and
- providing ANSP with real-time information of aircraft location for planning purpose (spreading out aircraft to minimise congestion) and flight following (tracking).

Furthermore, recordings of ADS-B data can be used by the stakeholders (airline operators, ANSP and regulators) to increase safety and efficiency practices (e.g. incident/accident investigation, pattern flow in/out airspace study, address noise complaint).

4.6.1 How ADS-B can improve the limitations in the current surveillance system?

It is clear that the performance of ADS-B is such that it has the potential to support the increase in air travel demand which current surveillance systems, given their operational limitations, cannot achieve. Table 4-11 shows a comparison of the ADS-B system and the current surveillance system based on the surveillance applications required by ICAO to accommodate the increasing air travel demand.

Table 4-11: A Comparison of the ADS-B system and the current surveillance system based on applications required by ICAO to accommodate increasing traffic

Surveillance Application	Current Surveillance System	ADS-B System
Improved situational awareness of the air traffic	Limited situational awareness in remote and oceanic areas, restricted to line of sight and subject to severe signal fading and interference.	Situational awareness in a particular area depends on the movement of ADS-B equipped aircraft in that area at time (t). Aircraft are independent of ATC to obtain situational awareness.
Radar equivalent	Able to detect both cooperative (SSR) and non-cooperative (PSR) target within limited range.	Provides improved accuracy and higher position update rate, which will enhance the surveillance service. Only detects ADS-B equipped targets.
Enhanced visual acquisition	Limited visual acquisition. Conventional “see and avoid” has reached its limit due to the increasing speed of aircraft, the poor visibility in modern cockpit and flight crew workload in some phases of flight.	Provides enhanced visual acquisition capability with respect to “see and avoid” procedure which applies to VFR/VFR and IFR/VFR operations. This is provided by use of Cockpit Display of Traffic Information (CDTI) application.
Airport surface operations	The Surface Movement Radar (SMR) output deteriorates during heavy rain and vanishes due to line of sight.	ADS-B provides a new source of airport surveillance information for safer and more efficient ground movement management in airports. Airport ground vehicles should also be equipped with ADS-B to generate a complete situational awareness display.
Enhanced separation	Provide low update rate of 4s-12s.	The improved accuracy and an update rate of 1-2 seconds enable reduced separation. Subsequently, this will enable redistribution of tasks related to sequencing and merging of traffic between the ATC and aircraft. It will also enable in-trail procedures in non-radar airspace, allowing ADS-B equipped aircraft to descend and climb through each others’ flight level. This will result in optimised airspace capacity utilization.

Potential mitigations based on the ADS-B system for the causal factors due to the limitations in the current surveillance systems (derived in Section 4.4) are described in Table 4-12.

Table 4-12: Potential mitigations for the limitations of the current surveillance systems

Derived causal factors for current system limitations (Section 4.4)		Potential mitigation based on ADS-B system
C1	Lack of situational awareness	Flight crew will have complete situational awareness of all ADS-B equipped aircraft and geographical structure for a specified range. Controllers will also have complete visual representation of air traffic in their territory.
C2	Limited surveillance coverage	ADS-B provides surveillance coverage in both radar and non-radar airspace.
C3	Inaccurate positioning information	ADS-B provides accurate positioning information derived from GNSS.
C4	Low update rate (position data)	ADS-B provides an update rate of (1-2) seconds in en-route and less than 1 second update rate in the terminal area.
C5	Loss of communication	ADS-B provides continuous broadcast of the aircraft position to ATC centers in the ground.
C6	Unsynchronised surveillance information between flight crew and ATC	Flight crew and controllers will have similar level of situational awareness.
C7	Visual deficiencies in extreme weather conditions	Cockpit Display of Traffic Information (CDTI) application supported by the ADS-B system will provide complete visual aid to flight crew despite of the weather condition.

4.7 Summary

This Chapter has identified and validated that, limitations exist in the current surveillance systems. The impacts of these limitations are increasing incidents and inability to support the required applications to cater for enhanced flight operations and future air traffic volume. In order to solve these issues, the capabilities of ADS-B system are analyzed. Findings in Section 4.6 and analysis in Tables 4-11 and 4-12 show that the system has promising capabilities to improve airspace capacity by providing accurate aircraft positioning information at high update rates and enhance traffic handling capacity by providing separation assistance and situational awareness to flight crew. In addition, high system performance (i.e. accuracy, reliability, integrity, availability) in comparison to the current surveillance systems should lead to improved system safety. However, the safety level of the ADS-B system has to be assessed and validated in various operational environments prior to consideration for global implementation by all stakeholders. It is important to have a systematic approach to assess the safety level of a safety critical system. The next Chapter presents a comprehensive, reliable and robust safety assessment framework for ADS-B system to ensure that the system is acceptable safety to operate in any operational environment.

Chapter 5

Safety Assessment Framework for ADS-B

This Chapter develops a comprehensive safety assessment framework for the ADS-B system, taking into account the limitations of the current systems and the capabilities of ADS-B identified in the previous chapters.

The first part of this Chapter, defines safety assessment, performance assessment and safety case. The second reviews the existing safety assessment approaches and safety cases for ADS-B system. Finally, the Chapter describes in detail the proposed 'Safety Assessment Framework for the ADS-B System' together with the relevant performance and safety level requirements.

5.1 Background

The ADS-B system is envisioned to support many new application concepts being developed for the future ATM operations e.g. reduced separation minima, complete situational awareness for flight crew and controllers, free flight and self separation. This is in line with the new concept of operation, based on 4D trajectory management. Each application concept can have its own safety assessment program. For example, a trial study on the safety and effectiveness of the In-Trail Procedure (ITP) application to enable aircraft surveillance in oceanic and remote areas, was conducted by EUROCONTROL in collaboration with Airbus (EUROCONTROL, 2009a). However, the safety and reliability of the source (ADS-B system) for the applications was neither assessed nor validated prior to the trial.

ICAO defines safety as "the state in which the possibility of harm to persons or of property damage is reduced to, and maintained at or below, an acceptable level through a continuing process of hazard identification and safety risk management" (ICAO, 2009c). This definition is not suitable for this thesis because it provides a general definition for operations. As this thesis focuses on the ADS-B system, and its operations within a specified operational environment, safety is defined as the state in which, the system operates within the required performance level in a nominal operational environment, and is able to notify users (within a specified time period) on its failure to function based on the requirements to avoid the possibility of harm to persons or property.

Hollnagel (2014) defines Safety-I as "a condition where the number of adverse outcomes was as low as possible". Safety-I is measured by counting the number of failures, responding to what goes wrong and identifying the risk of the failures. This definition is in line with ICAO's definition. Hollnagel also looked at safety from a different angle whereby focusing on what goes right rather than what goes wrong (Safety-II). Safety-II is measured by counting the number of cases where things go right (Hollnagel, 2014). Safety-I is a traditional risk assessment approach and hence, more established than the Safety-II approach.

The safety definition proposed in this thesis combines both approaches, Safety-I and Safety-II. However, the assessment conducted in this thesis only focuses on what may go wrong in the ADS-B system rather than what goes right. Safety-II requires the system to be operational for a duration that enables the safety analyst to analyze/study how the system functions succeed to provide the daily required performance level. It is a proactive rather than reactive approach, providing potentials for early intervention. ADS-B is still in its early implementation or trial in most part of the globe apart from Australia. Future work will improve the ADS-B safety assessment framework proposed in this thesis by reaping and integrating the Safety-II approach advantages into the framework.

The ADS-B system is very complex, being highly dependent on the navigation and communication elements. Hence, it is prone to more failure modes in comparison to the radar system. Therefore, it requires a rigorous, clear and comprehensive safety assessment method to ensure that the system is acceptably safe to operate in any particular context. Before developing a safety assessment method, it is important to understand and differentiate between safety assessment, performance assessment and safety case.

5.2 Safety Assessment, Safety Case and Performance Assessment

EUROCONTROL (2010d) envisages that the distinctions between safety assessment and safety case must be understood before they are established. EUROCONTROL states that safety assessment looks at hazards, and their effects and mitigations, and makes reasonable assumptions about the behavior of the system elements (such as their reliability and accuracy levels or failure rates) so as to be able to assess quantitatively the likelihood of hazards resulting in incidents or accidents. On the other hand a safety case collects data to verify that the assumptions are valid in a real life situation. The worthiness of a safety case depends on the suitability of the outcome to verify the parameters set in the safety assessment phase.

Performance assessment captures system behavior. Its objective is to ensure that the system will perform its intended function, while a safety assessment indicates that the system will not induce dangerous situations. Therefore, performance covers the nominal (*non-adjusted*) modes of operation whereas safety focuses on non nominal modes (ICAO, 2006b). Performance requirements such as accuracy, integrity and availability are integral to safety assurance of the ATC surveillance system (ICAO, 2006b). In order to ensure that ADS-B implementation is safe, both safety and performance assessments must be undertaken, whereby hazards are identified and barriers are introduced to reduce the risk that may be caused by these hazards.

5.2.1 Safety Assessment

Safety assessment is a structured and systematic process for the identification of hazards and assessment of the risk associated with each hazard. A safety assessment based on these concepts is essentially a process for finding answers to three fundamental questions (ICAO, 2005):

- What could go wrong?
- What would be the consequences? and
- How often is it likely to occur?

In relation to the equipment to be used, a safety assessment should consider the following sources of faults:

- Hardware faults;
- Software malfunctions;
- Environmental conditions;
- Dependencies on external services; and
- Operating and maintenance procedures.

5.2.1.1 Safety significant factors

According to ICAO, safety assessment shall consider all relevant factors determined to be safety-significant, including (ICAO, 2005):

a) types of aircraft and their performance characteristics, including aircraft navigation capabilities and navigation performance;
b) traffic density and distribution;
c) airspace complexity, ATS route structure and classification of the airspace;

d) aerodrome layout, including runway configurations, runway lengths and taxiways configuration;
e) type of air-ground communications and time parameters for communication dialogues, including controller intervention capability;
f) type and capabilities of surveillance system, and the availability of systems providing controller support and alert functions; and
g) any significant local or regional weather phenomena.

In this thesis, the proposed safety assessment framework focuses on the ADS-B system itself including the role of the human, operational environment and operational procedures.

5.2.1.2 The need for safety assessment

ICAO has clearly defined the need for safety assessment and when it is conducted. A safety assessment is required for significant airspace reorganizations, significant changes in the provision of ATS procedures applicable to an airspace or an aerodrome, and the introduction of new equipment, systems or facilities, such as (ICAO, 2005):

a) a reduced separation minimum to be applied within an airspace or at an aerodrome;
b) a new operating procedure, including departure and arrival procedures, to be applied within an airspace or at an aerodrome;
c) a reorganization of the ATS route structure;
d) a resectorization of an airspace;
e) physical changes to the layout of runways and/or taxiways at an aerodrome; and
f) implementation of new communications, surveillance or other safety significant systems and equipment, including those providing new functionality or capabilities.

Proposals are implemented only when the assessment has shown that an acceptable level of safety is achieved. The ICAO adds that, if the result of an assessment is that the system under review does not satisfy the safety assessment criteria, it is necessary to find some means of modifying the system in order to reduce the risk. This process is called risk mitigation. Therefore, the development of mitigation measures is an integral part of the assessment process, since the adequacy of the proposed mitigation measures must be tested by re-evaluating what the risk would be with the mitigation measures in place.

Therefore, the safety assessment framework in this thesis is developed to assess performance and validate safety of the ADS-B system as a surveillance source to the controller and the flight crew. The framework also aims to identify the risks related to the system implementation and to propose mitigations to reduce the identified risks based on the assessment.

5.2.1.3 Acceptable Level of Safety

The ultimate goal of any safety assessment method is to satisfy 'an acceptable level of safety'. Also referred to as the target level of safety (TLS), the way this term is defined is very subjective. The ICAO (2001a) specifies safety requirements in terms of TLS, which represents the risk of a fatal accident during the entire operation of an aircraft from the point it leaves the gate until it arrives at the destination gate (Schuster and Ochieng, 2011). The ICAO states that the TLS of the ATM system as a whole must be better than one fatal event per million operations (or approximately one fatal accident per 1.0E-07 flight hour) (Andrew and Thompson, 2007). Logically, the list of safety significant factors explained in section 5.2.1.1 should contribute to the above safety level figure stated by the ICAO. However, no absolute fraction of each factor is derived to date. A study by MITRE Corporation (Jones, 2005) recommended that the failure rate assigned to surveillance position measurement error of 2.0E-12 per surveillance report, which is an extremely demanding requirement.

In this thesis, the failure rate of a surveillance position derived by the ADS-B system is measured and the contributing factors are identified in Chapter 6. It is important to identify the sources that contribute to failures to enable mitigations or barriers to be implemented. As explained in Chapter 2, the Required Surveillance Performance (RSP) is derived based on the radar parameters. Hence, the issue with the RSP is the ability of new surveillance systems to achieve the required safety standards. The RSP should be derived independent of the surveillance technology giving flexibility to Air Navigation Service Providers (ANSPs) to deploy any type of technology suitable to their operational environment and budget having met the required safety standards. According to the M.I.T Lincoln Laboratory (Andrew and Thompson, 2007), a standard called the Required Total System Performance (RTSP) is developed as part of the NextGen concept. RTSP will involve a set of performance requirements covering communication, navigation and surveillance. The idea of RTSP fits the performance requirements of ADS-B system being highly dependent on the navigation and communication functions. The only generic requirements available to date for surveillance systems implementation independent of technology, is the Surveillance Performance and Interoperability

Implementing Rule (SPI-IR) (EUROCONTROL, 2011d), explained in Chapter 3. The ICAO has also provided a guide for Baseline ADS-B service parameters (ICAO, 2007d). The baseline parameters given cater for operational scenarios that complement the current operating environments, for example, radar or procedural control environment.

Another approach to define 'acceptable level of safety' is to use a comparative approach, in which, the risk of the new system is not greater than the reference system. This approach is adopted in this thesis as discussed in detail in section 5.3.2.

The next section reviews the existing system safety assessment approaches.

5.3 Existing safety assessment approaches

A number of approaches exist to assess the safety level of a system. These include 'Evaluation of system risk against a threshold value (Absolute Method)'(ICAO, 1998c); 'Comparison with a reference system (Relative Method)'(ICAO, 1998c) and (Butcher, 2002); and 'Safety assessment based on Fluid Stochastic Petri Nets' (Vismari, 2008). However, none of these methods are applicable fully to assess the ADS-B system due to its complex nature. In addition to the methods stated above, Hammer (2007) and Zeitlin (2001) proposed safety assessment methods for ADS-B based applications, with the current focus being on implementation. In this thesis, the aim is to develop a comprehensive safety assessment approach for ADS-B to ensure that the system is acceptably safe to support any airborne or ground based applications for ATC and aircraft navigation operations. It is crucial to verify that the data sources are reliable, before being used in any application to support operations. The development of a safety assessment approach for a complex and safety critical system, requires a detailed understanding of the system architecture including functionality and physical architecture.

5.*3.1* Evaluation of risk against threshold value (Absolute Method)

This approach is proposed by the International Civil Aviation Organization (ICAO). It is also known as the target-level-of-safety approach. It applies the Reich Model (Reich, 1964) as the modeling and analyses method, involves a number of tasks including:

- defining the proposed system by identifying its functional elements and their parameters;

- setting evaluation criteria by defining the safety metrics values or safety integrity level (SIL); identifying the potential hazards that may lead to collision;
- estimating the frequency of each hazard based on historical events, specialists judgements or indirectly from system parameters;
- modeling the consequences of each hazard and identifying their severity degree; and
- finally estimating the risk by applying the formula, *Risk(Hazard i) = Frequency *Consequences.*

If the risk value is less than the SIL value, then the proposed system is considered to be safe. Figure 5-1 depicts this approach. The safety level of the new system is calculated directly from models and data. However, this approach may not produce an accurate output due to the use of historical hazard data. In addition the pre-established value of the SIL is based on a different system e.g. radar system, which may have different parameters from the proposed system. Furthermore, this approach is based on a mathematical model with limitations, including inability to model controller's feedback and the flight crew's intervention when an aircraft is on a collision route.

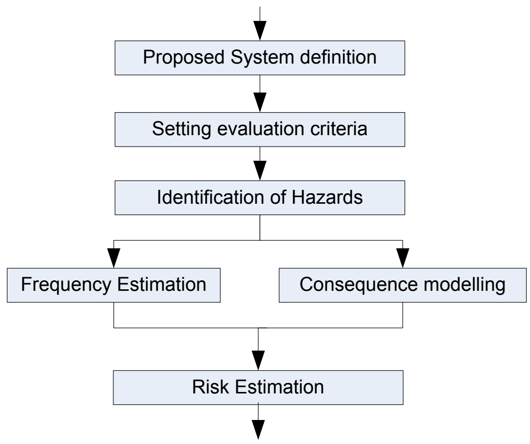


Figure 5-1: Evaluation of Risk against threshold value (Absolute Method) (ICAO, 1998c)

5.3.2 Comparison with a reference system (relative method)

This approach is also proposed by the ICAO. The safety evaluation based on this approach is made by comparing the performance parameters of the new system to a reference system. The reference system should be a system already in use and accepted as providing adequate safety. The approach is also conditioned upon the fact that both systems must be similar based on a set of minimum requirements. This approach is conducted in three steps:

- describing the differences and similarities between the two systems;

- verifying each analysed parameter if the differences can affect the risks, this analysis is done using a mathematical technique or operational judgement; and
- finally comparing the level of safety for each parameter.

However, the relative method cannot be applied when the new system is significantly different from the reference system. This approach has the advantage that it does not require complete modelling of all the factors that impact safety (Andrew and Thompson, 2007). Butcher (2002) applied the relative method by using the radar system as the reference system to validate ADS-B system safety. The work concluded that the ADS-B system is as safe as the radar system. The main reason why this is not acceptable is that the performance of ADS-B must be significantly higher than radar, to support the surveillance requirements for ever increasing air traffic. Moreover, the radar system is substantially different than the ADS-B system.

5.*3.3* Safety assessment method based on Fluid Stochastic Petri Nets (FSPN)

This approach combines the two approaches proposed by the ICAO in section 5.3.1 and 5.3.2. It is based on modeling, simulation and comparison with the radar system. It applies Fluid Stochastic Petri Nets (FSPN) as the modeling and analyses method. Figure 5-2 illustrates each step in the approach. However, it does not produce an accurate output due to the historical data used as input to the risk evaluation model. Furthermore, it is not suitable for a system which does not have a reference system.

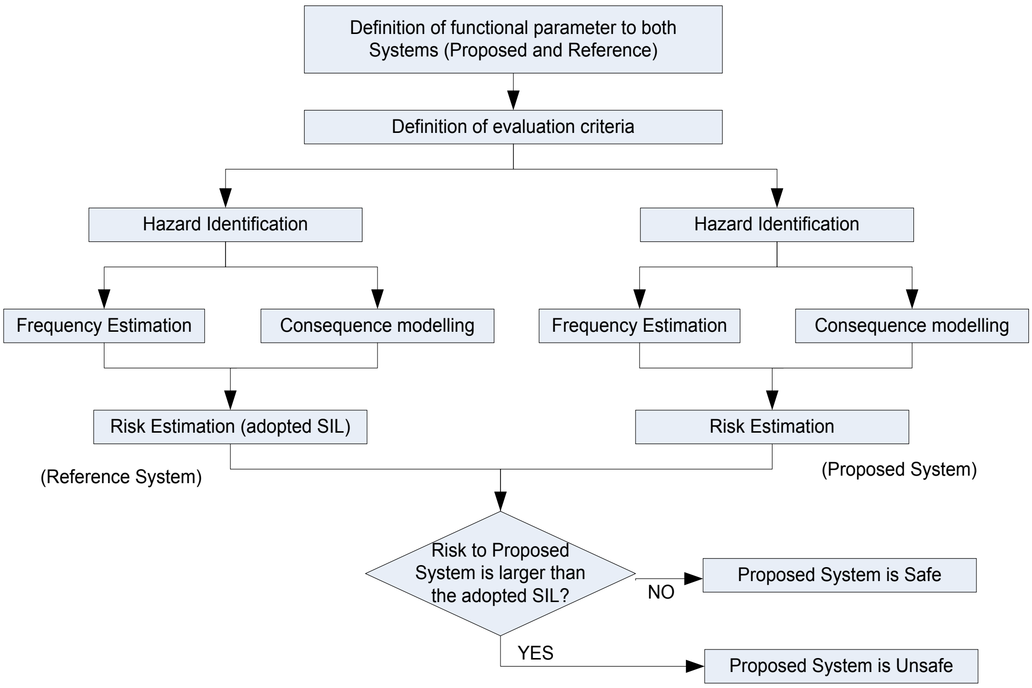


Figure 5-2: Safety assessment method based on Fluid Stochastic Petri Nets (FSPN)(Vismari, 2008)

5.*3.4* Issues with the existing system safety assessment approaches

Based on the analysis of the safety assessment approaches in the previous sections, the limitations of the existing approaches are summarized in Table 5-1.

Table 5-1: Issues with existing system safety assessment approaches

Safety Assessment Method	Issues
Evaluation of system risk against a threshold value (Absolute Method)	▪ Does not provide an accurate output due to historical hazard data ▪ The pre-established Safety Integrity Level (SIL) value is based on the radar system, which has a different set of parameters to ADS-B. ▪ Based on a mathematical model (Reich Model, 1964) which is unable to take into account human factors within the ATC loop.
Comparison with Reference System (Relative Method)	▪ Cannot be applied when the new system is significantly different from the reference system.
Safety assessment based on Fluid Stochastic Petri Nets	▪ Does not produce an accurate output due to the imprecise input values to the risk evaluation model. ▪ Not suitable for systems without a reference system.

5.4 Safety Case

The aim of a safety case is to enable system implementers to assure themselves and their regulators that the system under consideration for implementation will deliver an acceptable level of safety throughout its lifetime. This is publicized through documented logical arguments and the provision of supporting evidence. The development of a safety case is not an alternative to carrying out a safety assessment; instead it is a mean of structuring and documenting a summary of the results of a safety assessment to provide the evidence that the new system (service) can be considered safe (EUROCONTROL, 2006b).

5.4.1 Generic Safety Case development manual

EUROCONTROL has developed a generic safety case development manual (EUROCONTROL, 2006b). Figure 5-3 depicts the generic safety case development concept suggested by EUROCONTROL. Because of its generic nature, the safety case development manual is not sufficient for implementation of specific safety cases. Other documents such as the Safety Assessment Manual (EUROCONTROL, 2010d) could be required to complement it. However, the overall concept is logical and acceptable if precise methods for each step in the safety case development concept in Figure 5-3 are provided.

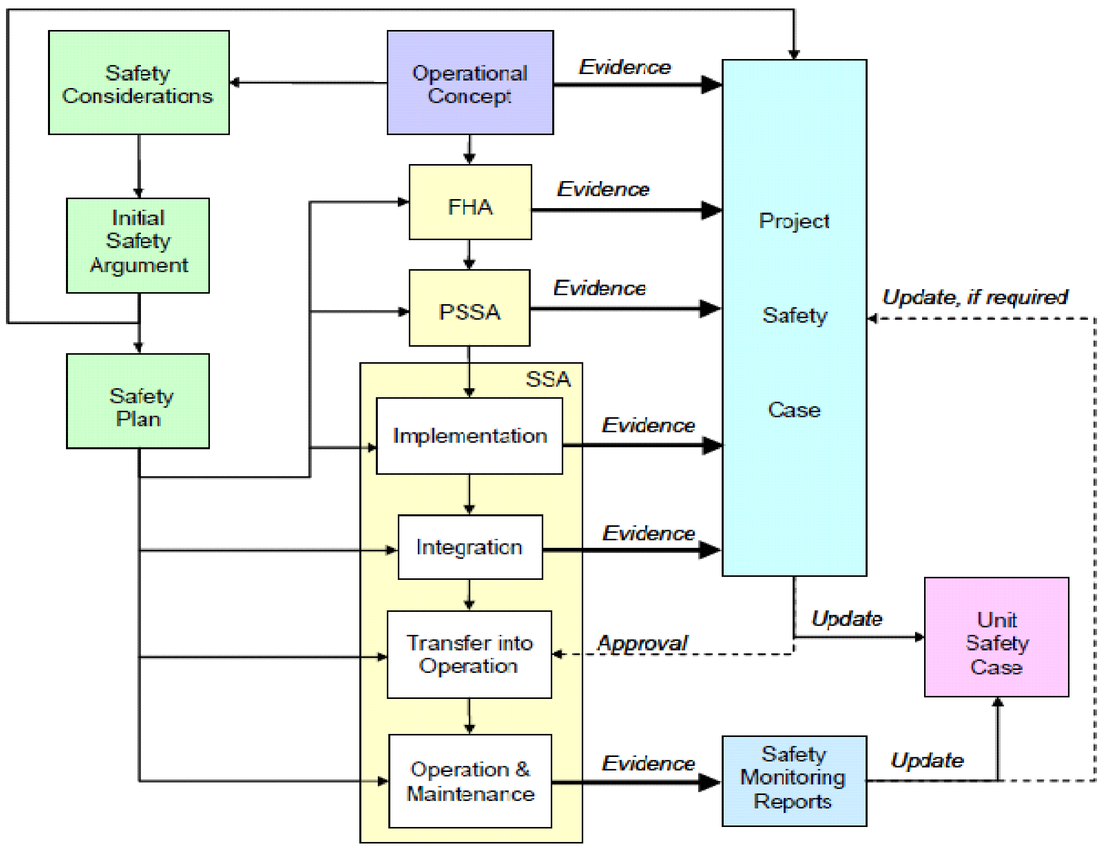


Figure 5-3: Safety Cases and the Project Safety Lifecycle (EUROCONTROL, 2006b)

5.4.2 Existing Safety Cases for ADS-B

In this section, various safety cases developed for the ADS-B system by EUROCONTROL, NATS, FAA and Airservices Australia, are discussed.

5.4.2.1 EUROCONTROL

EUROCONTROL has implemented preliminary safety cases for the ADS-B system in radar and non-radar airspace under the CASCADE programme. The CASCADE programme coordinates the deployment of initial ADS-B applications and Wide Area Multilateration (WAM) in Europe. The programme covers both ground surveillance (i.e. “ADS-B OUT” and WAM) as well as airborne surveillance applications (i.e. “ADS-B IN” / Air Traffic Situational Awareness (ATSAW)). The key deliverables of the CASCADE programme are: standardization, certification and integration support for the applications as well as airborne and ground based system components; safety case activities; validation of ADS-B applications and systems; functional performance analysis and, as necessary, support to the rectification of system anomalies. In the context of the CASCADE program, a

Preliminary Safety Case (PSC) does not include implementation, transition and in-service related issues; it includes design stages of the intended system, related requirements considering typical operating environment characteristics such as traffic density and the separation minima to be applied. The various PSCs developed are:

- PSC for ADS-B in Non Radar Area (NRA) (EUROCONTROL, 2008c)
- PSC for ADS-B in Radar Area (RAD) (EUROCONTROL, 2010c)
- Review of PSC for ADS-B in Radar Area (RAD) (Eurocontrol Safety Regulation Commission 2011)
- PSC for ADS-B in Airport Surface Surveillance (APT) (EUROCONTROL, 2011b)
- PSC for ADS-B in Visual Separation on Approach (VSA) (EUROCONTROL, 2011c)

In this thesis, the relevant concepts of PSC for ADS-B in NRA and PSC for ADS-B in RAD are discussed.

5.4.2.1.1 Preliminary Safety Case for Enhanced Air Traffic Services in Non-Radar Area using ADS-B Surveillance (PSC ADS-B NRA)

The purpose of this PSC is to document the results of the assessment of ADS-B to support and enhance Air Traffic Services (ATS) in both en-route and Terminal Area (TMA) airspace without radar surveillance. The safety assessment method applied is comparison with radar-based ATS operations using single Mode A/C SSR radar as a sole surveillance means in the nominal mode of operation and target level of safety method (EUROCONTROL, 2008c) (compliant with ESARR4 (EUROCONTROL, 2001) safety target values) in non-nominal mode of operation. The safety standard applied in this PSC ADS-B NRA is the “Safety Performance and Interoperability Requirements Document for ADS-B NRA application”(RTCA, 2006b). The PSC concludes that, ADS-B surveillance in non-radar areas for ATS is acceptably safe on the basis that the quality of service of ADS-B surveillance is similar to SSR radar and that appropriate (VHF) air-ground communication coverage is available.

5.4.2.1.2 Preliminary Safety Case for Air Traffic Control Services in Radar Area using ADS-B Surveillance (PSC ADS-B RAD)

The purpose of this PSC is to demonstrate the use of ADS-B to provide surveillance information together with radar to support Air Traffic Control Service (ATC) in radar airspace. The safety assessment method applied for this safety case is the reference method approach using only multiple radars as the reference system for the combination of ADS-B and other radar. The PSC considers three different operating scenarios:

Scenario 1: ATC services in a TMA area with medium traffic density (i.e. an average of 6 flight hours controlled per sector hour and a maximum of 15 instantaneous aircraft count in a sector), applying 3 NM as separation minima. The surveillance systems considered here for supporting the ATC services are based on:

- ADS-B-RAD system: ADS-B and PSR surveillance means.
- Reference system: SSR and PSR surveillance means.

Scenario 2: ATC services in En-route airspace with high traffic density (i.e. an average of 6 flight hours controlled per sector hour and a maximum of 20 instantaneous count aircraft in a sector), applying 5 NM as separation minima. Two sub-cases are used for the surveillance systems supporting the ATC services based on:

Case 2.1

- ADS-B-RAD system: ADS-B and SSR as surveillance means
- Reference system: two SSR as surveillance means

Case 2.2

- ADS-B-RAD system: ADS-B and Mode S (elementary surveillance) as surveillance means
- Reference system: two Mode S as surveillance means

Scenario 3: ATC services in TMA airspace with high traffic density (i.e. an average of 6 flight hours controlled per sector hour and a maximum of 15 instantaneous count aircraft in a sector), applying:

- 3 NM as separation minima in the wide area
- 2.5 NM separation minima for succeeding aircraft on the same final, and
- 2 NM separation minima for succeeding aircraft on adjacent ILS/MLS

The surveillance systems considered in this scenario for supporting the ATC services are based on:

- ADS-B-RAD system: ADS-B and PSR and SSR as surveillance means
- Reference system: two SSR and PSR as surveillance means

This PSC concludes that the use of ADS-B to provide surveillance information together with radar to support ATC service shows similar performance level to the reference system in the stated operating conditions.

5.4.2.1.3 CRISTAL UK – ADS-B in South East England

EUROCONTROL funded another case study called CRISTAL UK – ADS-B in South East England (NATS, 2007), led by NATS and Helios to assess the implementation of ADS-B in South East England due to Terminal Manoeuring Area (TMA) resectorisation in 2004. The assessment focused on the capability of ADS-B to supplement the radar coverage. The case study concluded that, ADS-B could supplement low level radar surveillance coverage with two ADS-B ground stations located at the current NATS infrastructure sites. However, the study also concluded that, the use of ADS-B alone may not be sufficient to provide 3NM separation service. Nonetheless, there was no credible methodology used to support this case study.

5.4.2.1.4 CRISTAL RAD HD

NATS, the main Air Navigation Service Provider (ANSP) in the UK has planned to either supplement or replace existing en-route radar coverage with WAM and the ADS-B system from 2019 (NATS, 2011a). The decision on the technology option to replace the current en-route Mode-S radars is to be taken by 2015. In achieving this objective, it was deemed necessary to deploy a pre-operational standard WAM/ADS-B system for validation and trials in high density and complex environment in the UK airspace under the CRISTAL RAD HD project. This was in line with the CASCADE Pre-operational validation exercise for the ADS-B RAD project. The project used the infrastructure installed under the CRISTAL RAD HD project to complete the safety case for its operation and validation of the ADS-B RAD preliminary safety case (EUROCONTROL, 2010c). The CRISTAL RAD HD has further expanded its scope to develop a detailed description of how a multi-sensor tracked environment could operate in the London TMA. This was verified by a discussion with Craig Foster, Project Manager of the Crystal Project at NATS. The ATC operations in the UK aim to merge old and new surveillance technologies using multi-sensor tracker called ARTAS (EUROCONTROL, 2001-2013a).

5.4.2.2 Airservices Australia

Airservices Australia has conducted an operational trial of ADS-B for Air Traffic Control (ATC) surveillance in the Burnett Basin of Queensland. The safety case design and implementation was developed based on a comparison of ADS-B to radar performance (ICAO, 2006b). The findings from the comparison study for ADS-B and SSR conducted by Airservices Australia showed that ADS-B tracks are solid and without any significant multipath problems or gaps. The study also highlighted that ADS-B coverage is very close to that of radar. The minor differences identified are due to the antenna heights. In addition, the study also found that one particular aircraft used ADS-B in excess of 360NM. A statement by Airservices Australia states that, it has been agreed that if ADS-B can be demonstrated to be as good as radar in the relevant system performance measures, then it can be used to deliver the services that radar currently supports. Apart from Airservices Australia, many other ANSPs and regulators worldwide such as EUROCONTROL, FAA, and others perform ADS-B system assessment using radar system as the baseline. The ICAO has designed a generic safety case based on a safety case conducted by Airservices Australia on the operational use of ADS-B in non-radar airspace (ICAO, 2003d). The safety case is based on the reference system approach by the ICAO (refer to section 5.3.2).

5.4.2.3 The Federal Aviation Administration (FAA)

The Federal Aviation Administration (FAA) has conducted a number of trials in non-radar areas such as Capstone in Alaska. The Capstone project was designed to determine the safety and efficiency levels of ADS-B technology in Alaska and to demonstrate its capabilities for use nationally. Alaska was chosen as the test-bed due to its reliance on air transport more than other states, whereby only 10% of the state is accessible by road. In addition, Alaska contributes 35% of the nation's air transport accidents due to the state's mountainous terrain and extreme winter climate. A study by MITRE and the University of Alaska found that from year 2000 to 2004, the rate of accidents for ADS-B equipped aircraft was reduced by 47% (Federal Aviation Administration, 2011a). Therefore the Capstone project demonstrated that ADS-B would improve aviation safety in Alaska.

The other trials for ADS-B demonstration were conducted in Philadelphia and the Gulf of Mexico, where the traffic has grown at twice the rate in domestic airspace over the last decade (Esler, 2007). Radar coverage is not possible over the Gulf of Mexico due to its geographical structure. However, air traffic in the Gulf is as busy as the traffic in the East Coast Corridor, with 5000 to 9000 helicopters offshore platform operations daily including commercial flights between US, Mexico, and South America. Low altitude aircraft are isolated and high altitude commercial aircraft are separated by 100 miles to ensure safety due to unavailability of radar surveillance, and lack of communication and weather information. These lead to restricted capacity and efficiency (Federal Aviation Administration, 2011a). Initial ADS-B surveillance in the Gulf began in December 2009. This enabled controllers to separate high-altitude ADS-B equipped aircraft over the Gulf, reducing the 100 miles separation to 5NM in trail. This also enabled low altitude helicopters to receive air traffic services and weather information. The trial demonstrated a significant improvement in the aviation operation in the Gulf. However, in August 2010, an 11 hours ADS-B outage due to failure of the ground station network without any backup affected air traffic control over the Gulf. The outage also the affected FAA's Surveillance Broadcast Services (SBS) which was intended to monitor the ground station performance (Office of Inspector General, 2011). The FAA in collaboration with UPS Corporation also conducted an ADS-B terminal area proof of concept at the freight carrier's hub in Louisville. This trial was intended to increase airport capacity and address runway incursions at the busy cargo hub (Esler, 2007). The numerical outcomes of the trial are not publicly available. However, as a result of the successful trial, currently the controllers in Louisville are operating using ADS-B. Four ADS-B ground stations give the controllers coverage more than 60NM in all directions up to 10000 feet (Federal Aviation Administration-SBS ESA, 2013).

Based on the various safety cases designed and implemented by EUROCONTROL, Airservices Australia and FAA, it is obvious that there is no defensible evidence on the safety assessment of the ADS-B system. The safety argument used by the safety cases designed and conducted by EUROCONTROL and Airservices Australia is that, if the new system is able to perform at the level of the radar system, then it is considered safe. The FAA trials do not encompass any safety assessment. The safety argument for the trials conducted is based on the improvements on the number of incidents after the implementation of the ADS-B system. In this thesis, a comprehensive and defensible safety assessment framework is developed for the ADS-B system. The framework is developed based on the assumption that the ADS-B system is the sole surveillance source for the ATC in dense airspace. The next section describes the proposed framework in detail.

5.5 Proposed Safety Assessment Framework for ADS-B

In order to address the limitations identified in section 5.3 and 5.4, this thesis proposes a novel safety assessment framework for the ADS-B system. The proposed framework combines Fault Based Safety Assessment (FBSA) and Performance Based Safety Assessment (PBSA) methods. The FBSA is based on a Failure Modes Identification approach and Fault Tree Analysis (FTA), while the PBSA measures the system performance parameters (accuracy, integrity, availability, continuity, latency). The parameters are then validated using onboard Global Navigation Satellite System (GNSS) as the reference system to validate ADS-B system performance. The findings from the PBSA are fed into the FBSA. Finally, the overall safety assessment output is used to develop a safety case for the ADS-B system. The safety case aims at two different scenarios:

- ADS-B operating as the sole surveillance system in a particular airspace
- Surveillance data fusion between ADS-B and existing surveillance system (ADS-B/WAM, ADS-B/SSR, ADS-B/WAM/SSR) operating in a particular airspace

The data fusion is to be developed using the Kalman Filtering based optimisation. Then the complete PBSA and FBSA are conducted for each scenario. Finally the safety case is validated by the required performance requirements as stipulated in Chapter 3.

The framework (Figure 5-4) proposed in this thesis is comprehensive in the sense that it assesses the system design, implementation and operational performance. It is defensible in the sense that it provides a valid safety argument using concrete safety validation approach and safety evidence by means of the system performance quantification. The next sections describe the specific methods and the processes integrated in the framework.

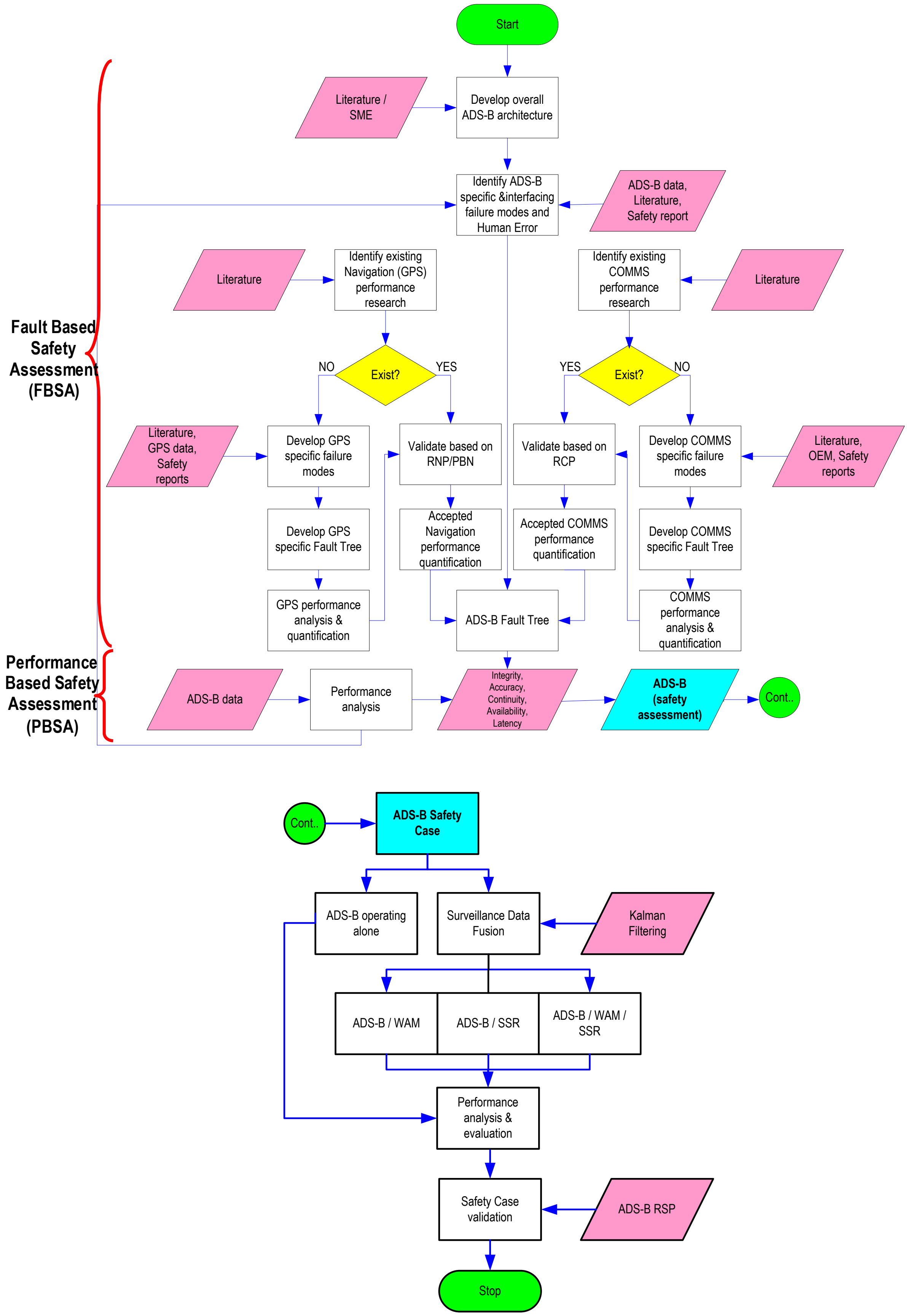


Figure 5-4: Proposed Safety Assessment Framework for ADS-B system

5.5.1 Performance Based Safety Assessment (PBSA)

Performance Based Safety Assessment (PBSA) is conducted by measuring actual system performance parameters and validating the parameters using a safety validation approach. In the proposed framework, the reference system method is used for the performance validation. The PBSA consists of the following processes:

a) Defining the system performance parameters and requirements. ADS-B performance is specified in terms of the following parameters:
   - Accuracy
   - Integrity
   - Continuity
   - Availability
   - Latency

b) Data collection
   - ADS-B data from ground stations; and
   - Onboard navigation data (reference) for each aircraft over a given time interval.

c) Justification of the suitability of the ‘reference system’.

d) Data decoding into useable format.

e) Deriving reference data for ADS-B

f) Data correlation between ADS-B data and onboard navigation data

The processes and formulas derived to measure each parameter are discussed in detail in Chapter 6.

In the PBSA, the onboard Global Positioning System (GPS) is used as the reference system to validate ADS-B positioning performance. GPS-based positioning and navigation enables four dimensional (4D) position determination for all phases of flight from departure, en-route, and arrival to airport surface navigation. It supports concepts such as Area Navigation (RNAV), which allow aircraft to fly optimal routes without depending on ground infrastructure. (National Coordination Office for Space-Based PNT, 2006). In addition, GNSS is also a key enabler of operations using Reduced Vertical Separation Minima (RVSM) proposed by the ICAO for aircraft flying between FL290 (29000 ft) to FL410 (41000 ft). Moreover, GNSS is constantly being improved and modernized to support safety critical applications. Therefore, this will make GPS even more robust navigation service for various aviation applications. Above all, GNSS is the key driver for the 4D trajectory-based operations proposed by NextGen in the United States and SESAR in the Europe. ICAO has established stringent standards

(ICAO, 2004b) to use GNSS for aviation applications. The requirements include integrity, a measure of safety, and defined as a measure of the degree of trust in the correctness of navigation information (Bhatti, 2007). For safety critical applications such as ADS-B, real time integrity information is required (ICAO, 2004b). This is achieved at the GPS receiver level through receiver autonomous integrity monitoring (RAIM) (TSO-C129a and RTCA-DO208) and externally with Ground Based Augmentation Systems (GBAS) and Satellite Based Augmentation Systems (SBAS). The technical standard order (TSO-C129) provides detailed minimum performance standards that airborne supplemental RNAV equipment using GPS must meet. TSO-C129 also states that, the requirements in RTCA-DO208 "Minimum Operational Performance Standards for Airborne Supplemental Navigation Equipment Using Global Positioning System (GPS) have to be met. Required Navigation Performance (RNP) and Performance Based Navigation (PBN) requirements are also applicable. Table 5-2 shows the GPS receiver models used by the aircraft navigation system included in this thesis to evaluate ADS-B system performance. The receivers comply with the real time integrity monitoring requirements.

Table 5-2: GPS Receiver model and specifications

GPS receiver model	RAIM augmentation	GBAS	SBAS
Thales TLS755	✔	✔	✔
Honeywell GNSSU	✔	✔	✔
Honeywell Mercury Card equipped EGPWC MkV	✔	✔	✔
Rockwell Collins GLU920	✔	✔	✔

It is important to note that GPS position accuracy and integrity performance is dependent on GPS Signal-In-Space (SIS) availability. An analysis conducted by Imperial College London (2011) for CAA Safety Regulation Group (SRG) to monitor GPS performance and to determine if GPS performs as specified the International Civil Aviation Organisation's (ICAO) Standards and Recommended Practices (SARPS) Annex 10 (ICAO, 2004b), is reviewed for this purpose. The analysis report describes the performance of GPS for Enroute to Non-Precision Approach (NPA) for the period of 1 January 2010 to 31 December 2010. The performance is analyzed and measured using data recorded at one site in the East Midlands region of the UK (augmented with data from the Hailsham and Zimmerwald International GNSS Service (IGS) stations). The East Midlands station covers a significant portion of the UK airspace and thus provides a credible measure of GPS performance within the airspace (Imperial College London, 2011). The performance analysis covers the following parameters quantification and compliance to the determined standard:

a) Horizontal Accuracy 95%

b) Horizontal Alert Limit

c) Integrity

d) Time to Alert

e) Continuity

f) Availability

Table 5-3 summarizes the GPS performance analysis results.

Table 5-3: Summary of GPS performance analysis results (Imperial College London, 2011)

	Performance parameter	Results	ICAO SARPS GPS performance standard
1.	Horizontal Accuracy 95%	<10m	220m
2.	Horizontal Alert Limit	No horizontal position errors were above or close to 556m	556m
3.	Integrity	100% level (measured in terms of number of samples below the alert limit and expressed as a percentage) for each day over the period analysed	$1\text{-}1\times10^{-7}$/hour
4.	Time to Alert	No samples exceeded the alert time and no cases of RAIM unavailability. Therefore the continuity risk was zero.	10 seconds
5.	Continuity	100% for each day over the period analysed	$1\text{-}1\times10^{-4}$/hour to $1\text{-}1\times10^{-8}$/hour
6.	Availability	100%	0.99 to 0.9999

The literature review, findings and analysis in this section indicates that GPS is acceptably safe for aviation applications based on its performance to the stipulated requirements.

5.5.1.1 Reference system and ADS-B system

Similarity between GPS and ADS-B lies in the aircraft data output by both systems. In the scope of this thesis, aircraft state data broadcast by the ADS-B system from the onboard GPS. Therefore the output data types are of similar a nature. This is a strong point to indicate that the GPS is a good 'reference system' for ADS-B position performance validation. It is appropriate to compare two entities of a similar nature as they will have similar characteristics. For example, for GPS and ADS-B, accuracy and integrity might vary between aircraft and in time depending on the equipment and method of position determination (ICAO, 2006b). Unlike radar, the accuracy and integrity information in GPS and ADS-B are provided as variables.

The ADS-B system performance is partly determined by the performance of the GPS and partly due to the performance of the data processing and data link from ADS-B avionics to ADS-B ground stations. Therefore, it can be forecast that the performance can either be similar to that of the GPS or worse, but definitely not better than the GPS.

The PBSA is carried out in Chapter 6. The failure modes identified throughout the PBSA process from the ADS-B data and the corresponding onboard navigation system (GPS) data analysis are input to the next process; Fault Based Safety Assessment (FBSA).

5.5.1.2 Relationship between the performance parameters and ADS-B system safety

Based on the definition of safety in section 5.1, it is related to system failure. The integrity performance parameter is directly related to safety. It provides alerts on the detection of system malfunction/failure, to the system users within the required time-to-alert. In terms of aircraft positioning, the alert limit defines the largest position error, which results in a safe operation (Ochieng and Sauer, 2003). The integrity parameter determines the level of trust on the positioning information based on the position error (i.e. accuracy of the position). The system continuity is determined based on its capability to provide the system output (positioning information) with specified level of accuracy and integrity throughout the intended period of operation without non-scheduled interruptions. Finally, the system is considered to be available, if the system output satisfies accuracy, integrity and continuity requirements. Therefore, it is clear that all the performance parameters are related to each other. This is illustrated in Figure 5-5. The position performance quality indicators (explained in Chapter 3) included in the ADS-B message serves as alert to the ATC on the state of the ADS-B surveillance report. In other words, these values act as safety indicators for the ADS-B system. However, the reliability of these quality indicators is arguable and is addressed in Chapter 6.

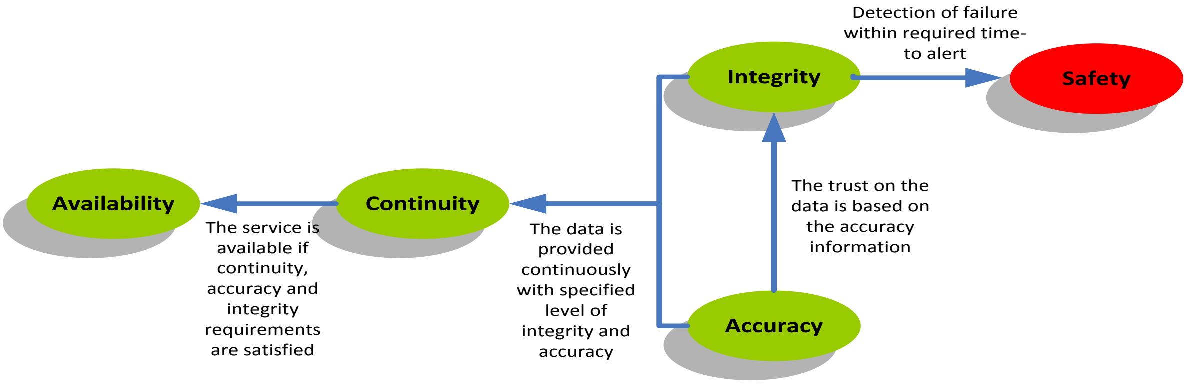


Figure 5-5: ADS-B performance parameters and safety

5.5.1.3 Data

Two types of data are used in the PBSA for the ADS-B system for aircraft manoeuvering in the London Terminal Manoeuvering Area (LTMA):

- ADS-B surveillance data recorded from the ADS-B ground stations (ASTERIX CAT021)
- Navigation data from aircraft navigation system (GPS)

The surveillance data for the work in this thesis are obtained from the CRISTAL UK Project by NATS UK as discussed in Section 5.4.2. Data from the reference system, GPS positioning data from aircraft, are obtained from British Airways, recorded within the same time interval as the surveillance data from ADS-B ground stations. A descriptive statistical analysis is conducted to identify the percentage of fields present in the ASTERIX Category 021 message used for ADS-B performance analysis in this thesis. This is shown in Figure 5-6.

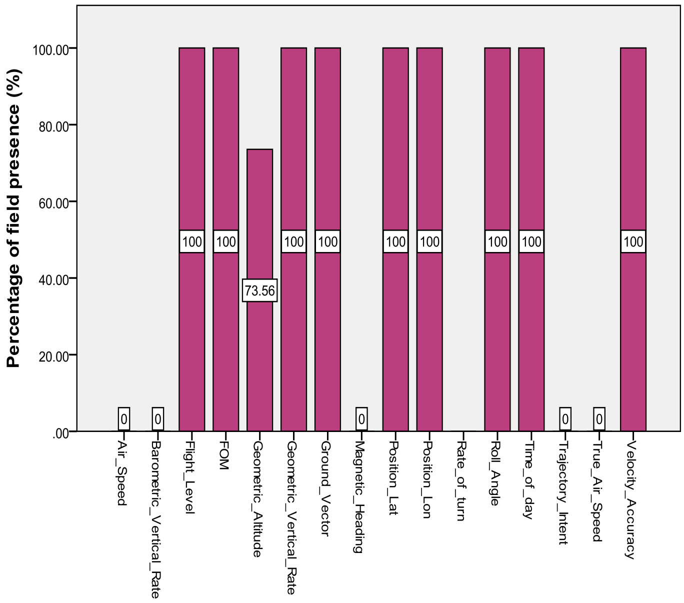


Figure 5-6: Analysis of fields present in ADS-B report (ASTERIX Category 021)

Based on Figure 5-6, the time of detection, target position, aircraft address and Figure of Merit (FOM; target integrity level) are always present in the ASTERIX message contrary to for example, the air speed or trajectory intent. The fields present and Flight Level are important in the scope of the research analysis in this thesis. As can be seen, the geometric vertical rate is present more often than geometric altitude. The data fields present in the ADS-B message depends on the ADS-B avionics make model and also on the performance currently required for the system. The data used in this thesis comply with the requirements in RTCA DO-260 (RTCA, 2003). However, the latest standard available is RTCA DO-260B (RTCA, 2011). Table 5-4 indicates the data field descriptions present in the ADS-B message. A detailed description of each data field is available in the EUROCONTROL Standard Document for Surveillance Data Exchange - Cat 021 ADS-B Messages (EUROCONTROL, 2003).

Table 5-4: ADS-B data field description

Data	Description
System Area Code (SAC)	An area identifier code, unique to a specific area, usually a whole country, displayed in decimal however usually displayed in hexadecimal, the UK is allocated 34 and 35 (Hex).
System Identification Code (SIC)	A unique identifier code allocated to each Radar / Surveillance System, the Cristal ADS-B system is counted as one consolidated surveillance source and hence is allocated one SIC code.
Target Report Descriptor (TRD)	Each of these items reports on the type and quality of the data received from the aircraft, for example, ARC refers to the altitude reporting capability of the aircraft, when aircraft report their altitude in the 1090 MHz Extended Squitter, it is quantized into either 100ft or 25 ft bands, the ARC reports which of these bands are being used.

Data	Description
Time of Day (TOD)	Time of day in seconds after midnight
Latitude (LAT) Longitude (LONG)	Latitude and Longitude in WGS-84 format displayed in decimal degrees.
ADD	The aircrafts unique ICAO 24 bit address in Hexadecimal, most registered aircraft in the world and all registered aircraft in the UK has a unique address that is hard coded into the Mode-S transponder.
GALT	Geometric Height in feet from a plane tangent to the earth's ellipsoid.
Flight Level (FL)	The flight level of the aircraft, which is the altitude of the aircraft expressed at a standard pressure setting of 1013 Mb and rounded to the nearest 100ft. This is used by en-route aircraft flying IFR to ensure all aircraft fly at the same relative altitudes and thus retain vertical separation. This is as opposed to flying on local QNH pressure settings generally used during VFR flight.
GV-GS	Ground Vector – Ground Speed
GV-TA	Ground Vector – Track Angle, direction the aircraft is heading
Target Identification (TID)	This is the callsign or registration of the aircraft.

Position reference data (obtained from the aircraft navigation system, GPS) from British Airways contains less data fields from the ADS-B message. The GPS message includes the following data fields:

- Time
- Latitude –WGS84
- Longitude-WGS84
- Altitude (Flight Level based on standard pressure setting of 1013 Mb)
- Radio Height
- Compute Air Speed
- Ground Speed

The scope of the ADS-B data and the corresponding onboard GPS data are based on the aircraft manoeuvring in the LTMA airspace. Two different sets of data are collected at different time interval as specified in Table 5-5.

Table 5-5: ADS-B and onboard GPS data recording details

Date	Time Interval
10 January 2011	00:00:00 – 23:48:29
23 May 2011	9:13:14 - 11:42:14

5.5.1.3.1 Air Traffic Environment in NATS London Terminal Control

The main responsibility of ATC at NATS London Terminal Control (TC) is to manage the streams of aircraft arriving and departing from airfields within LTMA and to provide service to aircraft transiting the same airspace. The airspace is divided into 5 sectors (refer to Figure 5-7 and Table 5-6). The sectors are designed to manage traffic arriving and departing from London Heathrow, Gatwick, Luton, Stansted, City as well as Birmingham, East Midlands and smaller airfields in the region. All sectors are low-level, from the base of controlled airspace to FL195–215. London TC handles flights operating at or below FL210, regardless of whether another unit is online or not. Figure 5-7 shows the London TC airspace structure. Table 5-6 provides the details of each sector.

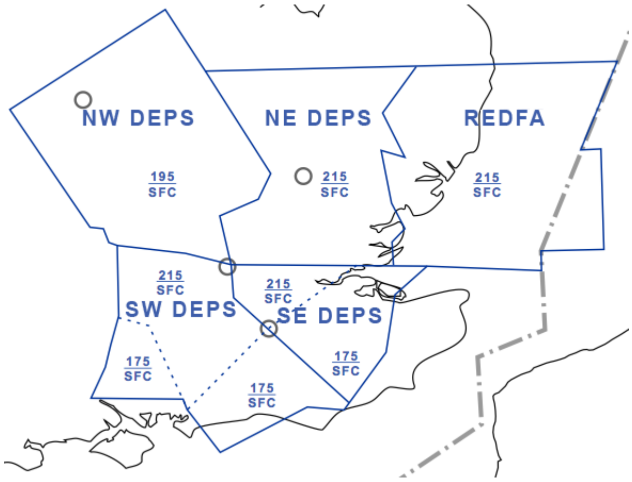


Figure 5-7: London Terminal Airspace Structure (IVAO, 2012)

Table 5-6: London Terminal Control Sectors description (IVAO, 2012)

ID	Name	IVAC IDENT	RT Frequency
SE DEPS	South East Departures	EGTL_SE_CTR	120.525
NW DEPS	North West Departures	EGTL_NW_CTR	119.775
NE DEPS	North East Departures	EGTL_NE_CTR	118.825
SW DEPS	South West Departures	EGTL_SW_CTR	134.125
REDFA	Redfa	EGTL_E_CTR	121.225

In 2011, the London TC handled an average of 3419 movements daily. The traffic analysis indicates a decrease from 2008 to 2010, and a 3% growth from 2010 to 2011 (refer Figure 5-8). The majority of the traffic is either climbing or descending, indicating that the airspace is highly complex (NATS, 2007). Due to a high rate of vertical traffic movements, controllers need tactical freedom to enable aircraft to reach their required levels safely and expeditiously. This requires the application of radar vectors and manipulation of the aircraft's required routes (NATS, 2007). A high volume traffic indicates that a large number of control instructions need to be conveyed; resulting in both RT frequencies (refer to Table 5-6) and the airspace being often congested. Air Traffic Services (ATS) are provided based on radar control with separation standard of 3NM or 5NM laterally and 1000ft vertically. Reduced radar separation (2.5NM) may be used on approach under criteria and larger separation is used for wake vortex considerations as necessary (NATS, 2007).

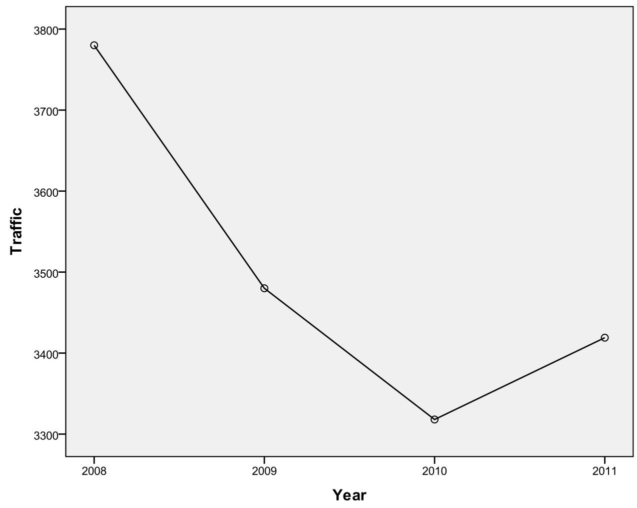


Figure 5-8: Average daily traffic in London TC from 2008-2011 (EUROCONTROL, 2012)

Current operational surveillance infrastructures in the United Kingdom consist of 22 radars (NATS, 2011b) including secondary radars and co-mounted primary radars; and multilateration system for airport ground surveillance. These systems support NATS ATS with surveillance information in the NATS controlled airspace with the required operational and safety performance. Figure 5-9 and Table 5-7 show the radar locations and descriptions of the LTMA coverage respectively.

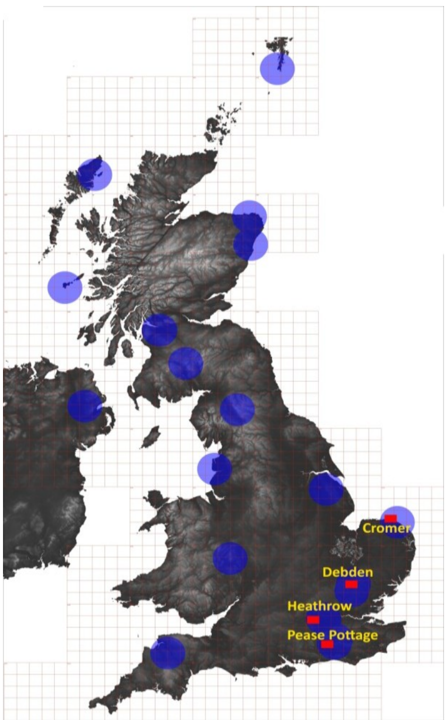


Figure 5-9: Radar locations and coverage for LTMA

Table 5-7: Radar description for London Terminal Manoeuvring Area (LTMA) coverage

Radar Name	Latitude (WGS84)	Longitude (WGS84)	Height (WGS ellipsoid - to ground)	Rotation (rpm)
Debden	51 59 24.923785	0 15 49.94932 E	162.965	9.7
Cromer	52 54 37.734515	01 20 58.820655 E	65.459	12
Heathrow	51 27 37.58	000 26 22.448 W	60.572	15
Pease Pottage	51 05 00.30993	00 12 51.750605 W	187.816	9.71

As discussed in Section 5.4.2, the ADS-B positioning data for this research are obtained from the CRISTAL RAD HD project led by NATS and carried out in collaboration with industry partners; QinetiQ, Raytheon and SITA. The surveillance infrastructures under the project include the ADS-B system and Wide Area Multilateration System (WAM) network for surveillance coverage in the LTMA. It involves installation of ADS-B and WAM ground receiver sensors and also equipage of ADS-B emitters onboard aircraft involved in the project. More than 500 aircraft have received their EASA airworthiness certification (EUROCONTROL, 2011a) based on AMC-20-24 avionics requirements for ADS-B in non-radar airspace. To date, no certification rules for aircraft avionics to operate in radar airspace have been published. Six ADS-B ground stations (receiver sensors) are installed at the existing NATS radio transmitter communication sites at Ventnor, Winstone, Chedburgh, Warlingham, Greenford and Reigate. The central processors, central monitoring servers and remote control and monitoring systems are located within the Test and Development equipment room at NATS CTC (NATS, 2011a). Figure 5-10 and 5-11 illustrates the ground receiver sensor installation sites and the corresponding coverage. Each sensor is providing a coverage of 256NM (NATS, 2011a).

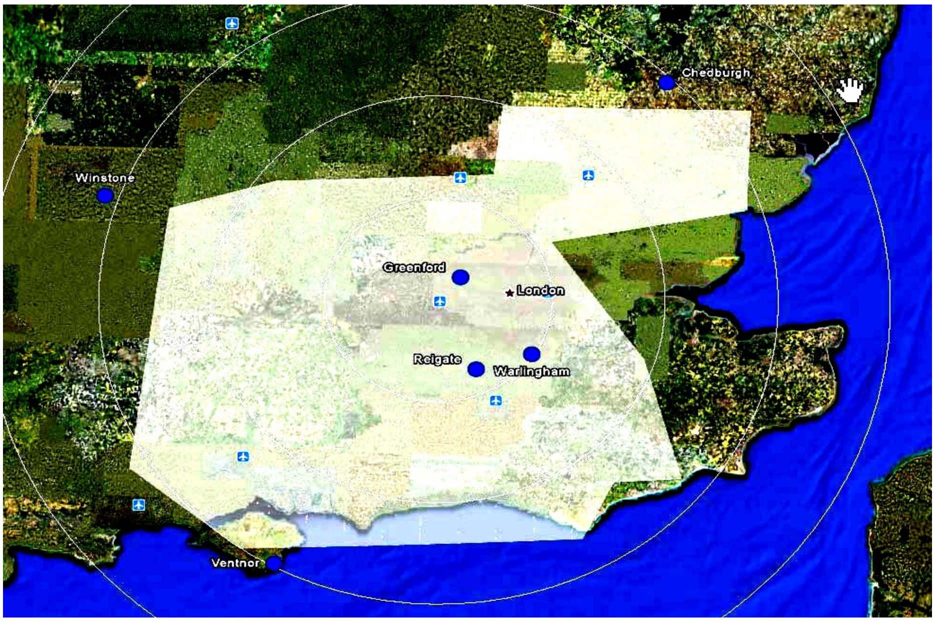


Figure 5-10: ADS-B ground stations for LTMA coverage (NATS, 2011a)

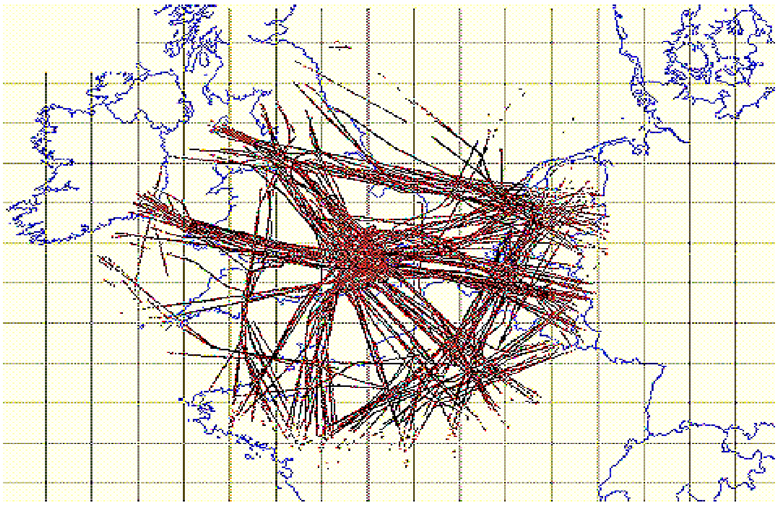


Figure 5-11: ADS-B Coverage (NATS, 2011a)

5.5.2 Fault Based Safety Assessment (FBSA)

In this thesis, the concept of 'Fault Based Safety Assessment (FBSA)' is introduced and defined as the 'measure of Safety Integrity Level (SIL) of a system based on the probability of the system not functioning due to system component failures'. The term SIL is a measure of the confidence with which the system can be expected to perform its safety function (Dutuit et al., 2008). The SIL concept was introduced in the IEC 61508 standard (Bell, 2005). The standard defined SIL for system functions with high demand rate or functions that operate continuously, such as accident rate is the probability of failure per hour. The definition is not clearly defined in the standard. However, it is applicable to the ADS-B system as the system is safety critical, required to operate continuously. In this thesis, the SIL is derived from the unavailability 'Q' of the system. Unavailability of the system may vary with the parameters of the various reliability models applied to the system components which are of a different nature. The ADS-B system is composed of various system components that are of a different nature.

FBSA is a comprehensive step-by-step approach comprising of methods to identify failure modes in a system and quantify the failure modes using the fault tree analysis method (FTA). Apart from these two methods, other methods such as Petri Nets or Markov Graphs can be used to assess complex systems. However, the design of the models in these methods are complex and error prone (Dutuit et al., 2008). In the proposed framework, the failure mode identification approach is developed to identify ADS-B failure modes, analyze the failure mode consequences on the system functionalities and subsequent ATC and aircraft navigation operations. The impact of the failure is also analyzed if it affects one or all aircraft within a specific airspace. The nature of the failure is further analyzed to determine if the failure is detectable or undetectable by the ADS-B system users. The final output of the approach is a failure mode register for the ADS-B system. A failure mode register tracks the potential failure that may occur in a system. The information captured in a failure mode register includes the failure mode description, components that contribute to the failure and the failure effects. The failure mode identification approach proposed in the FBSA adopts some of the steps in the Failure Mode and Effect Analysis (FMEA) method. The FMEA is not applied in the proposed framework, because it requires historical failure data, not available for ADS-B to date apart from the AsA database (called ASID) used within Airservices Australia for reporting all problems in their ATC systems. However, the AsA data were not available to this thesis. In addition, the amount of data available in the database to date may not be sufficient to conduct a rigorous quantitative FMEA for ADS-B. Hence, failure quantification is conducted using the FTA approach.

In the proposed framework, the information gathered to perform the failure mode identification process is obtained from:

- extensive literature review on each ADS-B specific component and the integrated navigation and communication system components;
- review of safety reports on ADS-B trials from various Air Navigation Service Providers (ANSPs) worldwide including FAA (2000), Air Services Australia (ICAO, 2006b) and NATS (2007, 2002, 2011a);
- analysis of ADS-B reports gathered from ADS-B ground stations and corresponding positioning data from onboard navigation system (GPS) for 37 aircraft through collaboration with NATS' CRISTAL Project and British Airways; and
- input from Subject Matter Experts (SME) (with more than five years of experience on ADS-B system design and trial implementation) from EUROCONTROL, QinetiQ, Airbus and NATS via structured interviews.

Figure 5-12 shows ADS-B specific components and external system components integrated with the ADS-B system included in the failure mode identification approach. Initially, the process is conducted with the assumption that the ADS-B system is operating as the primary surveillance system in support of ATC operations. The process comprises the following tasks:

- identification of the failure modes of the ADS-B system;
- identification of failure mode effects on the ADS-B system;
- determination of the consequences of the failure effect on the overall ATC surveillance operations;

- determination of the failure hazards to ATC operations and aircraft navigation;
- categorisation of failure modes into failure models;
- development of a mitigation approach for each failure mode;
- determination of the extent of failure impacts (e.g. single or multiple aircraft); and
- determination of the failure detectability.

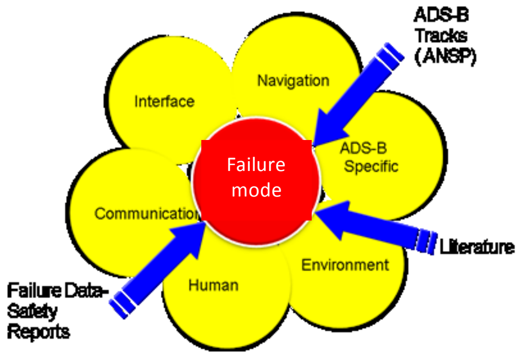


Figure 5-12: ADS-B specific and external systems

The failure mode identification process begins by developing a comprehensive ADS-B system architecture diagram based on inputs from the literature and Subject Matter Experts (SME). Then, the failure mode identification is conducted for ADS-B specific components and interfacing components between the external systems (navigation, communication, human and operational environment) as illustrated in the architecture diagram. The inputs for this task are obtained from the literature, safety reports and from the PBSA output. Based on the output, a fault tree is developed for the ADS-B system. Next, the availability of existing research on onboard navigation system performance, that feeds the aircraft position to the ADS-B system, is determined. If available, the system performance quantifications are validated against the Required Navigation Performance (RNP) / Performance Based Navigation (PBN) requirements and fed into the ADS-B fault tree. If no relevant research is identified, then, a separate failure mode identification process is developed for the onboard navigation system with the literature, navigation data analysis from aircraft and safety reports as inputs. Then a fault tree is developed for the navigation system to quantify the system performance. The quantification values are then validated against RNP / PBN requirements and fed into the ADS-B fault tree. The same process is repeated for the data link system used by the ADS-B system to broadcast ADS-B message to ATC in the ground and other aircraft within a specified range. The data link performance quantifications are then validated against the Required Communication Performance (RCP) for ADS-B and fed into the ADS-B fault tree.

A fault tree is a model that graphically and logically represents combinations of possible events in a system that lead to a top (undesired) event. Three types of failure events are identified as causes (Barlow et al., 1974) :

- Primary failures – due to internal characteristics of the system element under consideration;
- Secondary failures – due to excessive environmental or operational stress placed on system elements;
- Command fault – inadvertent operation or non-operation of a system element due to failure of initiating element.

Primary failures of the ADS-B system may include the failure of the onboard navigation system that feeds the aircraft position to the system or failure of the data link that enables the ADS-B message to be broadcast to users. The secondary failures of the ADS-B system are due to the deteriorization of airborne (e.g. ADS-B antenna mounted on aircraft) or ground equipment due to environmental effects. Command faults may be initiated by human error for example, a pilot forgetting to switch on the ADS-B transponder or selecting a wrong operational mode on the transponder.

The probability of top event occurrence is important from a safety point of view. On the other hand, from a reliability point of view the probability of non-occurrence of the top event is of interest. The main aim of the FTA is to calculate the probability of occurrence of the top event. Based on the FTA, the performance measure of the ADS-B system is the unavailability (Q) or probability of the system not functioning as required to enable surveillance service provision and assist aircraft to navigate safely. Based on the failure mode identification, potential hazards for the ADS-B system are identified and defined as tabulated in Table 5-8.

Table 5-8: Potential hazards for ADS-B system

Hazard	Definition
Loss of Data	Unavailability of ADS-B surveillance data (including position data) to the controllers or other ADS-B equipped aircraft.
Corruption of Data	Incorrect ADS-B surveillance data transmitted to controller or other aircraft.
Corruption of Altitude Data	Incorrect altitude data transmitted (in the ADS-B message) to controllers or other ADS-B equipped aircraft.
Corruption of Position Data	Incorrect position data transmitted (in the ADS-B message) to controller and other ADS-B equipped aircraft.
Loss of Altitude Data	Unavailability of altitude data in the ADS-B message transmitted to controllers and other ADS-B equipped aircraft.
Corruption of Position Quality Indicator	Incorrect position quality indicator transmitted (in the ADS-B message) to controllers and other ADS-B equipped aircraft.
Human Error	Incorrect system input and mishandling/ misinterpretation of the system functionalities due to inadequate knowledge or human sensory limitations.

Based on the hazards identified, the FTA for the ADS-B system is conducted for the following top events:

- Corruption of data for all aircraft
- Corruption of data for one aircraft
- Corruption of position data for one aircraft
- Loss of data for all aircraft
- Loss of data for one aircraft

A major disadvantage in FTA and other safety analysis methods is the possibility that important failure modes are overlooked in the analysis (Barlow et al., 1974). A key problem for ADS-B is the lack of pertinent failure rate data of the system components to perform quantitative fault tree evaluation. Additionally, the human element within the system is difficult to quantify.

5.6 Summary

This Chapter has proposed a comprehensive safety assessment framework for the ADS-B system. The next Chapter analyses ADS-B system performance based on the PBSA approach explained in this Chapter. The detailed methods and results for each performance parameter analysed are provided in the next Chapter.

Chapter 6

Performance Based Safety Assessment (PBSA)

In Chapter 5, a novel and comprehensive safety assessment framework for ADS-B was developed. The framework comprises two parts: Performance Based Safety Assessment (PBSA) and Failure Based Safety Assessment (FBSA). This Chapter describes the PBSA method, identifies the errors in the ADS-B data collected from the ADS-B ground stations and in the corresponding GPS data collected from the onboard navigation system, and presents the ADS-B performance analysis results in terms of accuracy, integrity, availability, update rate and latency. Next, correlation analysis is conducted to identify the potential factors that may influence the ADS-B horizontal position accuracy. Finally, due to the unexpected update rate performance obtained from the results, structured statistical analysis is conducted to identify the potential factors that may have contributed to the performance. A model is derived to represent the ADS-B message update rate distribution based on various correlation analyses and a generalized linear modeling approach.

6.1 Background

ADS-B has been deployed on a large scale in Australia, with the safety justification for its implementation based on the finding that ADS-B is as good as the radar system (ICAO, 2006b). However, ADS-B implementation in Australia is in low traffic density airspace. From an operational perspective, the requirements for surveillance in low traffic density and high-traffic density airspace are completely different (Radio Technical Commission for Aeronautics (RTCA) standards for radar (RTCA, 2009) and non-radar (RTCA, 2007) airspace). This Chapter assesses the performance of ADS-B in one of the most high-traffic density airspaces in the world; the London Terminal Manoeuvring Area (TMA).

Figure 6-1 shows the components that may influence ADS-B system performance. These include:

- positioning system on-board;
- ADS-B avionics on-board;
- data link;
- ADS-B ground station; and
- ADS-B data and quality indicators

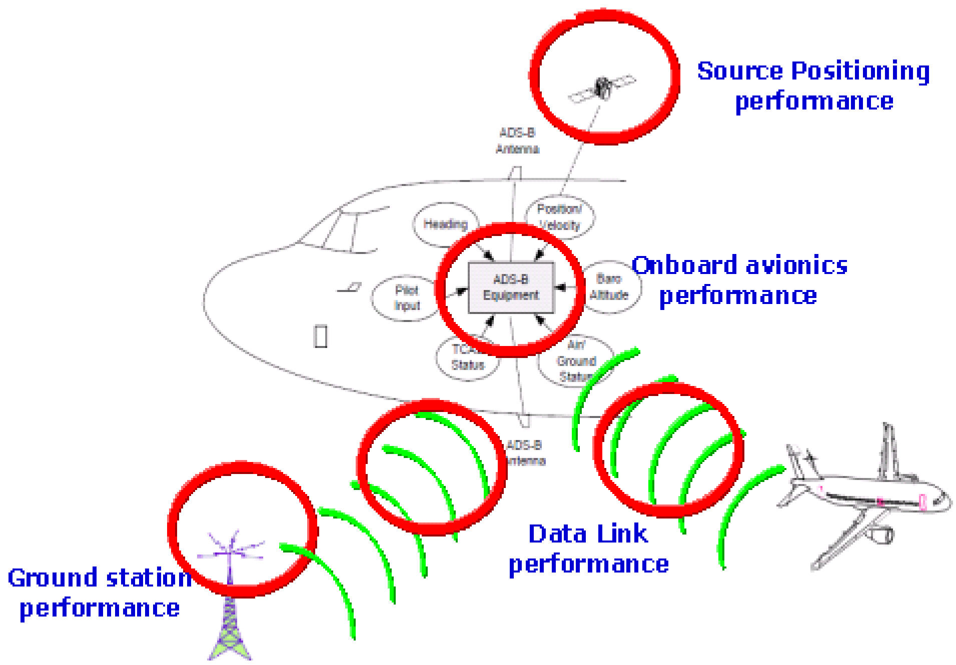


Figure 6-1: Components influencing ADS-B system performance

Numerous methods have been used by various parties to assess ADS-B system performance. Airservices Australia used a comparison method with Secondary Surveillance Radar (SSR) (ICAO, 2006b) while EUROCONTROL (EUROCONTROL, 2010c, EUROCONTROL, 2008c) generated a reference from multi-radar fusion using the ARTAS system (EUROCONTROL, 2001-2013a). However, none of these methods proposed a framework or detailed processes for ADS-B data evaluation in order to assess system performance. In addition, the anomalies or difficulties identified throughout the assessment process were not made available to the public. It is worth noting that the reference to be used to assess the ADS-B system should be of a very high performance, in order to support the implementation of various safety critical ground and airborne applications envisioned in the future by having ADS-B data as the source. For example, the reference should have an accuracy level higher than the most stringent requirement for reduced separation between aircraft. Therefore, even multi-radar fusion as the reference is insufficient for this purpose.

In the method proposed in this thesis, specifically for ADS-B position accuracy, latency and integrity performance assessment, navigation data from the onboard navigation system is used as the reference. Justification for this is provided in Chapter 5. All the aircraft included in this thesis use GNSS based navigation system (with augmentations) as the onboard navigation system. A detailed description of the data available in the ADS-B and onboard GPS messages are provided in Chapter 5. In addition to the available data, additional data required for the performance analyses are generated based on the available data, including ground stations that detected the aircraft at each epoch and aircraft range from the detected ground station. The next section proposes a novel ADS-B data evaluation framework.

6.2 Data Evaluation Framework

The framework is intended to assess the performance of the ADS-B system in terms of accuracy, integrity, availability, update rate and latency. In order to achieve this, ideally the framework should include the following characteristics:

- data collection method;
- conversion of the data into useable form;
- derivation of a reference position for the assessment particularly for accuracy, integrity and latency;
- data correlation method; and
- robustness to handle different data characteristics, for example, unsynchronized datasets.

The framework is shown in Figure 6-2. In this framework, the GPS data obtained from the aircraft is used to derive the reference position against which the ADS-B horizontal position data are compared. The GPS derived position from the aircraft satisfies the requirement for the navigation system (Department of Defense, 2008, ICAO, 2004b). In addition, the GPS receiver onboard all the aircraft included in this thesis is enabled with Satellite Based Augmentation System (SBAS) or Ground Based Augmentation System (GBAS) and Receiver Autonomous Integrity Monitoring (RAIM), which indicates the GPS positioning integrity. In this Chapter therefore, the framework is developed based on the assumption that the GPS positions are error free. The measured error encompasses cumulated errors beyond the onboard GPS receiver which includes errors in the FMS, ADS-B specific components (e.g. interfacing and transponder), communication system and ADS-B ground station.

In the first part of the process (Figure 6-2), ADS-B data collected from ground stations were decoded from the ASTERIX 021 to ASCII format. It was found that the two datasets are generally asynchronous. Prior to correlation, the time stamp accuracy of both datasets was checked. A correlation algorithm was developed and applied to correlate the datasets. The algorithm uses time stamp and horizontal position differences as well as the 24 bit aircraft address. The correlated dataset is then stored in a Surveillance database and the GPS position extrapolated to derive a reference position (the TRUTH). Next, various statistical analyses are conducted to clean up the dataset. Finally, performance analysis is conducted to measure data latency, accuracy, integrity, availability and update rate was conducted. The methods for each analysis are described in detail in the following sub-sections.

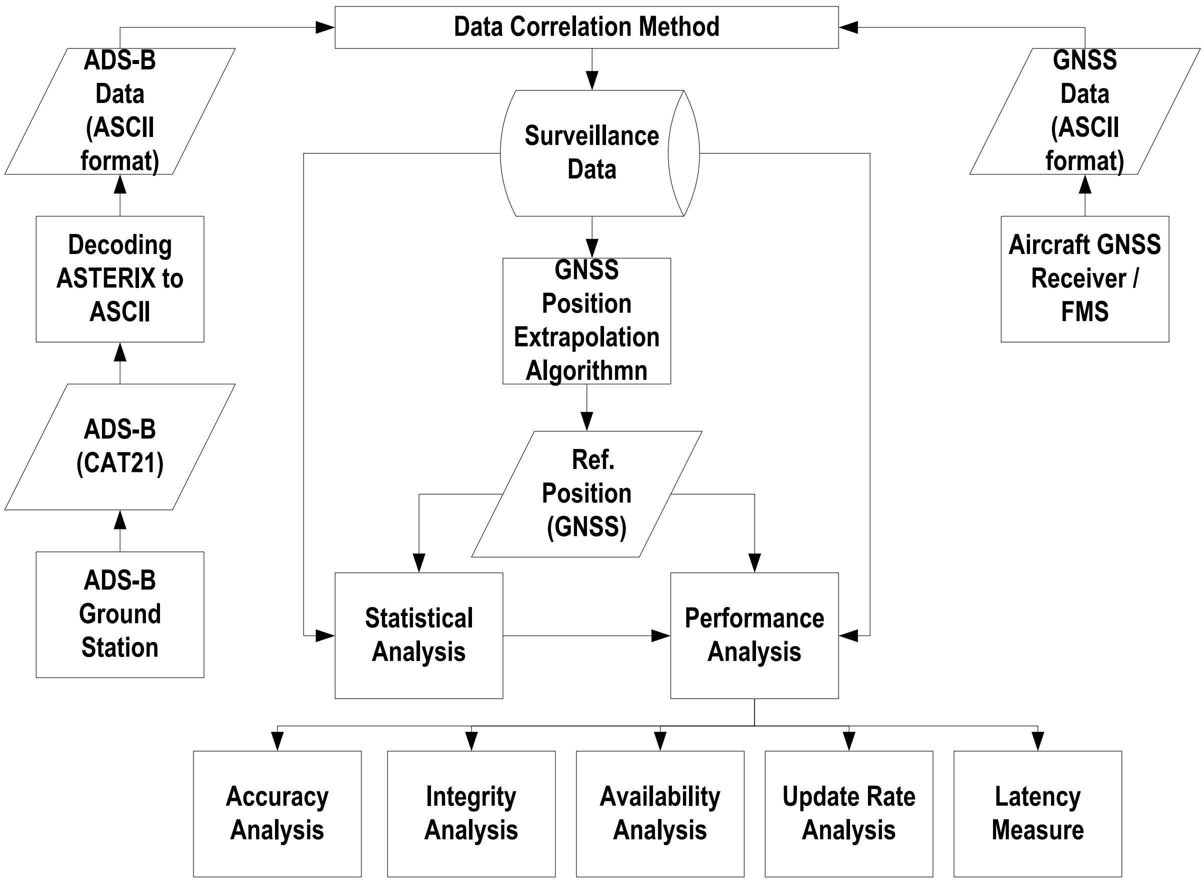


Figure 6-2: ADS-B Data Evaluation Framework

6.2.1 Data Correlation

Correlation of ADS-B data recorded from the ground stations and the corresponding GPS data from aircraft is challenging due to vast differences identified in the data characteristics:

- Different update rates between datasets whereby GPS data shows a consistent update rate at one second, while ADS-B data do not have a deterministic pattern in the update rate;
- Inconsistent update rates of ADS-B data;
- Lack of ADS-B data due to a lack of coverage of the ADS-B ground station especially for lower altitude operations and lower update rate level;
- Differences in the decimal precision of the horizontal position data from each source; and
- Time differences due to the delay in the ADS-B 'time' data with respect to GPS data.

Due to the discrepancies identified above in the nature of the datasets, neither the 'time stamp' nor the 'horizontal position' data could be used to correlate the datasets directly. A systematic data synchronization method is thus a crucial prerequisite.

The method initially identifies the GPS datasets corresponding to a given ADS-B time stamp on the basis of the relative timing for the identified GPS subset. Geometrical differences with respect to the ADS-B position data (latitude and longitude) are assessed and the final GPS candidate is chosen on the basis of minimal difference. This process is repeated for each ADS-B data point. The flow chart in Figure 6-3 illustrates the flow of the processes. The method starts by identifying the first time stamp in the ADS-B dataset as 'T_ADS-B'. It then identifies the dataset with a time stamp 'T_GPS' from the GPS dataset which are less than the 'T_ADS-B'. For the identified subset, the difference between the ADS-B (latitude and longitude) at 'T_ADS-B' and all the GPS data (latitude and longitude) at 'T_GPS' when (T_GPS<T_ADS-B) are calculated. Based on the differences, the GPS (latitude and longitude) with the minimal difference is stored in the new database and the rest from the subset are discarded from the GPS dataset. The process is repeated for T_ADS-B (n+1) of the ADS-B dataset until the last data. All aircraft included in this thesis are based on the ADS-B avionics certified under RTCA D0-260 (2003) which performs extrapolation (by 200 ms) on the horizontal position received from the onboard GPS receiver due to the anticipated delay in the ADS-B transmitting subsystem.

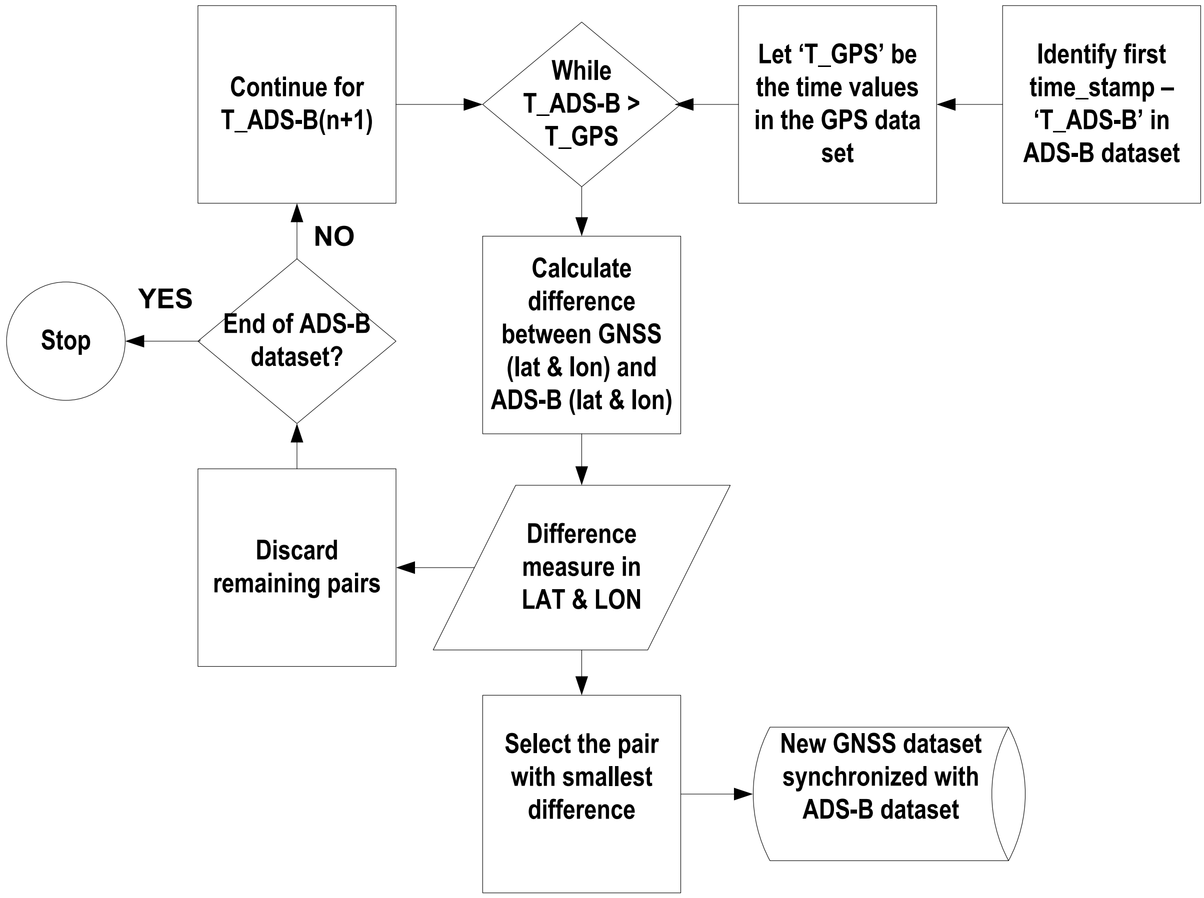


Figure 6-3: Flow chart for data correlation algorithm

6.2.2 Reference Horizontal Position Derivation Using Extrapolation Method

In this thesis, the reference method is used to assess the performance of the ADS-B horizontal position (latitude, longitude) recorded from ADS-B ground stations. GPS horizontal positions recorded from the aircraft FMS, are extrapolated to the exact time at which the ADS-B data is received at the ADS-B ground station. The extrapolated GPS horizontal position is used as the 'Reference' (or TRUTH).

The Reference (φ_{REF}, λ_{REF}) is derived as:

$$\varphi REF = \varphi GPS + \Delta\varphi \qquad \text{(Eq. 1)}$$

$$\lambda REF = \lambda GPS + \Delta\lambda \qquad \text{(Eq. 2)}$$

where,

φGPS is GPS latitude,

λGPS is GPS longitude,

$\Delta\varphi$, $\Delta\lambda$ is the function of distance and azimuth based on latency and speed.

6.3 Results of Evaluation

The aircraft assessed are equipped with a number of different types of GPS Receivers, ADS-B Emitters and FMSs, (described in Chapter 5) thereby enabling the assessment of the impact of variable avionics systems on ADS-B performance. All the aircraft use the Mode S 1090 MHz Extended Squitter (1090ES) as the data link to transmit ADS-B data from the aircraft to the ground stations. Two datasets were collected based on opportunity traffic and used in the various analyses. The first dataset comprises 29 aircraft with 15 minutes of flight duration while the second consists of 31 aircraft with 60 minutes of flight duration. Fortunately, four aircraft were found in both datasets. This gave the opportunity to analyze the ADS-B system performance consistency for those aircraft for the various parameters assessed. The first dataset was used for the accuracy, integrity and latency analysis. Before conducting the analysis, the data quality and suitability to be included in the performance (accuracy, integrity and latency) analysis were assessed. Among 29 aircraft in the dataset, twelve were found to be suitable for the analysis. The following problems were identified:

- Duplicate ADS-B messages, as recorded at ground stations. This is due to more than one ground station detecting the same aircraft at the same time and the central processing unit not removing the duplication;
- GPS Clock errors as recorded onboard the aircraft. This error could be due to the settings in the receiver;
- GPS position fluctuations recorded onboard the aircraft. This refers to jumps in position of about 0.1 degree every 100-200 seconds in latitude and more frequently in the longitude every 50 seconds. This is still under investigation with the British Airways ;
- Lack of a consistent GPS position format output by the aircraft. For example, at time t1, only the latitude information is given and at time t2, only the longitude information is provided. This may be the results of the setting in the Flight Management System (FMS);
- Uncorrelated time intervals between GPS data (at aircraft level) and ADS-B data (at ground level). This may be due to clock error in either the aircraft or the ground station.

Details of the problems in each aircraft data (ADS-B and GPS data) are provided in Chapter 7 and Appendix A.

6.3.1 ADS-B Latency

The RTCA (2009) defines total latency as the amount of time taken to broadcast a position relative to the time of applicability of the position measurement. Based on the notation in Figure 6-4, the total latency is represented as $\mathbf{TL = T_D - TOA_{B1}}$.

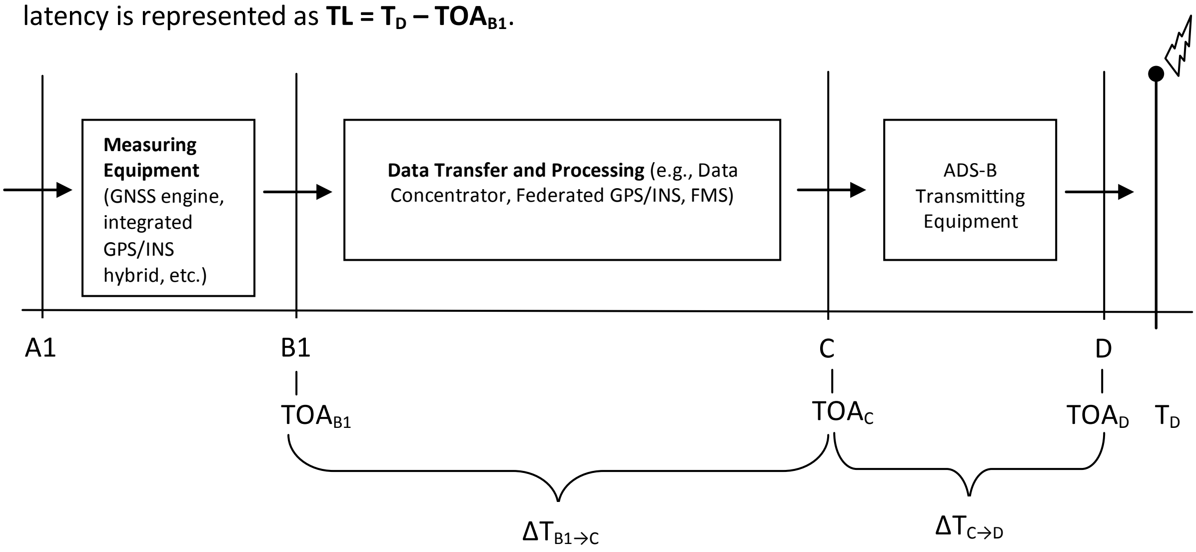


Figure 6-4: Onboard ADS-B functional architecture and timing diagram (modified from RTCA 2009)

The interfaces in Figure 6-4 are defined as:

- A1: Input to the position measuring equipment
- B1: Output of the position measuring equipment
- C: Input to the ADS-B transmitting equipment
- D: Output of the ADS-B transmitting equipment (i.e. the transmission)

While

- T_X :is the time that the data crosses interface X
- TOA_X: is the true time of applicability of the data that crosses interface X

The total latency is recommended to be less than 1.5 seconds. The total latency function is broken down into three components:

$$\mathbf{T_D - TOA_{B1} = (T_D - T_C) + (T_C - T_{B1}) + (T_{B1} - TOA_{B1})}$$

Where

- $\mathbf{T_{B1} - TOA_{B1}}$: Industry standards ensure that this does not exceed 200 milliseconds.
- $\mathbf{T_C - T_{B1}}$: The amount of time taken to deliver data from the position source to the data interface. This delay is recommended to be less than 200 milliseconds and a direct connection from the position source to ADS-B system is preferred.

- **$T_D - T_C$:** The amount of delay within the ADS-B transmitting subsystem (position update and the preparation of data for transmission) is limited to 100 milliseconds.

The total amount of onboard extrapolation ($\Delta T_{C\rightarrow D}$) performed by the ADS-B transmitting subsystem on the horizontal position is 200 milliseconds using the velocity data provided for the position fix. $\Delta T_{B1\rightarrow C}$ is assumed to be zero and $TOA_C = TOA_{B1}$.

The RTCA (2009) defines Uncompensated Latency (UL) as the amount of total latency that is not or cannot be compensated by the receiver. It is the difference between the time of applicability perceived by the ADS-B receiving subsystem and the true time of applicability of the transmitted data:

$$\mathbf{UL = TTOA - (TOA_{B1} + \Delta T_{B1\rightarrow D})}$$

Where

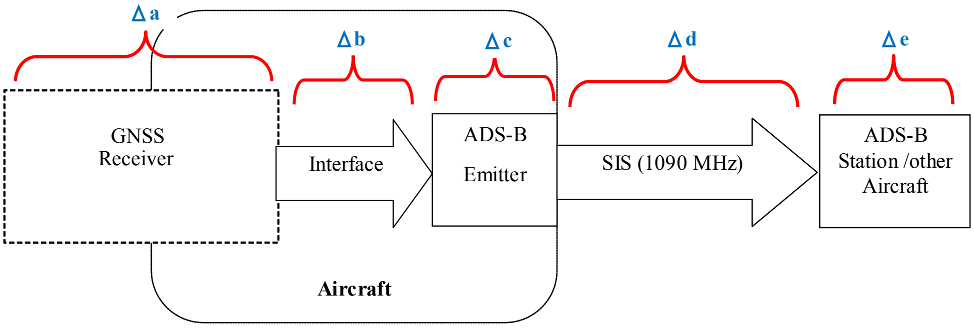
- **TTOA** : the transmit time of applicability is the time that is expected to be decoded by the ADS-B receiving subsystem as being the time to which the position contained in the ADS-B message is accurate.
- **$TOA_{B1} + \Delta T_{B1\rightarrow D}$** : is the time compensated for onboard latency.

The definitions proposed by the RTCA (2009), do not include various onboard delays which include delay in the GNSS receiver, interfacing between the receiver and data transfer and processing block (e.g. FMS), interfacing between the receiver and the ADS-B transmitting subsystem and the delay within the ADS-B transmitting subsystem. In addition the total latency definition does not include the propagation delay, which is the delay accumulated from $\mathbf{T_D}$ until the message is received by the ADS–B receiving subsystem at the ground station. This is critical in dense airspace prone to signal jamming problems. The uncompensated latency is defined based on the assumption that the **TTOA** is the transmit time ($\mathbf{T_D}$) from the ADS-B transmitting subsystem. However, neither the $\mathbf{T_D}$ nor any other time information is broadcast in the ADS-B message by the ADS-B transmitting subsystem.

In this thesis, ADS-B latency is defined as the delay between aircraft position determination by the onboard navigation system and position reception by the ground station. Figure 6-5 shows the ADS-B latency model. This model represents an additive function which incorporates delay in the navigation system (Δa), delay within the interfacing between the navigation system and the ADS-B emitter (Δb), delay in the ADS-B emitter (Δc), propagation delay (Δd) and delay in the ground station (Δe). Various potential sources for the latency are identified, including:

- Delay in the FMS (due to flight duration)

- Interfacing between FMS to transponder (ADS-B emitter)
- Interfacing between GPS receiver to FMS
- Interfacing between GPS receiver to transponder (ADS-B emitter)
- Data link delay (signal in space)
- ADS-B ground station antenna delay
- GPS antenna on the ground station (for clock)
- Time error at the ground station



Latency Model = Δa + Δb + Δc + Δd + Δe

Figure 6- 5: ADS-B Latency Model

Δb varies due to ADS-B avionics configuration based on either D0-260/D0-260A or D0-260B. The configuration based on D0-260/D0-260A requires connection from the GPS receiver to the FMS, in which case the positioning information will be transmitted to the ADS-B emitter from the FMS while for the configuration based on D0-260B, the position information from the GPS receiver will be directly transmitted to the ADS-B emitter, bypassing the FMS. The first configuration will increase Δb not only due to the additional transmission stage, but also the size of the FMS database will contribute to the delay by increasing the data transmission processing time with increasing database size. The size of the FMS database is influenced by the flight duration as more information is gathered throughout the flight. The latter type of configuration is expected to significantly improve Δb. Based on the requirements stipulated in RTCA 2009, ADS-B latency budgeting is derived using the latency model developed in Figure 6-5:

Δa + Δb + Δc + Δd + Δe < 1500 milliseconds

where

Δa ≤ 200 milliseconds

Δb < 200 milliseconds

$\Delta c \leq 100$ milliseconds

Therefore

$\Delta d + \Delta e < 1500 - (\Delta a + \Delta b + \Delta c)$

$\Delta d + \Delta e < 1500 - (200 + 199 + 100)$

$\Delta d + \Delta e < 1001$

The latency budget derived above indicates that the propagation delay plus the delay encountered at the ground station before the time stamp is generated upon the receipt of the ADS-B message by the ADS-B receiving subsystem at the ground station should not exceed 1001 milliseconds.

Latency performance for the eight aircraft are analyzed and tabulated in Table 6-1. The mean latency is measured according to Eq.3.

$$\mu\ Latency = \frac{\Sigma(T_{ADSB} - T_{GPS})}{\Sigma(ADSB\ data)} \qquad (Eq.3)$$

where,

- T_{ADSB} *is the position reception time stamp at the ground station,*
- T_{GPS} *is the position determination time by aircraft navigation system,*
- $ADSB\_data$ *is the number of reports received at the ground station.*

From Table 6-1, aircraft 40608F, 400246 and 40087B exceed the 1.5 seconds latency requirement stipulated by the RTCA 2009. Since the avionics make-model (Thales TLS755 MMR GPS receiver and Honeywell TRA-67A ADS-B transponder) is the same for all the aircraft in Table 6-1, no particular conclusion is made to justify the variation identified in the latency performance.

Table 6-1: Latency analysis results

Aircraft ID	Aircraft Type	Mean Latency (second)	Std. Dev (second)
40608F	A318	1.7227	0.4851
405A48	A320	0.6289	0.2430
400A26	A320	1.9050	0.6485
400877	A319	0.6927	0.1615
400878	A319	0.5597	0.2627
40087B	A319	1.7414	0.7008
4008F2	A319	0.6235	0.2584
400935	A319	0.7094	0.2158

Aircraft 40087B shows the highest and aircraft 400877 lowest variation (standard deviation) in the latency for each ADS-B message transmitted to the ground stations. However, the overall analysis results show small standard deviation values, indicating that the latency values for each epoch are close to the mean latency. Hence, no significant variation is found in the latency analysis. Aircraft 400A26 shows the highest mean latency 1.9050 seconds with a standard deviation of 0.6485 seconds while aircraft 400878 shows the lowest latency 0.5597 seconds with a standard deviation of 0.2627 seconds. Figures 6-6 to 6-9 show the latency distribution for the worst and best performing aircraft 400A26 and 400878, respectively.

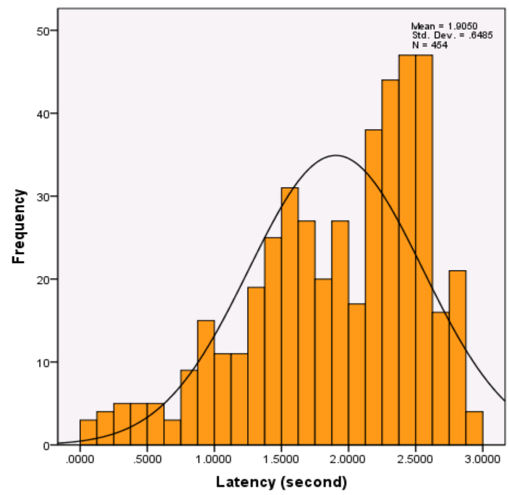


Figure 6- 6: Latency distribution for aircraft 400A26

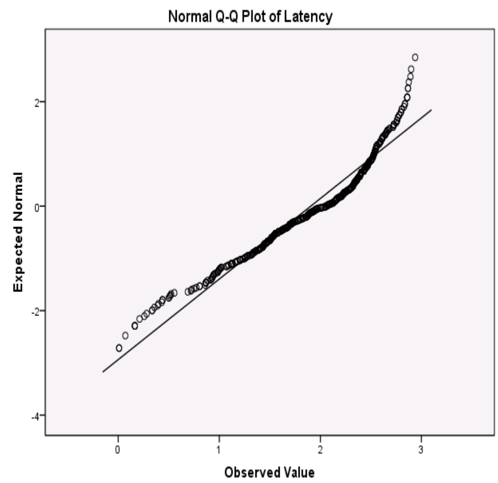


Figure 6- 7: Deviation from normal distribution for aircraft 400A26

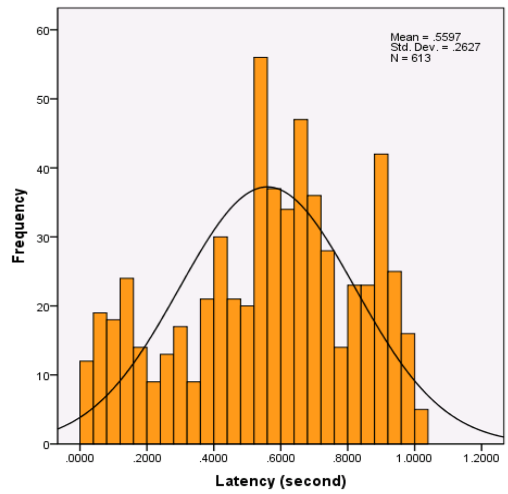


Figure 6-8: Latency distribution for aircraft 400878

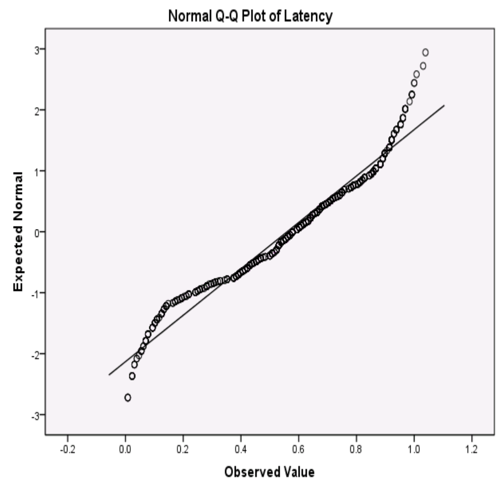


Figure 6-9: Deviation from normal distribution for aircraft 400878

Both aircraft show that the ADS-B message latencies are normally distributed despite the difference in the performance.

ADS-B latency performance consistency is evaluated using the data collected for the four aircraft in both the first and second dataset, which differ in terms of the flight duration. Consistent values are anticipated in Δa and Δc for the individual aircraft. The value in Δb may vary due to the size of the FMS database, as a result of the flight duration. The propagation delay, Δd, may depend on the range between the aircraft and the ground station and also on the traffic density of the airspace, whereby Δd may increase due to the signal jamming in a more dense airspace. Higher Δd is anticipated in lower altitude in TMA which is more prone to signal jamming where aircraft is closer to each other, higher duplex transmission between aircraft and radar, and also TCAS activities on the same frequency. Delay at the ground station Δe, may be incurred due to clock error or message queue at the ADS-B receiving subsystem before the time stamp is generated for the particular message received at the ground station. Table 6-2 shows the latency performance consistency for the four aircraft.

Table 6-2: Latency performance consistency

Aircraft	Aircraft Type	μ Latency (seconds)		Std. Dev	
		Dataset 1	Dataset 2	Dataset 1	Dataset 2
406250	A320	15.6877	5.6801	6.5012	2.0189
4008B4	A319	0.5895	1.1527	0.2760	0.2209
4009C7	A320	0.6837	0.4355	0.1493	0.3207
400942	A319	0.6787	47.9933	0.1666	8.0583

Based on the analysis, no consistency is identified in the latency performance between the two flights for each aircraft. Aircraft 406250 shows a very high mean latency during both flights with 15.6877 seconds and 5.6801 seconds respectively. However, the large standard deviation values 6.5012 and 2.0189 indicate that the latency values in both datasets are farther away from the mean on average. Aircraft 400942 shows drastic degradation from 0.6787 seconds to 47.9933 seconds with standard deviation 0.1666 and 8.0583 respectively. Aircraft 4008B4 shows a higher mean latency in dataset two, 1.1527 seconds in comparison to dataset one, 0.5895 seconds. Aircraft 4009C7 shows fairly good performance in both flights 0.6837 seconds and 0.4355 seconds respectively with small standard deviation values. Aircraft 406250 and 400942 are analyzed further due to the peculiarities found in the aircraft latency performances. Further analysis investigates the latency distribution and the impact of altitude on the latency.

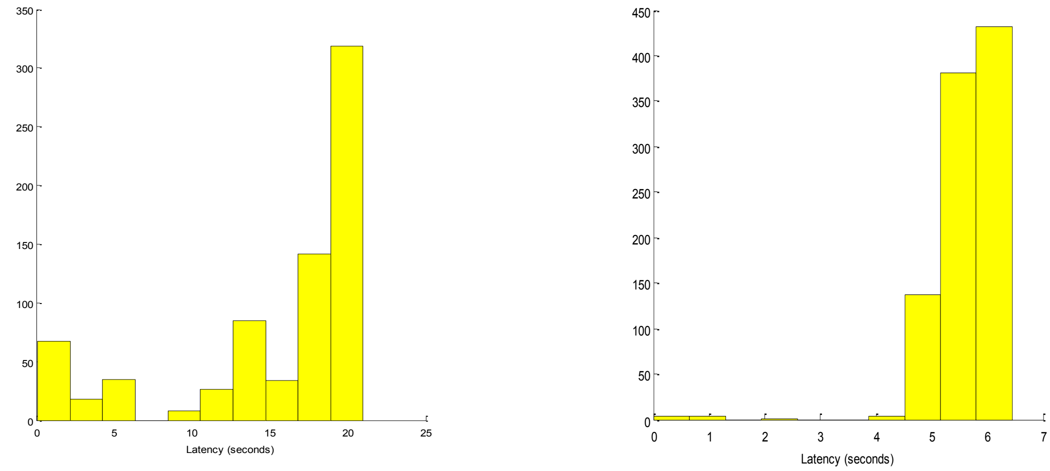


Figure 6-10 and 6-11: Latency distribution for dataset 1 and dataset 2 for aircraft 406250

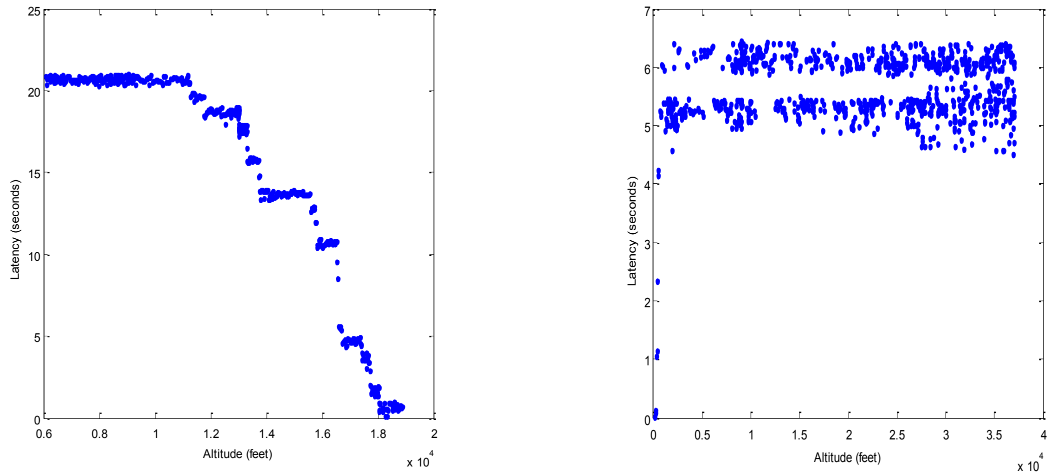


Figure 6-12 and Figure 6-13: Latency vs altitude for dataset 1 and dataset 2 for aircraft 406250

The latency distribution for aircraft 406250 in dataset one (Figure 6-10) varies between 0.1 to 20 seconds with the highest distribution between 18 to 20 seconds. While the latency distribution for the same aircraft is consistent between 5 to 6.5 seconds in dataset two. Latency performance across the flight altitude for aircraft 406250 in dataset one (Figure 6-12) indicates that the latency increases as the altitude decreases. This complies with the hypothesis proposed earlier whereby lower altitude in the TMA is more dense hence the signal jamming would be worst than in higher altitude. However, the same aircraft does not comply with the hypothesis in dataset two (Figure 6-13), instead showing consistent performance across the altitudes.

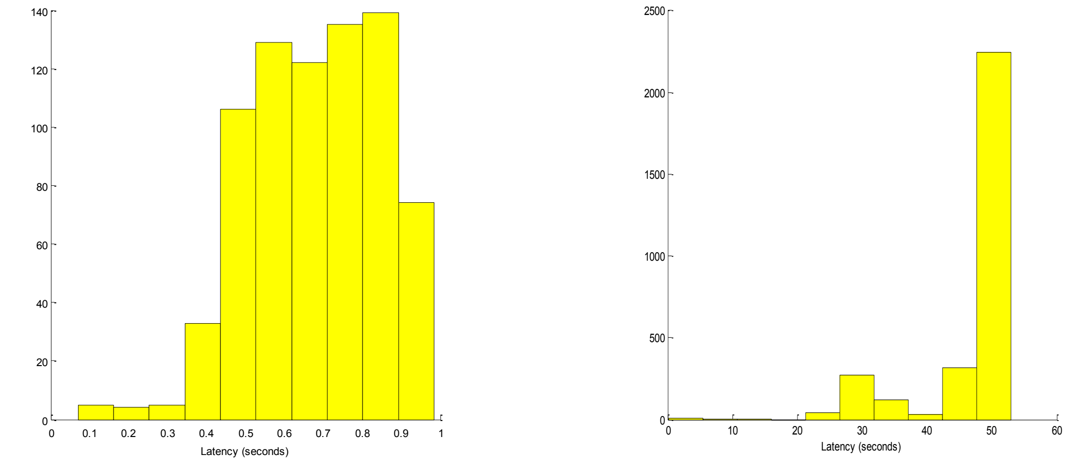


Figure 6-14 and 6-15 : Latency distribution for dataset 1 and dataset 2 for aircraft 400942

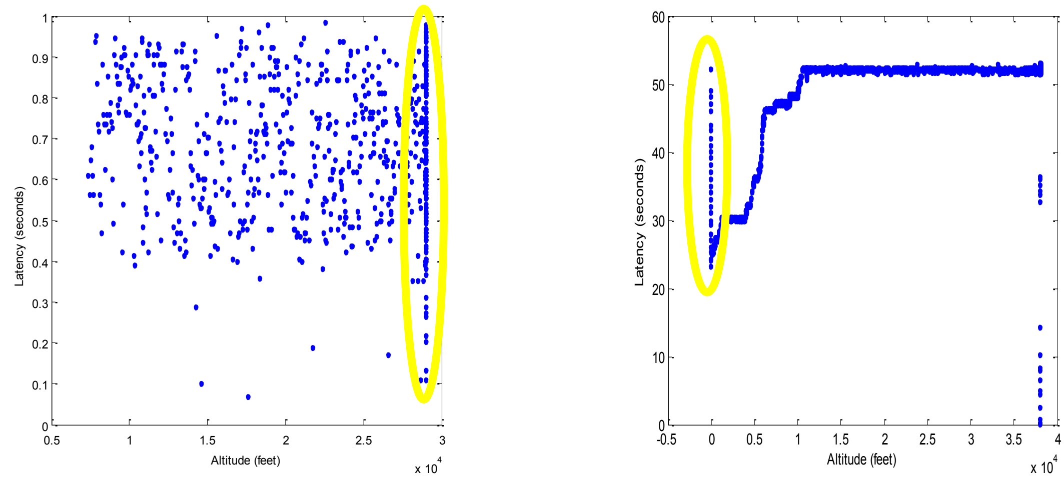


Figure 6-16 and 6-17: Latency vs altitude for dataset 1 and dataset 2 for aircraft 400942

The latency distribution for aircraft 400942 in dataset one is consistent between 0.4 to 0.9 seconds (Figure 6-14) complying with the requirements while the performance in dataset two is extremely bad with the highest distribution between 45 to 50 seconds (Figure 6.15). The latency performance across the altitudes for aircraft 400942 in dataset one is scattered between 0.4 to 0.9 seconds (Figure 6-16) while in dataset one the performance is consistent at 45 to 50 seconds after 10000 feet (Figure 6-17). The latency performances for aircraft 406250 and 400952 do not comply with the requirements and do not show consistency in the performance. The plausible reasons for the inconsistency were not identified. However, the consistency analysis in Appendix B concludes that the latency performance is not correlated to the change in the flight altitude.

In addition, an interesting finding from, Figures 6-16 and 6-17 (highlighted in yellow) is that the latency performance varies significantly when the aircraft is level at a specific altitude. In order to verify this finding, all the aircraft in Table 6-1 were analyzed to assess latency performance across the flight level (Appendix B). Based on the analysis, all the aircraft also show that the latency performances vary significantly when the aircraft is cruising at specific level, at both low and high altitude. These findings indicate that, the latency performance is not influenced by the aircraft altitude.

The latency performance impacts the situational awareness by Air Traffic Control (ATC). Assuming for example, that an aircraft travels at 400 knots, the highest mean latency as identified in the analysis of 1.9050 seconds (Table 6-1) translates into an error in the 3D geometrical distance of 392 meters. This is not sufficient for ATC to provide 3NM separation based on the requirements in ED-142 (EUROCAE, 2010). Therefore, latency is one of the factors that contribute to the ADS-B positioning accuracy, in addition to the onboard navigation system accuracy that feeds to the ADS-B system.

6.3.2 ADS-B Horizontal Position Accuracy

In this thesis, ADS-B horizontal position accuracy is evaluated by comparing the received position from the ADS-B ground station with the reference position (derived from Eq. 1 and Eq. 2). The Horizontal Position Error (HPE) is measured for each ADS-B position by applying Eq. 4 and Eq. 5. In Eq. 4, the WGS84 ellipsoidal co-ordinates (latitude (λ), longitude (ϕ), altitude (*h*)) for both the ADS-B position and the reference position are transformed into the Earth-Centred Earth-Fixed (ECEF) Cartesian co-ordinate (*x*, *y*, *z*). Eq.5 measures the HPE.

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} (N+\boldsymbol{h})cos\boldsymbol{\varphi}cos\lambda \\ (N+\boldsymbol{h})cos\boldsymbol{\varphi}sin\lambda \\ (N(1-e^2)+\boldsymbol{h})sin\boldsymbol{\varphi} \end{bmatrix} \quad \text{(Eq.4)}$$

where,

- *e is the first eccentricity of ellipsoid, denoted as e = 0.08181919,*
- *N is the distance along the normal from the position (λ, φ, h) to the meridian ellipse, denoted by:*

  $N = \frac{a}{\sqrt{1-e^2 sin^2 \varphi}}$, *a=6378137 (Equatorial Radius)*

$$\boldsymbol{HPE} = \sqrt{(\boldsymbol{R}(\boldsymbol{X_{ADSB}} - \boldsymbol{X_{REF}}))^2 + (\boldsymbol{R}(\boldsymbol{Y_{ADSB}} - \boldsymbol{Y_{REF}}))^2} \quad \text{(Eq. 5)}$$

where,

$$\mathbf{R} = \begin{bmatrix} -sin\,(\varphi_{REF}) & cos\,(\varphi_{REF}) & 0 \\ -sin(\lambda_{REF})cos\,(\varphi_{REF}) & -sin(\lambda_{REF})sin\,(\varphi_{REF}) & cos\,(\lambda_{REF}) \\ cos(\lambda_{REF})sin\,(\varphi_{REF}) & cos(\lambda_{REF})cos\,(\varphi_{REF}) & sin\,(\lambda_{REF}) \end{bmatrix}$$

Table 6-3 tabulates the Root Mean Square (RMS) horizontal position error (HPE) computed for the eight aircraft.

Table 6-3: RMS horizontal position error (HPE)

Aircraft ID	Aircraft Type	HPE (meter)
40608F	A318	476.2826
405A48	A320	66.2622
400A26	A320	552.8482
400877	A319	109.4822
400878	A319	113.1374
40087B	A319	14287
4008F2	A319	48.8772
400935	A319	145.4744

As shown in Table 6-3, aircraft 40087B exhibits an unacceptable position error of 14287 metres. Further investigation is in progress with British Airways on the performance of this particular aircraft. Aircraft 4008F2 shows a good position error of 49 meters. Five of the aircraft are compliant with the requirement of 3NM separation i.e. <150 meters RMS error (EUROCAE, 2010). Figures 6-18 to 6-21 show the largest and least position error over time and the position error distribution for aircraft 40087B and 4008F2, respectively.

For aircraft certified with DO-260B, the ADS-B report includes a data item called Navigational Accuracy Category (NAC), an indicator of receiver positioning accuracy (RTCA, 2011). NAC is derived based on GPS accuracy (Horizontal Figure of Merit-HFOM). HFOM does not reflect unannounced faults in a GPS satellite (ICAO, 2007b). The NAC is not suitable for making integrity decisions where safety of life is concerned. The resultant NAC is presented as a numerical value, from 0 to 9, whereby higher the NAC value, more accurate the position magnitude value.

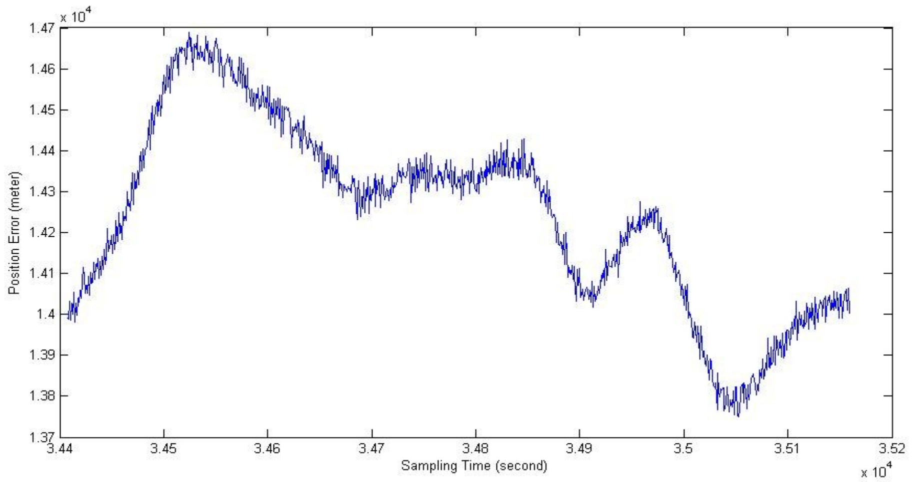


Figure 6-18: Position error over time for aircraft 40087B

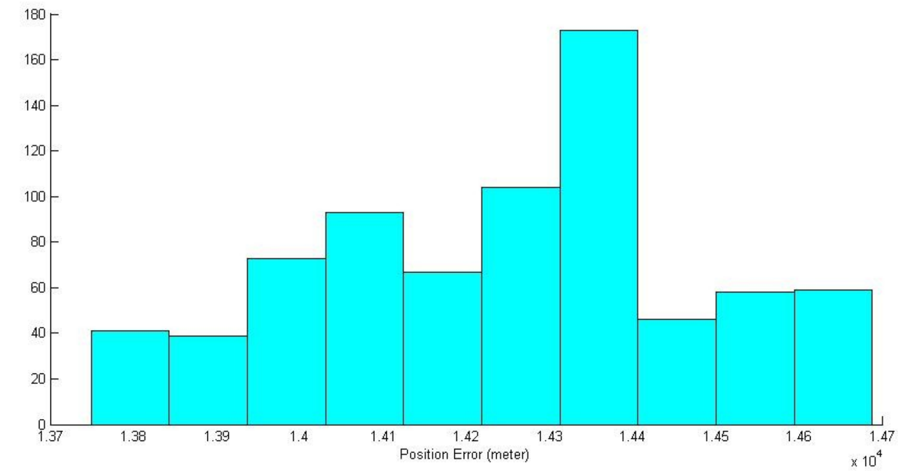


Figure 6-19: Position error distribution for aircraft 40087B

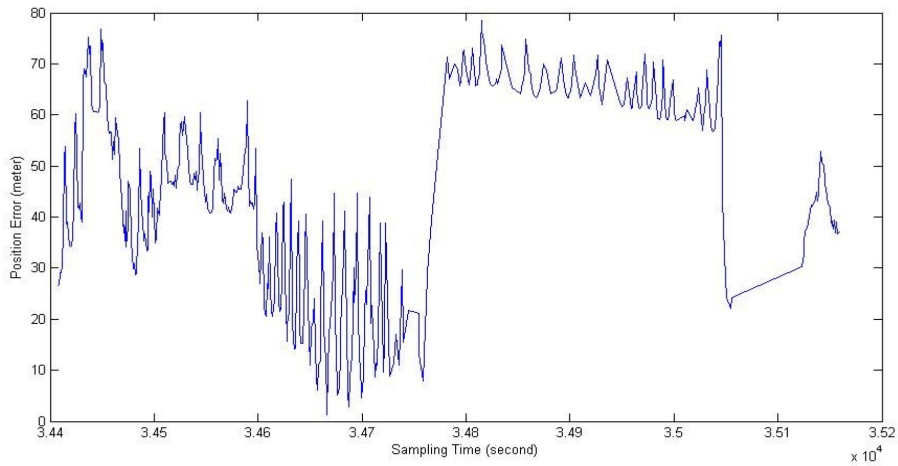


Figure 6-20: Position error over time for aircraft 4008F2.

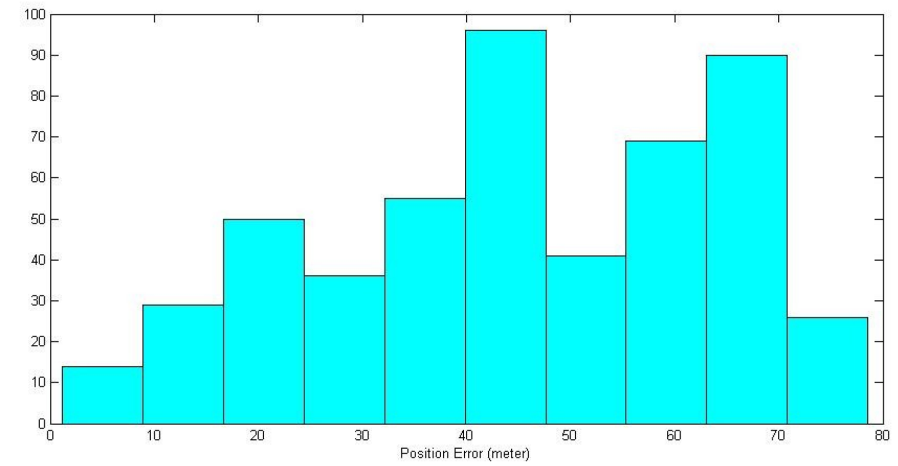


Figure 6-21: Position error distribution for aircraft 4008F2

The HPE performance consistency is evaluated using the data from the four aircraft recorded during two different flights. Table 6-4 shows the performance consistency.

Table 6-4: HPE performance consistency

Aircraft	Aircraft Type	HPE (meters)		Std. Dev	
		Dataset 1	Dataset 2	Dataset 1	Dataset 2
406250	A320	11093	1134	1096	305
4008B4	A319	26	279	17	66
4009C7	A320	169	130	36	39
400942	A319	11026	7713	1378	2677

Based on the analysis in Table 6-4, none of the aircraft is showing consistency in the horizontal position accuracy between the two flights. Aircraft 406250 and 400942 show extremely bad HPE in both flights and hence the positioning information cannot be used to perform separation. It is also found that there are jumps in the GPS position in latitude and longitude in dataset one for aircraft 400942. These anomalies are investigated and discussed further in Chapter 7. However, the HPE measured in Table 6-4 is after removing the outliers due to position jumps. While aircraft 4008B4 shows good HPE with 26 meters in dataset one and the performance degraded to 279 meters in dataset two. Aircraft 4009C7 shows almost similar HPE in both flights 169 meters and 130 meters respectively. Figure 6-22 to 6-29 shows the HPE distributions for the four aircraft.

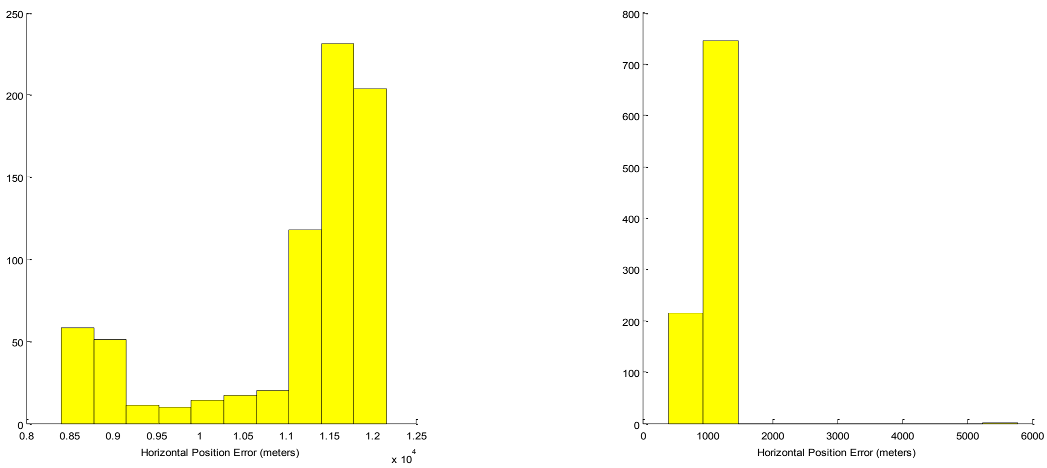


Figure 6-22 and 6-23: HPE distribution for dataset 1 and dataset 2 for aircraft 406250

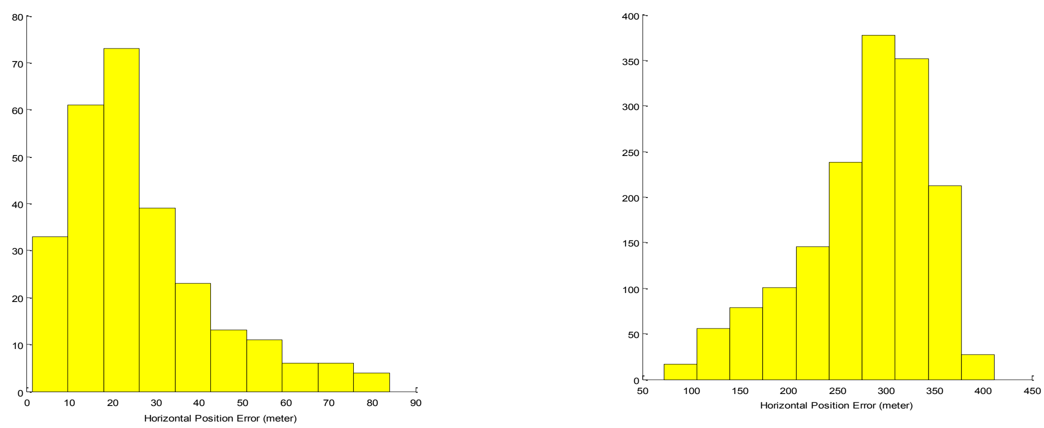


Figure 6-24 and 6-25: HPE distribution for dataset 1 and dataset 2 for aircraft 4008B4

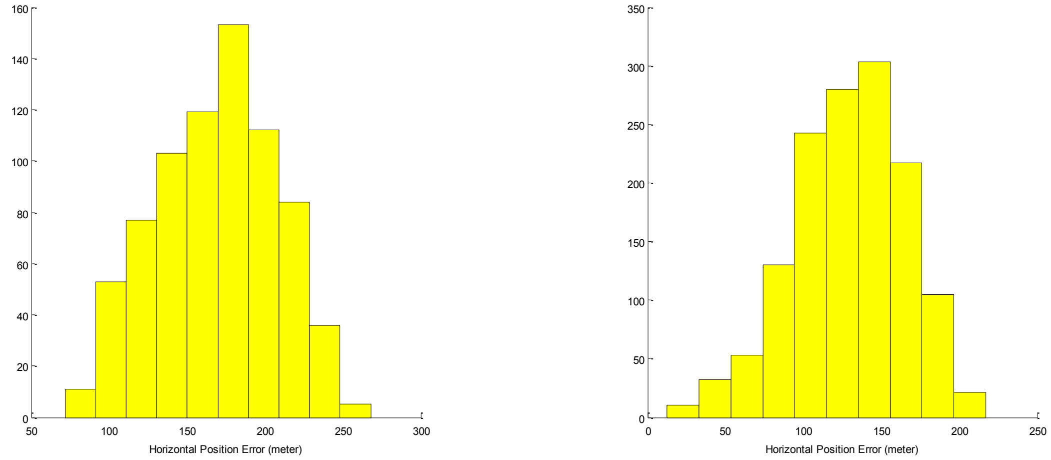


Figure 6-26 and 6-27: HPE distribution for dataset 1 and dataset 2 for aircraft 4009C7

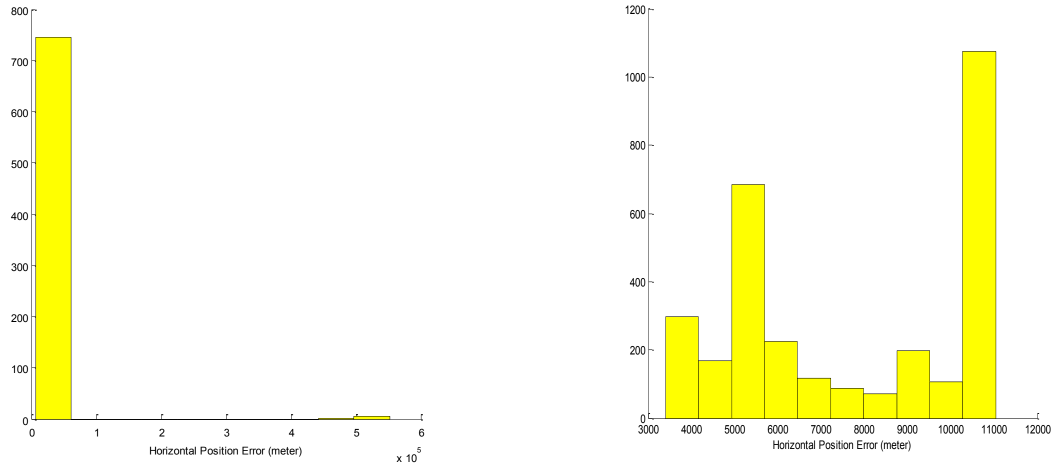


Figure 6-28 and 6-29: HPE distribution for dataset 1 and dataset 2 for aircraft 400942

Among the four aircraft only HPE for aircraft 4009C7 are normally distributed in both flights. Next, the correlation between the HPE and latency is investigated for the four aircraft in both flights in Figures 6-30 to 6-37.

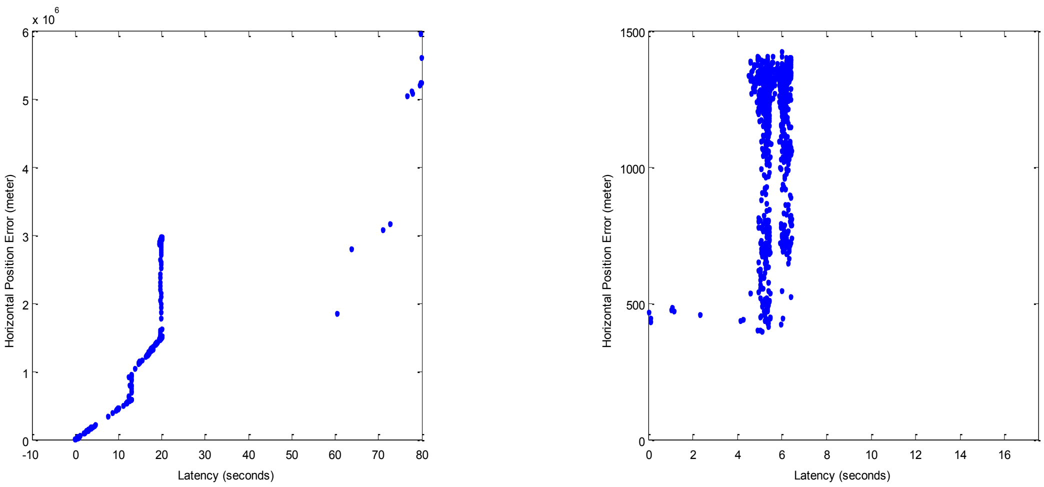


Figure 6-30 and 6-31: HPE vs Latency for dataset 1 and dataset 2 for aircraft 406250

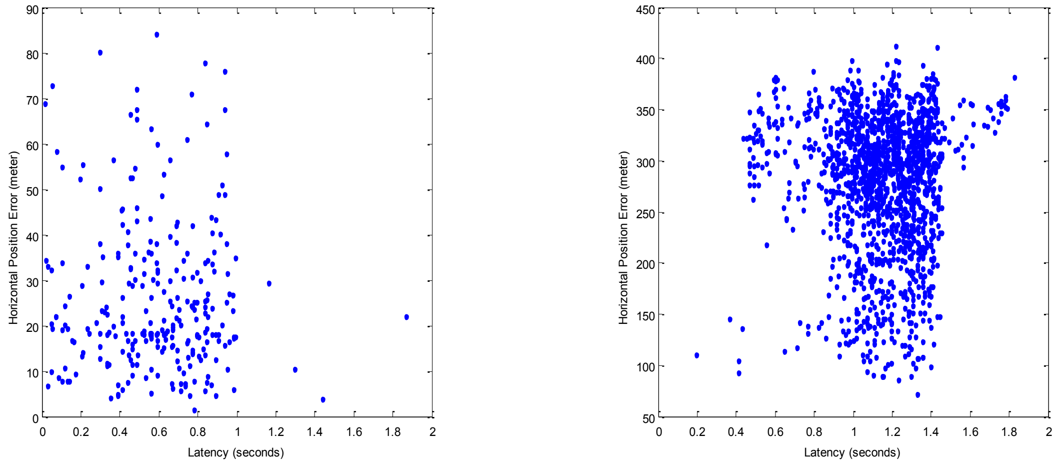


Figure 6-32 and 6-33: HPE vs Latency for dataset 1 and dataset 2 for aircraft 4008B4

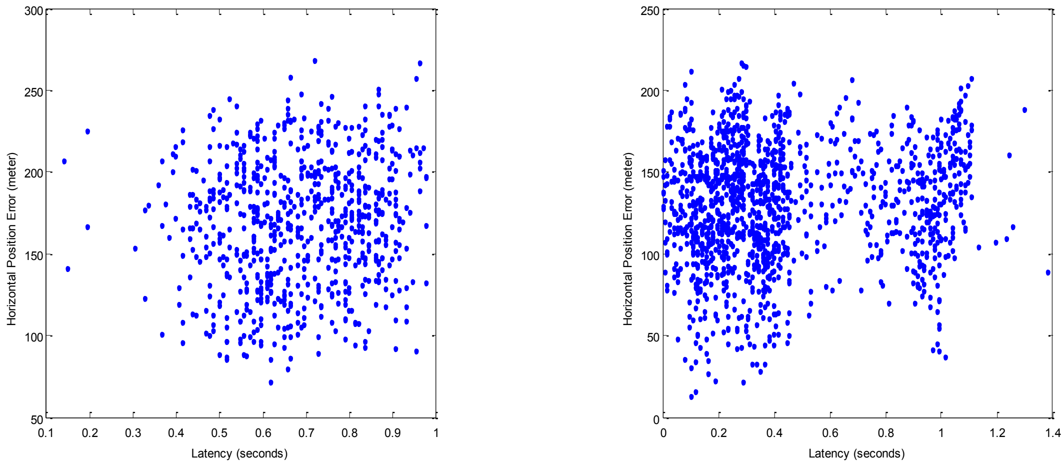


Figure 6-34 and 6-35: HPE vs Latency for dataset 1 and dataset 2 for aircraft 4009C7

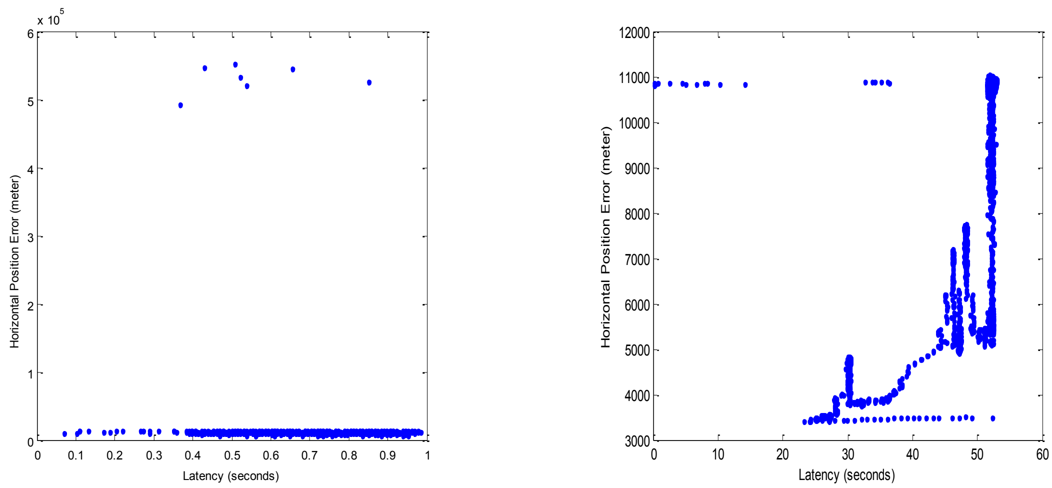


Figure 6-36 and 6-37: HPE vs Latency for dataset 1 and dataset 2 for aircraft 400942

Based on the analysis in Figures 6-30 to 6-37, no correlation was identified between HPE performance and latency for all the aircraft in both flights. However, the HPE performance for aircraft 406250 and 400942 may be influenced by the errors in the data correlation process between the GPS position and ADS-B position due to the position jumps identified in both aircraft datasets. The results of the correlation between the HPE performance and change in altitude are investigated, and shown in Figures 6-38 to 6-45.

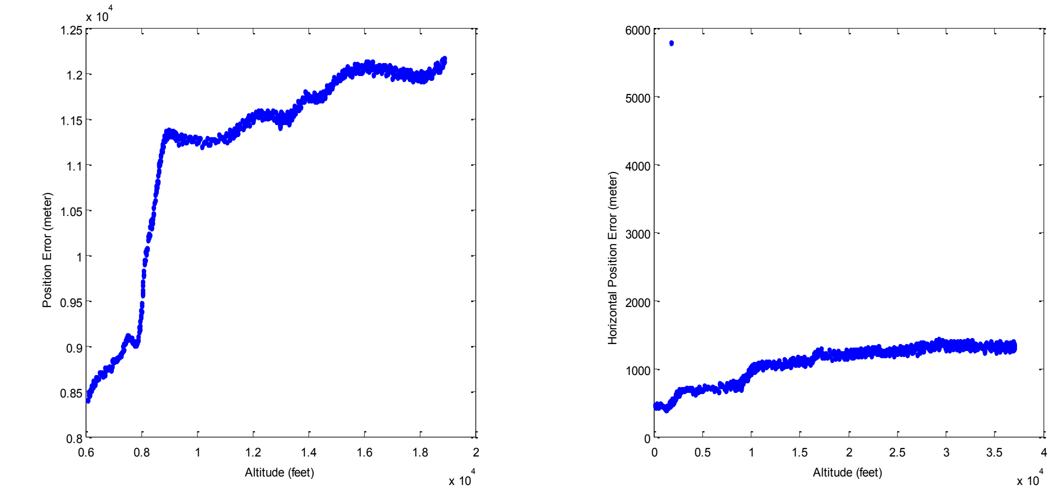


Figure 6-38 and 6-39: HPE vs Altitude for dataset 1 and dataset 2 for aircraft 406250

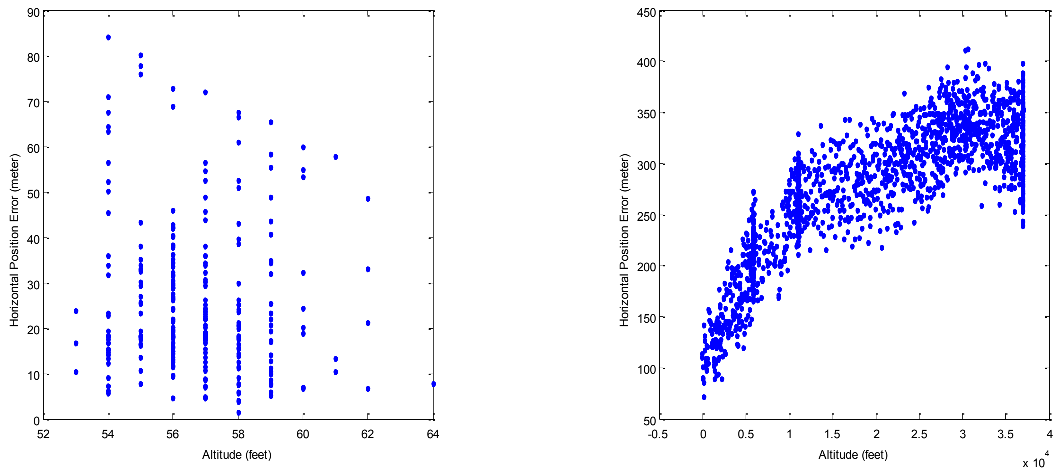


Figure 6-40 and 6-41: HPE vs Altitude for dataset 1 and dataset 2 for aircraft 4008B4

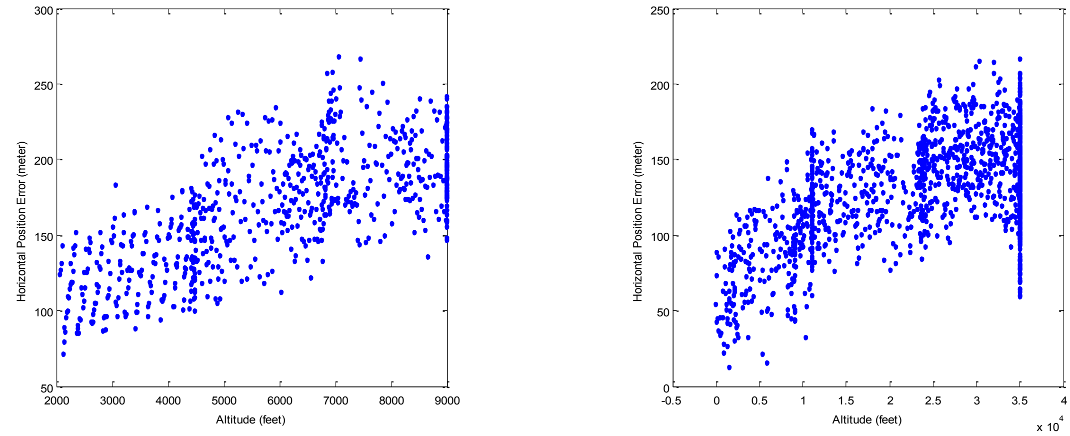


Figure 6-42 and 6-43: HPE vs Altitude for dataset 1 and dataset 2 for aircraft 4009C7

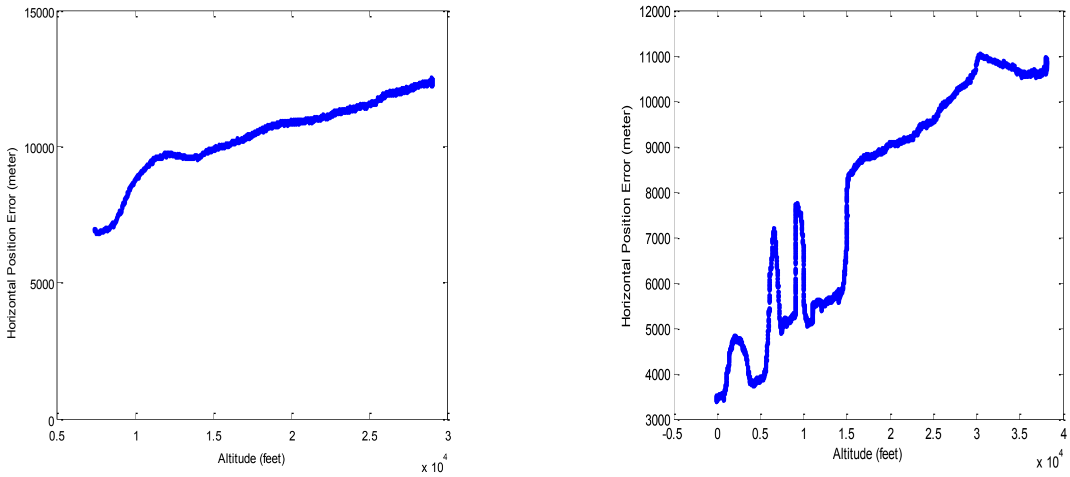


Figure 6-44 and 6-45: HPE vs Altitude for dataset 1 and dataset 2 for aircraft 400942

The results in Figures 6-38 to 6-45 indicate that there is a significant correlation between HPE performance and the change in altitude, whereby as the altitude increases the HPE also increases. This can be clearly seen for example, in Figure 6-40 (dataset 1) and Figure 6-41 (dataset 2), whereby in dataset 1, aircraft 4008B4 is manoeuvring at a very low altitude between 52 to 64 feet, resulting in a mean HPE of 26 meters while in dataset 2, the aircraft is manoeuvring between 1000 to 40000 feet, resulting in a mean HPE of 278 meters. In order to verify this finding, a statistical correlation test is conducted. Both the HPE and altitude data are not normally distributed; therefore a non-parametric correlation test, Spearman's Rho is used. The test results are presented in Table 6-5.

Table 6-5: Correlation between HPE and flight altitude

			Altitude	HPE
Spearman's rho test	**Altitude**	Correlation Coefficient	1.000	.321**
		Sig. (2-tailed)	.	.000
		N	9496	9496
	HPE	Correlation Coefficient	.321**	1.000
		Sig. (2-tailed)	.000	.
		N	9496	9496

***. Correlation is significant at the 0.01 level (2-tailed).*

The correlation test in Table 6-5 verifies that there is significant correlation between HPE and flight altitude with a correlation coefficient of 0.321 significant at ($p<0.05$). The correlation itself is positive: therefore, it can be concluded that as the altitude increases, there is a corresponding increase in the HPE.

6.3.3 ADS-B Horizontal Position Integrity

In order to determine whether ADS-B data may be used to provide ATC separation service, a position integrity quality indicator is required (ICAO, 2007b). The ADS-B data available for this thesis includes a position integrity quality indicator called Figure of Merit (FOM). The FOM represents the Navigational Uncertainty Category (NUC), which encodes the integrity bound, on the basis of Horizontal Protection Limit (HPL) provided by the GPS receiver (for avionics based on DO-260), as a numerical value, from 0 to 9. The higher the value, the higher the position integrity. For aircraft certified with DO-260B, the indicator is known as Navigation Integrity Code (NIC). In addition, another indicator called Surveillance Integrity Level (SIL) is also included in the report. The SIL defines the level of integrity by providing the probability of being outside the NIC radius without equipment at the transmitting aircraft detecting that might be the case: 10^{-3}, 10^{-5}, or 10^{-7} per flight hour (RTCA, 2002). Based on the data analysis in Table 6-6, the mean position integrity of the sample is 5.43, i.e. above the threshold specified in Table 6-9 for radar and non radar airspace separation. FOM=0 cases are associated with position jumps. Such position jumps can result from avionics faults, and sometimes at the edge of coverage (ICAO, 2009a). When the ADS-B ground stations detect such a jump, the FOM value transmitted to ATC is zero (to prevent the position from being used by the ATC system).

Table 6-6: Descriptive analysis of Figure of Merit (FOM) for position integrity quality indicator

	N	Min	Max	Mean	Std. Dev
FOM	95676	0	8	5.43	2.620

The ADS-B position accuracy is presented in the previous section as the Horizontal Position Error (HPE). The integrity risk of the ADS-B position is the probability that an error larger than the Alert Limit (AL) is undetected. The AL based on the NUC/FOM for aircraft certified under DO-260 is given in Table 6-7.

Table 6-7: Alert Limit (AL) based on NUC/FOM

NUC in DO-260	HPL in DO-260 (Alert Limit)
0	≥ 20NM
1	< 20NM
2	< 10NM
3	< 2.0NM
4	< 1.0NM
5	< 0.5NM
6	< 0.2NM
7	< 0.1NM
8	< 25meters
9	< 7.5meters

The FOM/NUC or NIC value is transmitted to the ADS-B ground station for ATC use is the only indication of the aircraft position integrity. But how reliable is the quality indicator value? It is critical to verify this value at the ground station, before the aircraft position information is used for the various ATC applications. Therefore, in this thesis, a set of algorithms is developed for this purpose as follows:

- Correct detection event occurs when the FOM value presented to the controllers is less than the alert limit and the actual HPE is also less than the alert limit; (HPE<FOM<AL).
- Missed detection event occurs when the FOM value presented to the controllers is less than the alert limit while the actual HPE is greater than the alert limit; (FOM<AL<HPE).
- False alert event occurs when the FOM value presented to the controllers is less than the alert limit while the actual HPE is greater than the FOM but less than the alert limit; (FOM<HPE<AL).

The set of algorithm is used to validate the integrity quality indicator (FOM/NUC or NIC) and to identify the actual ADS-B system performance for all the aircraft included in this thesis. The integrity performance (correct/missed/false detection) is evaluated for each ADS-B sample from each aircraft. Then the percentage of the categories and the integrity risk of each aircraft are measured. The results are shown in Table 6-8. It is found that three aircraft indicate 100% missed detection. Aircraft 400878 shows 99.8% correct detection and 0.2% missed detection. Aircraft 400935 shows 91.2% correct detection and 8.8% missed detection. No false detection events are identified. Missed detections are most critical as ATC relies on the integrity quality indicator provided by the ADS-B system to ensure aircraft separation. The integrity risk of aircraft 40608F, 400A26 and 40087B are measured as 1. While aircraft 400878 has integrity risk of 1.6×10^{-03} and aircraft 400935 has integrity risk of 8.8×10^{-02}.

Table 6-8: ADS-B Integrity quality indicator validation

Aircraft ID	Integrity Performance Category			Integrity Risk
	Correction Detection (%)	Missed Detection (%)	False Detection (%)	
40608F	0	100	0	1
405A48	100	0	0	0
400A26	0	100	0	1
400877	100	0	0	0
400878	99.8	0.2	0	1.6×10^{-03}
40087B	0	100	0	1
4008B4	100	0	0	0
4008F2	100	0	0	0
400935	91.2	8.8	0	8.8×10^{-02}

The error identified in the FOM may be due to the decoding process in the ADS-B transmission subsystem. Hence, it is crucial to have a validation mechanism at the ADS-B ground station to avoid such errors impacting the ATC system. This mechanism will also aid the ANSP to inform the airline on the problems detected in the avionics.

6.3.4 ADS-B Availability

ADS-B availability is impacted at three levels: availability of position integrity indicator from the GPS receiver, and the performance of ADS-B data transmission and ADS-B data reception at ground stations. The ATC system only displays ADS-B data to controllers when the FOM value is above the required threshold (Table 6-9). If the FOM does not reach this threshold, the ADS-B service is disrupted to that aircraft. The percentage of suitable FOM during the sample period effectively represents the availability of the GPS position data to the ADS-B transmitter. Acceptable FOM/NUC requirements were developed by the FAA-EUROCONTROL Requirements Focus Group (RFG) for Non Radar Airspace (NRA) and the Radar Airspace (RAD) ADS-B applications. These are summarised in Table 6-9.

Table 6-9: Separation requirement based on NUC as quality indicator

RTCA standard for Non Radar Airspace (NRA) : DO303 (RTCA, 2007)	RTCA standard for Radar Airspace (RAD) : DO318 (RTCA, 2009)
5 NM en-route separation : NUC = 4 3 NM separation: NUC = 5	5 NM en-route separation: NUC = 4 3 NM separation: NUC = 5

The percentage of reports (with NUC > threshold) during the sampling period effectively represents the availability of the GPS position data to the ADS-B transmitter during the sample period. Failures of the ADS-B transmitter and of the ADS-B ground station receiver will also impact ADS-B availability. Based on the data analysis in Figure 6-46 and Table 6-9, the percentage of received ADS-B reports is 81.80% and the availability is 81.78%. This shows an unavailability of 0.02%.

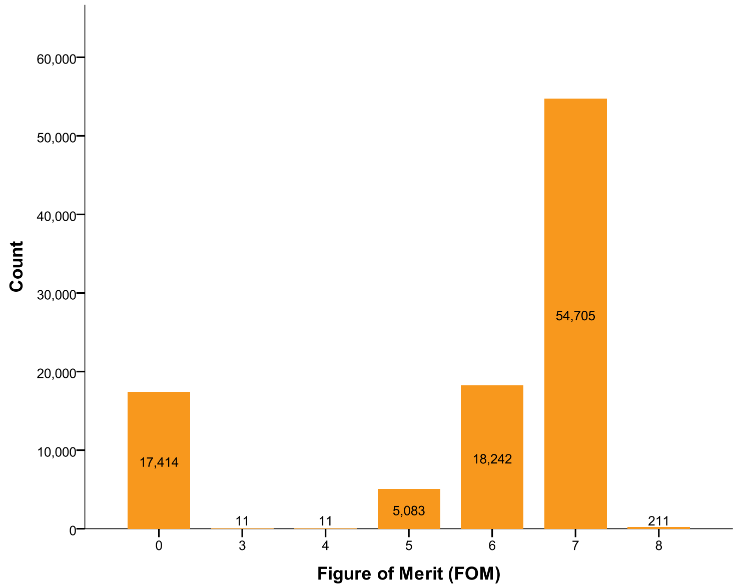


Figure 6-46: Availability of the ADS-B positional data based on Integrity Quality Indicator

6.3.5 ADS-B Continuity

ADS-B continuity is defined in detail in Chapter 3. The variable that denotes continuity parameter performance is the 'ADS-B message update rate'; measured as the rate (seconds) at which periodic ADS-B messages were received at the ground stations.

Initially the update rate analysis was conducted using the first dataset comprising ADS-B messages recorded for 15 minutes flight duration for 34 aircraft based on opportunity traffic in the LTMA. However, the scatterplot analysis clearly showed that there was no deterministic pattern on the message update rate. The cause for this finding was verified when the same analysis was conducted using the second dataset comprising ADS-B messages for 45-60 minutes flight duration for 31 aircraft recorded in the same airspace based on opportunity traffic. The analysis conducted with the second dataset clearly showed a pattern in the message update rate. Therefore, it can be concluded that, to conduct ADS-B continuity analysis, the data has to be recorded for at least 45 minutes. Coincidently, four aircraft were identified in both datasets. Figure 6-47 shows the update rate vs. flight duration for one of the aircraft.

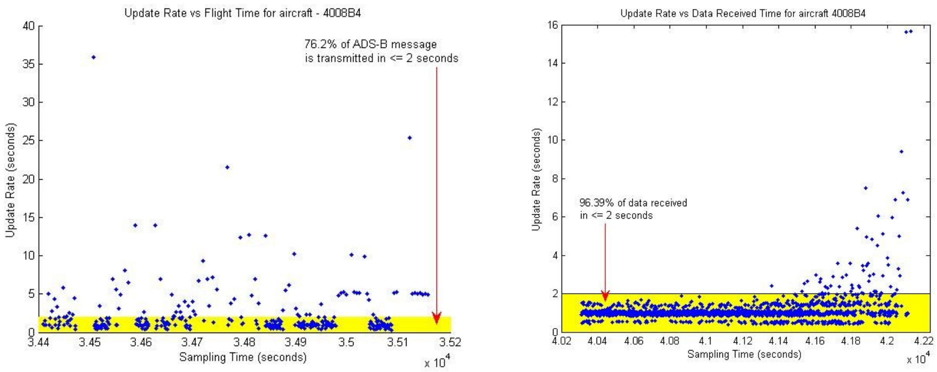


Figure 6-47: Update rate vs. Flight time for the same aircraft in different time intervals

Therefore, the first dataset was not used to conduct the ADS-B update rate analysis.

General aircraft avionics information and descriptive statistic of ADS-B message update rate for each aircraft included in this analysis are given in Appendix C. The general aircraft information includes 24-bit aircraft address, onboard GPS receiver model, ADS-B transponder model and aircraft type. The descriptive statistics information includes mean, standard deviation, minimum and maximum update rate value in seconds.

Due to the unanticipated update rate pattern which does not completely meet the required performance (0 to 2 seconds) based on the findings in Appendix C and Appendix D (scatterplot update rate vs. flight time), further effort is placed to investigate the factors that may have affected the performance were investigated. A number of possible factors affecting ADS-B message update rate were identified based on the review of ADS-B system operations:

- Aircraft model (categorical variable)
- Phases of flight (categorical variable)
- Ground station (categorical variable)
- GPS receiver model (categorical variable)
- Transponder model (categorical variable)
- Range (continuous variable)
- Flight level (continuous variable)

The analysis is structured in a way to finally derive an update rate model to introduce the factors that contribute to the update rate performance. In the first part of the analysis, scatterplot of the update rate against flight duration is produced for all the 31 aircraft (Appendix D). The scatterplot analysis clearly shows that there is a pattern on the ADS-B message update rate. It is also found that obvious outliers and duplicate messages exist in the data. The findings are provided in Appendix C for each aircraft. The reason for the duplicate messages is due to ADS-B message transmission to more than one ground station within the aircraft range at the same time and the central processing unit for the ground stations did not discard the duplicate messages.

It is important to determine if the update rate distribution is normal or non-normal to choose the correct correlation test for the correlation analysis. Therefore the Kolmogorov-Smirnov and Shapiro-Wilk normality tests are used to check the data distribution. These tests compare the set of data in the sample to a normally distributed set of data with the same mean and standard deviation. If the test is non-significant ($p>0.05$), the sample distribution is not significantly different from a normal distribution (i.e. normal). If, however, the test is significant ($p<0.05$), then the sample distribution is different from a normal distribution (i.e. non-normal). Based on the tests results, the update rate data are not normally distributed. Therefore, the correlation or association between the variables (potential factors) and ADS-B message update rate are tested using non-parametric tests; Friedman test, Wilcoxon Signed-rank test or Spearman's rho tests depending on the variable type; categorical or continuous .

The Friedman test is used to test for differences between two or more groups when the dependent variable being measured is ordinal or continuous data (that deviates from normality) and the independent variable being categorical data. This test is chosen to identify if the following variables (categorical) contribute to the ADS-B update rate (continuous) performance in Appendix D. If the result of the Friedman Test is significant (i.e. there is a significant difference between the tested groups), then it can be concluded that the variables contribute to the ADS-B message update rate performance. However, the Friedman test does not pinpoint which group in particular differs from each other. Therefore, further analysis on the data is performed to identify the differences between the groups using the Wilcoxon Signed-rank test. The Wilcoxon test is run separately on the different combinations of the related groups. The test uses Z-statistics to measure the differences between the groups combination. If there are more than two group samples, Bonferroni adjustment is used to derive the adjusted significance level p, by dividing the initial significance level (in this case, 0.05) by the number of group samples.

The Spearman's Rho test is used to measure the strength and direction of association between the following variables (continuous) and update rate performance. The test produces two statistics values; correlation coefficient, r and significance level, p. The correlation coefficient, r, measures the averaged sum of combined difference for two variables with different units (refer to Equation 6).

$$r = \frac{\sum(xi-\bar{x})(yi-\bar{y})}{(N-1)SxSy} \qquad \textit{(Eq.6)}$$

where $Sx \rightarrow standard\ deviation\ of\ update\ rate$

$Sy \rightarrow standard\ deviation\ of\ flight\ level$

The corresponding value of 'r' should be between -1 and +1. If it is out of this range, then something must be wrong with the calculation. Interpretations of the 'r' values are as follows

- +1 → indicates that the two variables are perfectly positively correlated, when one variable increases, the other increases by a proportionate amount.
- -1 → indicates a perfect negative relationship.
- 0 → indicates no linear relationship at all between the two variables. When one variable changes, the other stays the same.

The correlation between the potential factors identified and ADS-B message update rate are analysed based on the availability of the required data and information from the ANSP and airline operator; in this case, NATS and British Airways.

6.3.5.1 Aircraft model

The Friedman test in Table 6-10 indicates that, there is an overall statistically significant difference in the mean rank of ADS-B message update rate for aircraft model A319, A320, A321, B744 and B777-200 with $\chi^2(4) = 504.325$, $p < 0.01$. This suggests that the aircraft model contributes to the ADS-B message update rate performance.

Table 6-10: Friedman test for Aircraft model vs. Update rate

Aircraft model	Rank	Friedman Test Statistics			
		N	Chi-Square	df	Asymp. Sig.
A319	2.62	4403	504.325	4	.000
A320	3.31				
A321	3.17				
B744	3.01				
B777-200	2.88				

In order to identify the differences among the aircraft models, further analysis is conducted by calculating the percentage of update rates within 2 seconds as shown in Figure 6-48. The results show that the ADS-B message update rate performance varies based on the aircraft model. A319 shows the best performance with 87.35% of the message update rates within 2 seconds, followed by A321 with 82.32% and B777-200 with 80.55%. While B744 shows the worst performance with 72.24% followed by A320 with 74.49%. The potential reason for this variation maybe due to the differences in the avionics models used by the aircraft. Therefore, the next sections investigate the update rate performance based on the GPS receiver and ADS-B transponder models.

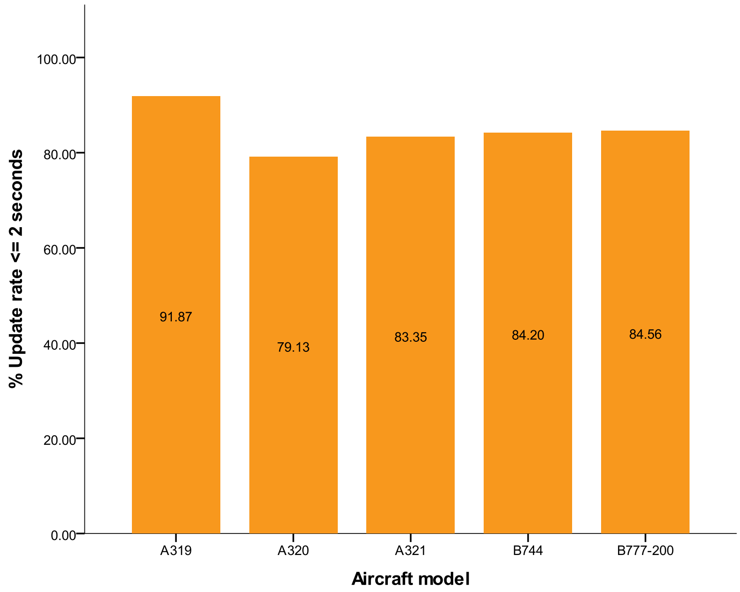


Figure 6-48: Percentage update rate ≤ 2 seconds based on aircraft model

6.3.5.2 GPS receiver model

The Friedman test in Table 6-11 indicates that there is an overall statistically significant difference in the ADS-B message update rate based on GPS receiver onboard; Honeywell GNSSU , Rockwell Collins GLU920 MMR and Thales TLS755 MMR with $\chi^2(4) = 327.904$, $p < 0.01$. This suggests that the GPS receiver type is associated with the ADS-B message update rate performance.

Table 6-11: Friedman test for GPS receiver model vs. Update rate

GPS receiver model	Rank	Friedman Test Statistics			
		N	Chi-Square	df	Asymp. Sig.
Honeywell GNSSU	2.22	3628	327.904	2	.000
Rockwell Collins GLU920 MMR	1.99				
Thales TLS755 MMR	1.79				

However, by looking at the performance based on the percentage of update rate within 2 seconds (Figure 6-49), no significant difference is identified between the GPS receivers based on the aircraft make model. However, if the data were more diverse; with each aircraft model using different types of GPS receivers, the findings would have been more concrete. Based on Figure 6-49, only B777-200 uses two different GPS receivers; Honeywell GNSSU and Rockwell Collins GLU920 MMR which shows 80% and 86% of update rate within 2 seconds respectively. These conclude that the GPS receiver model affects the update rate performance.

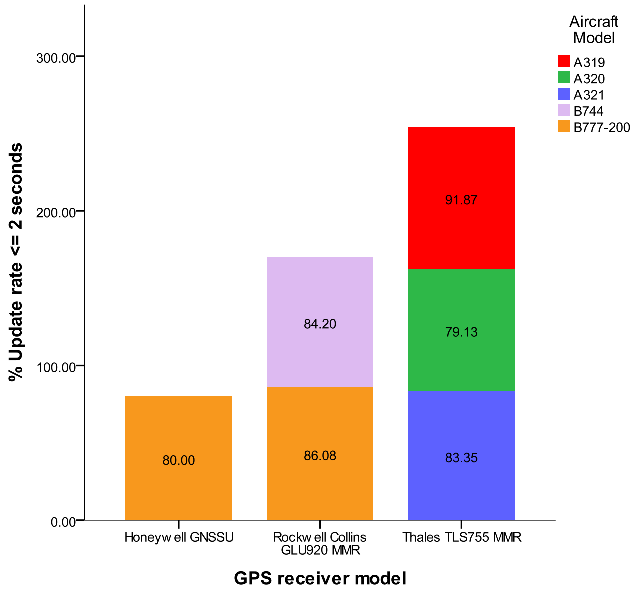


Figure 6-49: Percentage update rate ≤ 2 seconds vs. GPS receiver model based on aircraft model

It is important to recall at this point as explained in Chapter 3, that the GPS position received onboard is fed to the ADS-B system. The GPS data analysis shows that the GPS position update rate by all the onboard GPS receivers included in this analysis is consistent at 1 second. Therefore, no anomalies are identified on the GPS position update rate by the receivers that might have affected the performance of the ADS-B message update rate.

6.3.5.3 Transponder model

The Friedman test in Table 6-12 indicate that, there is an overall statistically significant difference in the mean rank of ADS-B message update rate based on the transponder; ACSS XS-950 and Honeywell TRA-67A with $\chi^2(4) = 364.88, p < 0.01$. This suggests that the transponder type contributes to the ADS-B message update rate performance.

Table 6-12: Friedman test for Transponder model vs. Update rate

Transponder model	Rank	Friedman Test Statistics			
		N	Chi-Square	df	Asymp. Sig.
ACSS XS-950	1.59	12092	364.888	1	.000
Honeywell TRA-67A	1.41				

However, further analysis in Figure 6-50 measuring the percentage of ADS-B message transmitted within 2 seconds, does not show any significant differences between the transponder models. This is due to lack of diversity in the data. Comparison can only be made between the transponder models if the same aircraft model has different transponders.

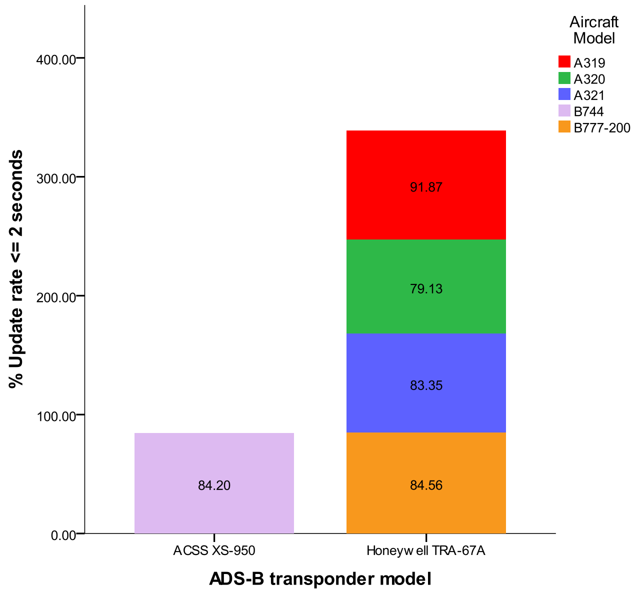


Figure 6-50: Percentage update rate ≤ 2 seconds vs. transponder model based on aircraft model

Therefore, it can be concluded that the transponder model affects the ADS-B update rate performance. However, diverse data are required to obtain a more concrete result.

6.3.5.4 Flight level

The correlation between aircraft flight level and ADS-B message update rate is tested using Spearman's rho test. The test results are tabulated in Appendix E. The results show that 30 aircraft have significant correlation between flight level and update rate with positive correlation coefficient, r, significant at 0.01 level, indicating that when the flight level increases, the update rate also increases. However, the correlation was not significant for one aircraft with a correlation coefficient, r=0.038 and significance, p = 0.077. This is assumed to be an outlier in the sample. Further analysis is conducted by grouping the flight level and identifying the update rate performance between each group.

The Friedman test in Table 6-13 shows that, there is an overall statistically significant difference in the ADS-B message update rate between flight level grouped as 0 – 10000 (FL1), 10001 – 20000 (FL2), 20001 – 30000 (FL3), 30001 – 40000 (FL4) and 40001 – 50000 (FL5) with $\chi^2(4) = 323.446$, p = 0.000. This suggests that the flight level groups contribute to the ADS-B message update rate performance. In order to analyze the differences between the flight level groups, a post-hoc analysis with the Wilcoxon signed-rank test (Table 6-14 and Table 6-15) was conducted with a Bonferroni correction applied, resulting in a significance level set at p<0.01. Median (Table 6-14) update rate for ADS-B message at FL1, FL2, FL3, FL4 and FL5 were 1.03 (0.95 to 1.14), 1.01 (0.93 to 1.11), 1.02 (0.93 to 1.32), 1.38 (0.97 to 2.09) and 1.43 (0.98 to 2.29) respectively. There was a statistically significant decrease in update rate in FL2 vs. FL1 (Z = -5.035, p= 0.000). However, there was no significant difference between the FL2 and FL1 update rate range. There was a statistically significant increase in the update rate in FL3 vs. FL1 (Z = -18.877, p= 0.000), FL4 vs. FL1 (Z = -39.211, p= 0.000), FL5 vs. FL1 (Z = -13.251, p= 0.000), FL3 vs. FL2 (Z = -11.821, p= 0.000), FL4 vs. FL2 (Z = -30.744, p= 0.000), FL5 vs. FL2 (Z = -16.349, p= 0.000), FL4 vs. FL3 (Z = -19.676, p= 0.000) and FL5 vs. FL3 (Z = -14.196, p= 0.000). However, there was no significant difference between FL4 and FL5 despite and overall increase in FL5 vs. FL4 (Z= -0.960, p = 0.337).

Table 6-13: Friedman test for Update rate vs. Flight level group

Flight level group	Rank	Friedman Test Statistics			
		N	Chi-Square	df	Asymp. Sig.
0 - 10000	2.82	1197	323.446	4	.000
10001 - 20000	2.58				
20001 - 30000	2.73				
30001 - 40000	3.39				
40001 - 50000	3.48				

Table 6-14: Median update rate based on flight level groups

		Percentiles		
	N	25th	50th (Median)	75th
FL1	1197	.9500	1.0300	1.1350
FL2	1197	.9300	1.0100	1.1100
FL3	1197	.9300	1.0200	1.3200
FL4	1197	.9700	1.3800	2.0900
FL5	1197	.9800	1.4300	2.2900

Table 6-15: Wilcoxon signed-rank test statistics

	FL2 - FL1	FL3 - FL1	FL4 - FL1	FL5 - FL1	FL3 - FL2	FL4 - FL2	FL5 - FL2	FL4 - FL3	FL5 - FL3	FL5 - FL4
Z	-5.035[a]	-18.877[a]	-39.211[a]	-13.251[a]	-11.821[a]	-30.744[a]	-16.349[a]	-19.676[a]	-14.196[a]	-.960[a]
Asymp. Sig. (2-tailed)	.000	.000	.000	.000	.000	.000	.000	.000	.000	.337

a. Based on negative ranks.

The analysis concludes that the ADS-B update rate is performance is influenced by the aircraft flight level whereby the update rate increases as the flight level increases.

6.3.5.5 Phases of flight

The phase of flight variable is derived based on the aircraft flight level pattern throughout the flight duration as; climbing, cruising and descent.

The Friedman test in Table 6-16 shows that there is an overall statistically significant difference in the ADS-B message update rate for aircraft models A319, A320, A321, B744 and B777-200 based on the phases of flight with $\chi^2(2) = 116.818$, $p = 0.000$; $\chi^2(2) = 194.577$, $p = 0.000$; $\chi^2(2) = 11.875$, $p = 0.003$; $\chi^2(2) = 151.405$, $p = 0.000$ and $\chi^2(2) = 222.213$, $p = 0.000$ respectively. This suggests that the phases of flight (climbing, cruising, and descent) contributes to the ADS-B message update rate performance. Further analysis is undertaken to identify the specific differences between the phases of flight (Figure 6-51) and phases of flight based on aircraft model (Figure 6-52).

Table 6-16: Friedman test for Update rate vs. Phases of flight based on aircraft model

Aircraft model	Rank			Friedman Test Statistics			
	Phases of flight			N	Chi-Square	df	Asymp. Sig.
	Climbing	Cruising	Descent				
A319	2.15	1.87	1.98	3003	116.818	2	.000
A320	2.13	2.13	1.74	1879	194.577	2	.000
A321	2.20	1.86	1.94	190	11.875	2	.003
B744	1.99	2.17	1.84	2599	151.405	2	.000
B777-200	1.89	2.19	1.93	4202	222.213	2	.000

Figure 6-51 indicates that the ADS-B message update rate performance is worst when the aircraft is in the cruising phase while no significant difference is found between the climbing and descent phases. However, further investigation is conducted to identify if all aircraft models included in this study comply with these findings. Figure 6-52 shows that aircraft models A320, B744, and B777-200 comply with the findings. However, aircraft models A319 and A321 show fairly high performance in descent and cruising phases despite lower performance in the climbing phase.

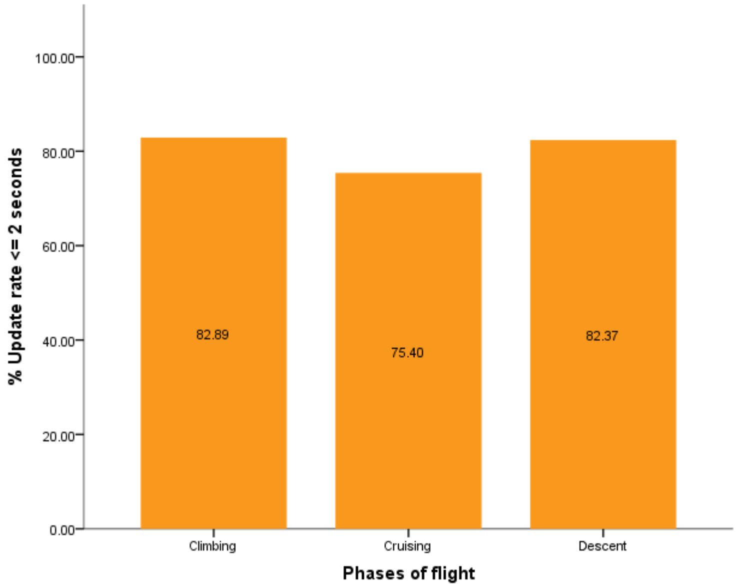


Figure 6-51: Percentage Update rate vs. Phases of flight

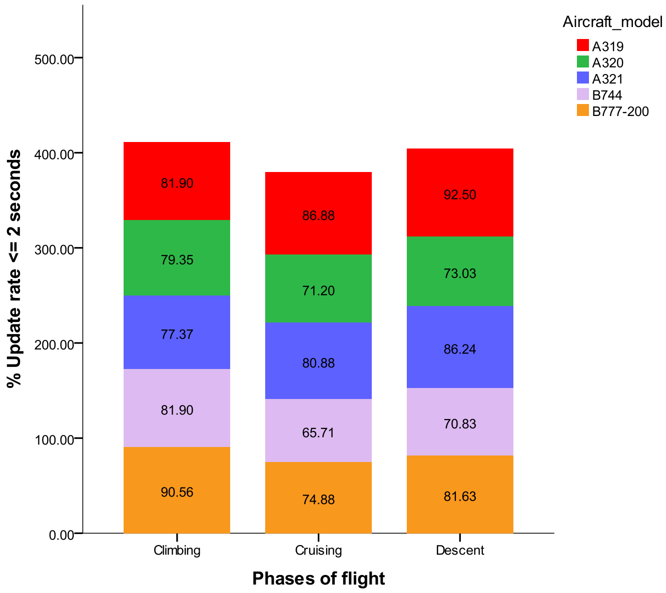


Figure 6-52: Percentage Update rate vs. Phases of flight based on aircraft model

Further investigation is conducted to see if there is any association between the update rate and flight level for each phases of flight (Figure 6-53 to 6-55).

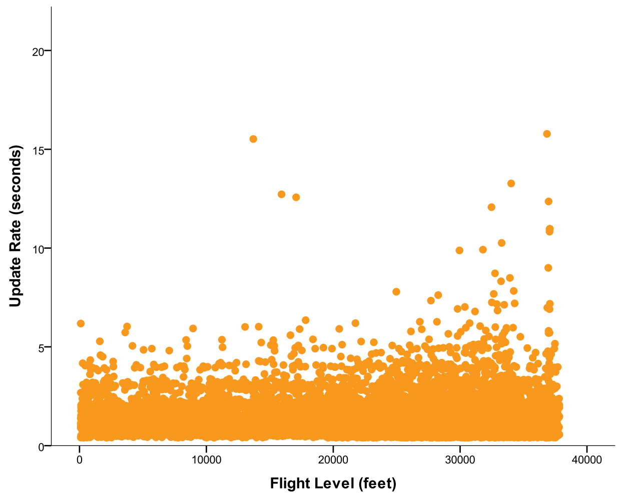


Figure 6-53: Update rate vs. Flight level for Climbing phase

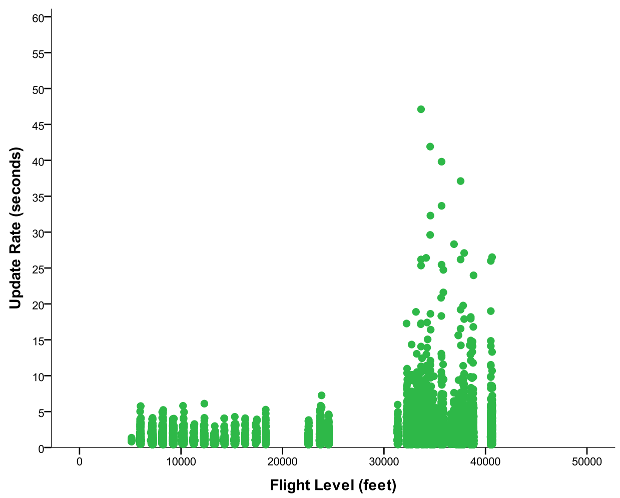


Figure 6-54: Update rate vs. Flight level for Cruising phase

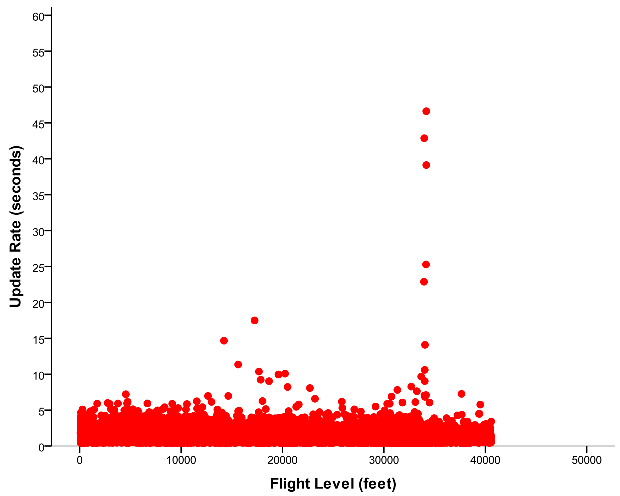


Figure 6-55: Update rate vs. Flight level for Descent phase

Figures 6-53 to 6-55 indicate that there are more data points deviating from the normal towards higher flight levels (specifically 30000 to 40000 feet). This is more obvious in the cruising phase.

In summary, the analysis concludes that the update rate performance is influenced by the phases of flight. It also concludes that the performance is worst during the cruising phase specifically at higher flight levels between 30000 to 40000 feet. The reason for this finding is may be due to the ADS-B Out antenna mounting angle on the aircraft and the range relative to the ground stations.

6.3.5.6 Ground station

The Friedman test in Table 6-17 show that, there is an overall statistically significant difference in the ADS-B message update rate for ADS-B ground stations; Chedburgh, Greenford, Reigate, Ventnor, Winstone and Warlingham with $\chi^2(5) = 181.404$, $p = 0.000$. This suggests that the ground station contributes to the ADS-B message update rate performance.

Table 6-17: Friedman test for Update rate vs. Ground station

Ground Station	Rank	Friedman Test Statistics			
		N	Chi-Square	df	Asymp. Sig.
Chedburgh	3.72	1980	181.404	5	.000
Greenford	3.11				
Reigate	3.29				
Ventnor	3.76				
Winstone	3.53				
Warlingham	3.60				

Further analysis is conducted to identify the differences in station performance by calculating the percentage of ADS-B message update rate within 2 seconds in Figure 6-56. Reigate station shows the best performance while Winstone shows the worst performance, 97.02% and 81.44% of ADS-B message update rate in ≤ 2 seconds respectively.

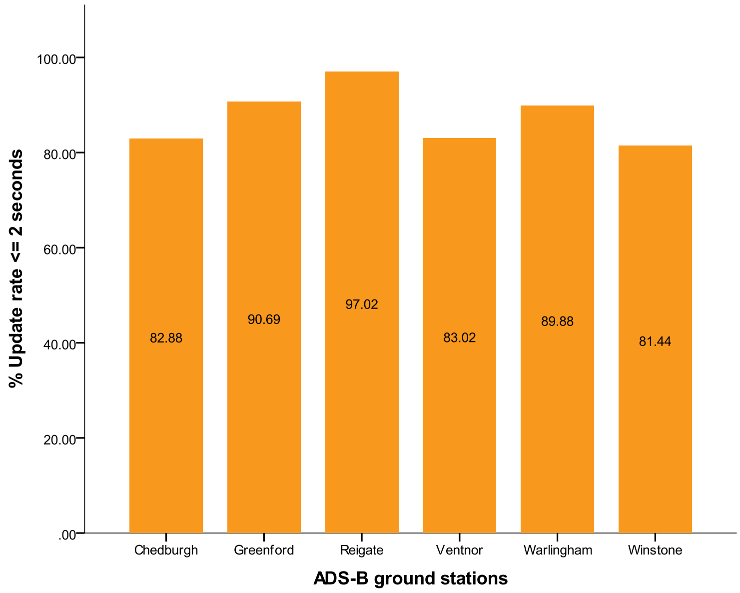


Figure 6-56: Percentage Update rate vs. ADS-B ground stations

An analysis was undertaken to see if there is any relationship between station performance and the phase of flight of the aircraft while transmitting the message to the particular station. In order to statistically prove if the relationship exists, Crosstabulation and the Chi-square test are conducted. The crosstabulation method analyses the relationship between two categorical variables (in this case Station and Phases of flight). The data are tabulated and then the chi-square test is carried out to see if the variables are associated. The chi-square test detects whether there is a significant association between the two categorical variables. However, it does not give any indication on the strength of the association. Table 6-18 shows the crosstabulation between the two variables. Taking a random case and based on Figure 6-56, Reigate station has the best performance. Hence the hypothesis based on the findings in section 6.3.5.5 (whereby the lowest % update rate ≤ 2 seconds is while cruising) should be true if the Reigate station has the lowest count of messages while in the cruising phase. Table 6-18 shows that this is true whereby, 906 messages were sent while climbing, 368 while cruising and 706 while descending. Hence, the lowest count is in the cruising phase.

Table 6-18: Phase of flight * Station Crosstabulation

		Station						
		Chedburgh	Greenford	Reigate	Ventnor	Warlingham	Winstone	Total
Phase	Climbing	1455	890	906	1552	8655	2178	15636
	Cruising	616	2236	368	2615	5612	6919	18366
	Descent	528	7011	706	1146	12629	3309	25329
Total		2599	10137	1980	5313	26896	12406	59331

Table 6-19: Chi-Square Tests

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	10797.321[a]	10	.000
Likelihood Ratio	10621.710	10	.000
N of Valid Cases	59331		

To statistically prove this, the chi-square test in Table 6-19 indicates that the station performance (in terms of ADS-B message update rate) and the phases of flight are associated with $\chi^2(5)$ = 10797.321, p = 0.000. This finding has led to another assumption, that there might be an association between the update rate and aircraft track angle based on phases of flight with reference to the station. In the first step, scatterplots (Figure 6-57 to 6-62) are produced for update rate against aircraft track angle grouped by phases of flight for each station. There seem to be a general trend in the data for all stations whereby, the data are clustered in the lower region of the update rate scale in all phases of flight in spite of the aircraft track angle. There are obvious outliers in the cruising phase for Ventnor, Warlingham and Winstone stations and in the climbing phase for Reigate station in spite of the aircraft track angle. However, Chedburgh and Greenford stations do not show any obvious trend. In general the scatterplots do not show any obvious association between the aircraft track angle and ADS-B message update rate.

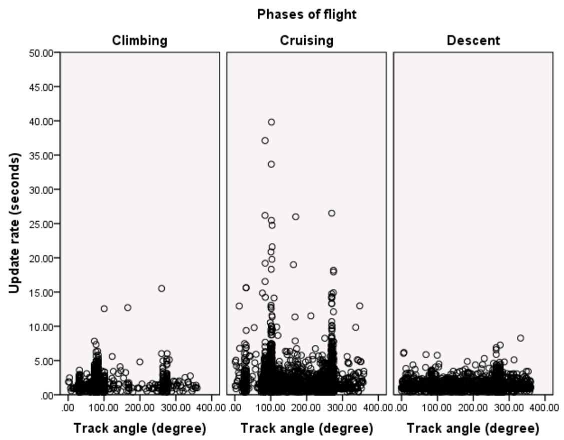


Figure 6-57: Winstone

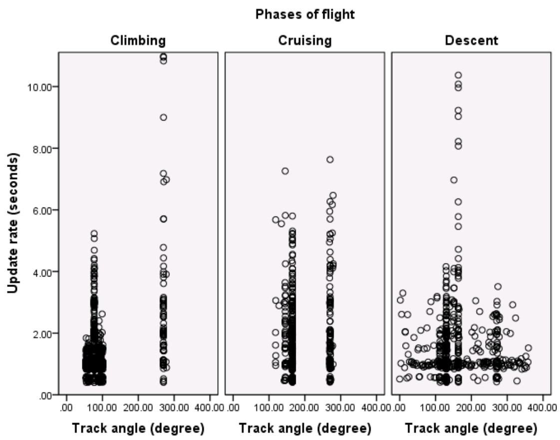


Figure 6-58: Chedburgh

Figure 6-59: Greenford

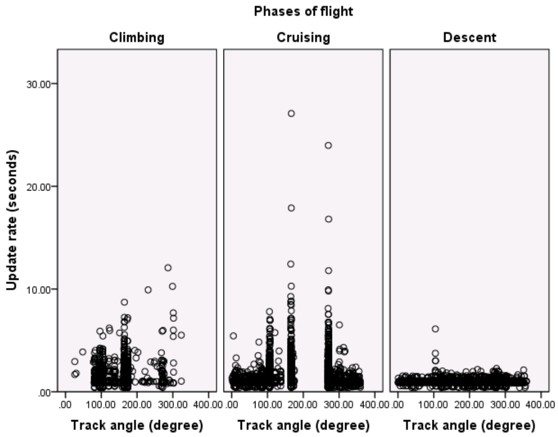


Figure 6-60: Ventnor

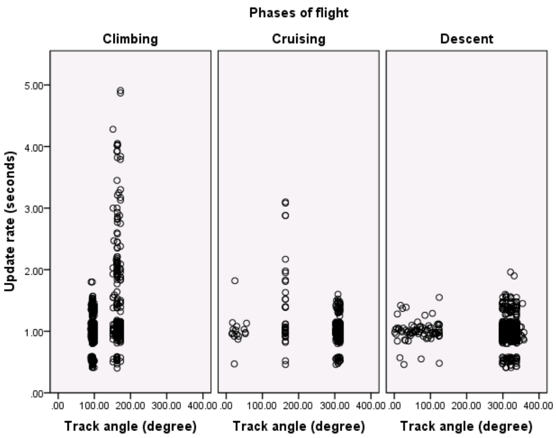


Figure 6-61: Reigate

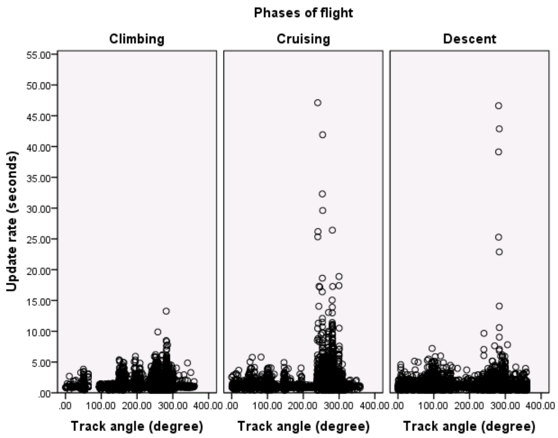


Figure 6-62: Warlingham

In order to statistically verify this observation, correlation analysis using Spearman's Rho test is conducted to see how the aircraft track angle with respect to the stations affects the update rate performance. Table 6-20 presents the results.

Table 6-20: Correlation test between aircraft track angle and update rate based on stations

Station	Correlation Coefficient, r	Asymp. Sig.	Findings
Chedburgh	0.235	.000	Correlation is significant at the 0.05 level
Greenford	0.051	.000	Correlation is significant at the 0.05 level
Reigate	-0.002	.916	Correlation is not significant
Ventnor	-0.064	.000	Correlation is significant at the 0.05 level
Warlingham	0.013	.040	Correlation is significant at the 0.05 level
Winstone	-0.046	.000	Correlation is significant at the 0.01 level

The Spearman's test results in Table 6-20 indicate there is a correlation between update rate and aircraft track angel for all station in spite of the extremely small correlation coefficient, r value, except for Reigate station. The sign of the correlation coefficient indicates that the correlation direction depends on the station location as the aircraft track angles are measured from the north.

Based on the scatterplots (Figure 6-57 to 6-62) and the Spearman's test result (Table 6-20), no concrete conclusions can be made on the association between update rate and aircraft track angle based on phases of flight with reference to each station.

6.3.5.7 Range

Aircraft range between aircraft position (latitude, longitude, altitude) and the position of the station (latitude, longitude, altitude) receiving the ADS-B message, is computed using ellipsoid distance formula. The correlation between aircraft range and ADS-B message update rate is analyzed using Spearman's rho test. The test is conducted for the 31 aircraft manoeuvering in the LTMA airspace, broadcasting ADS-B message to six ground stations within its coverage. The test results are tabulated in Appendix F. The results indicate 30 aircraft show significant correlation between flight level and update rate with positive correlation coefficient, r, significant at 0.01 level, indicating that when the flight level increases, the update rate also increases. However, the correlation was not significant for one aircraft with correlation coefficient, r = 0.056 and significance, p = 0.009. This is the same aircraft identified as an outlier in the Flight level analysis in Section 6.3.5.4.

6.3.5.8 ADS-B Update rate model

The correlation analysis between the potential factors identified and the ADS-B message update rate in sections 6.3.5.1 to 6.3.5.7 indicate that aircraft model, GPS receiver model, transponder model, flight level, phases of flight, ground station, aircraft track angle and aircraft range from the station are associated with the ADS-B message update rate performance. However, the correlation tests neither indicate how these variables are related to the update rate nor the strength of the associations. Therefore, a mathematical model is derived for the ADS-B message update rate to identify the contributing factors to its performance. In the first step, the update rate distribution pattern is analysed. The histogram for update rate in Figure 6-63 shows that the update rate distribution is not normal and projects an exponential form. In addition, the update rate values are greater than zero.

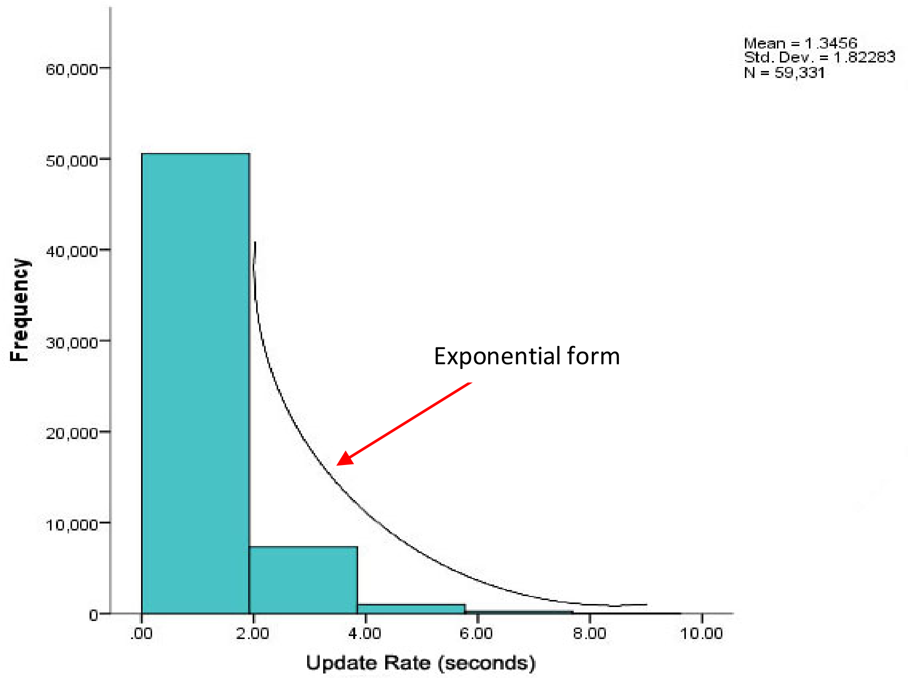


Figure 6-63: Update rate distribution

Due to these characteristics identified, it can be concluded that the update rate function is non-linear. Hence, the gamma probability distribution function is used to derive the model. The choice of the distribution-link function is guided by either a priori theoretical considerations or the combination that best fits based on the visual distribution observation of the dependent variable. The Gamma distribution is chosen because it is appropriate for variables with positive scale values that are skewed toward larger positive values. If a data value is less than or equal to 0 or is missing, then the corresponding case is not used in the analysis. The link function is a transformation of the dependent variable that allows estimation of the model. The Log link function: $f(x) = \log(x)$, is chosen for the model. This link can be used with any distribution.

The derived model's general information is provided in Table 6-21. The gamma probability distribution models the log of the Update Rate (dependent variable /outcome) as a function of the predictor variables (independent variables) which include the phases of flight, aircraft model, ground station, flight level, range between the aircraft and ground station, and aircraft track angle. The GPS receiver and transponder models are not included in the Model to avoid data redundancy. For example, all A319 aircraft are equipped with the Thales TLS755 GPS receiver and Honeywell TRA-67A transponder. Hence, the performance of the A319 also corresponds to the performance of Thales TLS755 GPS receiver and Honeywell TRA-67A transponder. By including aircraft, GPS receiver and transponder models will cause multicollinearity, which occurs when two or more independent variables are highly correlated with each other. This leads to problems in understanding which independent variable contributes to the variance explained in the dependent variable as well as technical issues in calculating the Model.

Table 6-21: Model Information

Dependent Variable	Update Rate
Probability Distribution	Gamma
Link Function	Log

The Omnibus Test in Table 6-22 gives the overall test for the model. The Likelihood Ratio Chi-Square value of 9635.939 with significance value (P-value) less than 0.0005 indicates that the model as a whole fits significantly better than the intercept-only model (i.e. model with no predictor). The probability distribution of the test statistics is approximated by the Chi-Square distribution with (df14) degrees of freedom. Overall, the result in the table indicates that the independent variables reliably predict the dependent variable (Update Rate) with *D (*14) = 9635.939, $p < .0005$ (i.e., the model is a good fit of the data).

Table 6-22: Omnibus Test

Likelihood Ratio Chi-Square	df	Sig.
9635.939	14	.000

The Wald statistic in Table 6-23 is used to ascertain whether a variable is a significant predictor of the outcome (i.e. Update Rate). Each predictor in the model is tested for whether it has any effect. Predictors with significance values less than 0.05 have some discernible effect. The results in Table 6-23 show that all the predictor variables contribute significantly to the prediction of the Update Rate. The effect of each predictor is provided in the Parameter Estimates in Table 6-24.

Table 6-23: Tests of Model Effects

Source	Type I		
	Wald Chi-Square	df	Sig.
(Intercept)	38.275	1	.000
Phase	685.406	2	.000
Aircraft	2071.290	4	.000
Station	251.069	5	.000
FL	1967.487	1	.000
Range	625.758	1	.000
Track Angle	311.034	1	.000

The parameter estimates in Table 6-24 summarize the effect of each predictor. While interpretation of the coefficients (B) in this model is difficult because of the nature of the link function, the signs of the coefficients for covariates (categorical variables) and relative values of the coefficients for factor levels (continuous variables) give important insights into the effects of the predictors in the model.

The significance of each predictor is measured using a Wald statistics, giving 95% Confidence Interval (CI) for the odds ratio (Exp (B)). If the significance value $p < 0.05$, then the coefficients (B) are statistically significantly different from zero. Notice that the Phase has three different values; Climbing, Cruising and Descent. These are interpreted as three independent variables. Each enters the Model with its own coefficient and p-value. The Aircraft have five different values; A319, A320, A321, B744 and B777-200. The Station has six different values; Chedburgh, Greenford, Reigate, Ventnor, Warlingham and Winstone.

The Climbing phase ($p = 0.431$) does not appear to be an important predictor of the Model while there is a significant predictive power for all other predictors with $p > 0.05$. The Model shows that compared to Descent, Cruising has 1.143 times higher odds ratio (95% CI = 1.130 to 1.155) to predict the Update Rate. Compared to the B777-200, A319 has 0.827 times higher odds ratio (95% CI = 0.808 to 0.837), A320 1.071 times higher odds ratio (95% CI = 1.004 to 1.040) and B744 1.051 times higher odds ratio (95% CI = 1.038 to 1.065) to predict the Update Rate.

Compared to the Winstone, Chedburgh has 1.034 times higher odds ratio (95% CI = 1.012 to 1.058), Greenford 1.052 times higher odds ratio (95% CI = 1.034 to 1.070), Reigate 0.908 times higher odds ratio (95% CI = 0.886 to 0.932), Ventnor 0.922 times higher odds ratio (95% CI = 0.906 to 0.939) and Warlingham 1.017 times higher odds ratio (95% CI = 1.000 to 1.034) to predict the Update Rate. For each 100 feet increase in FL, there is an increase in Update Rate of 1.209E-5 seconds. While for each one meter increase in Range, there is an increase in Update Rate of 7.629E-8 seconds. Interestingly, although the p-value for the Track Angle is small, notice that the odds ratio is 1.000 and the coefficient is 0.000. This seemingly contradicting information suggests that the values for the Track Angle are hiding the actual odds ratio in this Model, and hence, assumed irrelevant to the Model.

As a conclusion, the Model in Table 6-24 shows that the aircraft model with its corresponding avionics (GPS and transponder models) significantly impact the ADS-B update rate performance with A320 showing the highest impact, followed by B744, A321 and A319. The differences in the impact may be due to the performance of the aircraft avionics including FMS. The Model also indicates that, only when the aircraft is in the cruising Phase, the ADS-B update rate performance is affected. The possible reason for this may be the due to the ADS-B Out antenna mounting on the aircraft relative to the ground station location. The ground stations significantly impact the ADS-B update rate performance in the following order with the highest impact from Greenford, followed by Chedburgh, Warlingham, Ventnor and Reigate. The reason for the differences in the impact between the stations may be due to message congestions at the stations.

6.3.5.8.1 Model diagnostics

In order to validate the appropriateness of the Generalized Linear Model developed in section 6.3.5.8, residuals are defined and the residual plots and distributions are examined in this section. The difference between the observed value of the dependent variable (y) and the estimated value ($\bar{y}$) is called the residual (e). Each data point has one residual, whereby $e = y - \bar{y}$**.** The sum and the mean of the residual are expected to be equal to zero due to the laws of random errors. That is,

$\Sigma e = 0$ and

$\bar{e} = 0$

A residual plot is a graph that shows the residual on the vertical axis and the independent variable on the horizontal axis. If the points in the residual plot are randomly dispersed around the horizontal axis and centered on zero, than the Model is appropriate for the data. Figure 6-64 plots residuals vs. Flight Level and Figure 6-65 plots residual vs. Track Angle. Both plots show fairly random patterns, indicating that the Model provides a decent fit to the data.

The appropriateness of the Model is also determined based on the residual distribution. If the residuals are normally distributed, then the Model is a good fit for the data. The residual distribution is checked using:

- Normal probability plot of the residuals; and
- Histogram of residuals.

Figure 6-66 shows the normal probability plot of the residuals in a scatter plot diagram with Update Rate (dependant variable) on the y axis and the residuals on the x axis. The figure indicates that the relationship between the Update Rate and the residuals is approximately linear. This indicates that the residuals are normally distributed. The histogram of the residuals in Figure 6-67 also shows that the residuals are normally distributed, further verifying that the Model is a good fit for the data.

Table 6- 24: Parameter Estimates

Parameter	B	Std. Error	95% Wald Confidence Interval		Hypothesis Test			Exp(B)	95% Wald Confidence Interval for Exp(B)	
			Lower	Upper	Wald Chi-Square	df	Sig.		Lower	Upper
(Intercept)	-.071	.0114	-.093	-.048	38.275	1	.000	.932	.911	.953
[Phase=Climbing]	.004	.0055	-.006	.015	.620	1	.431	1.004	.994	1.015
[Phase=Cruising]	.133	.0056	.122	.144	574.514	1	.000	1.143	1.130	1.155
[Phase=Descent]	0[a]	.	.	.	.	.	.	1	.	.
[Aircraft=A319]	-.190	.0058	-.201	-.179	1079.446	1	.000	.827	.818	.837
[Aircraft=A320]	.068	.0073	.054	.083	87.400	1	.000	1.071	1.056	1.086
[Aircraft=A321]	.022	.0089	.004	.039	5.857	1	.016	1.022	1.004	1.040
[Aircraft=B744]	.050	.0066	.037	.063	56.811	1	.000	1.051	1.038	1.065
[Aircraft=B777-200]	0[a]	.	.	.	.	.	.	1	.	.
[Station=Chedburgh]	.034	.0113	.012	.056	8.951	1	.003	1.034	1.012	1.058
[Station=Greenford]	.051	.0088	.034	.068	33.580	1	.000	1.052	1.034	1.070
[Station=Reigate]	-.096	.0130	-.122	-.071	54.762	1	.000	.908	.886	.932
[Station=Ventnor]	-.081	.0093	-.099	-.063	76.085	1	.000	.922	.906	.939
[Station=Warlingham]	.017	.0085	-2.741E-5	.033	3.829	1	.050	1.017	1.000	1.034
[Station=Winstone]	0[a]	.	.	.	.	.	.	1	.	.
FL	1.209E-5	2.7260E-7	1.156E-5	1.263E-5	1967.487	1	.000	1.000	1.000	1.000
Range	7.629E-8	3.0497E-9	7.031E-8	8.227E-8	625.758	1	.000	1.000	1.000	1.000
Track Angle	.000	2.4979E-5	.000	.000	311.034	1	.000	1.000	1.000	1.000
(Scale)	.247[b]	.0014	.245	.250						

Dependent Variable: Update Rate
Model: (Intercept), Phase, Aircraft, Station, FL, Range, Track Angle
a. Set to zero because this parameter is redundant.
b. Maximum likelihood estimate.

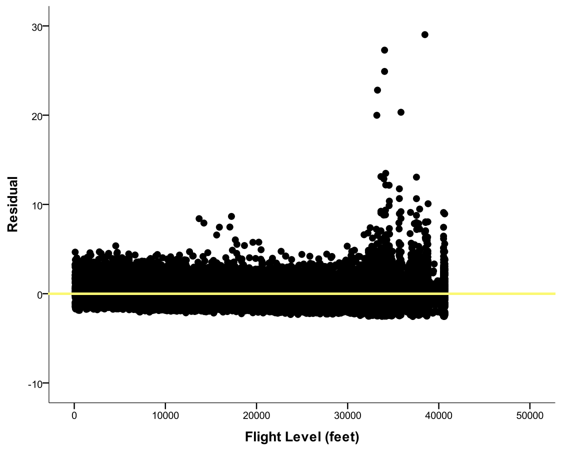


Figure 6-64: Residual vs. Flight Level

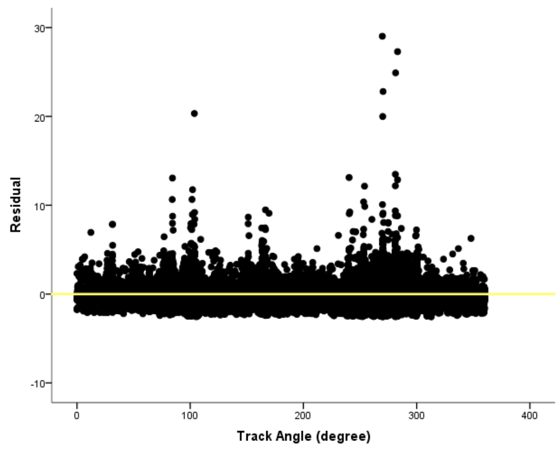


Figure 6-65: Residual vs. Track Angle

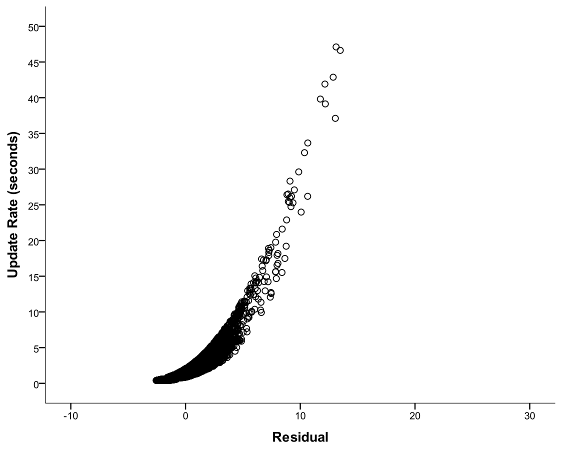


Figure 6-66: Normal Probability Plot

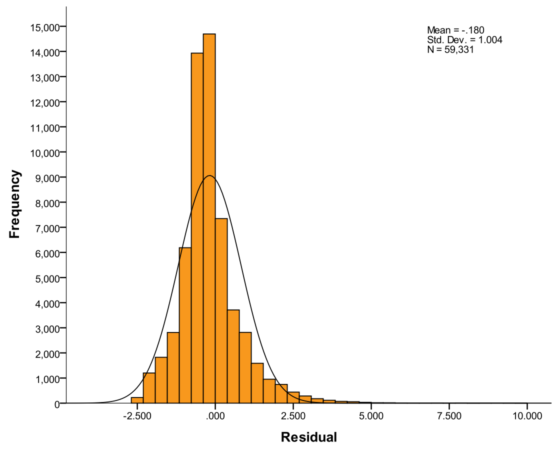


Figure 6-67: Histogram of Residuals

6.4 Summary

The ADS-B data and onboard GPS data (reference) are asynchronous. This has made it more complicated to correlate the datasets to perform data evaluation. The data evaluation framework developed in this Chapter is robust enough to handle this difficulty. The onboard GPS has been used as the reference for the ADS-B system, due to its superior performance. The radar system is not appropriate for this purpose.

The latency budget derived in this Chapter indicates that the propagation delay including the delay encountered in the ground station should not exceed 1001 milliseconds. The latency analysis shows that five aircraft have latency more than 1.5 seconds. In addition, there is no consistency in the latency performance between flights of the same aircraft. An investigation of the impact of altitude change on latency shows that as the altitude decreases, the latency increases. This could be due to the signal jamming anticipated in the lower altitude of dense TMA airspace.

The ADS-B horizontal position accuracy analysis shows that five aircraft are compliant with the 3NM separation requirement (RMS HPE < 150 meters). Two aircraft have RMS HPE > 10000 meters. Further investigation is in progress with British Airways on the performance of these aircraft. In addition, there is no consistency in the RMS HPE between flights. Correlation analysis between HPE and latency indicates that there is no association between the horizontal position accuracy performance and latency. However, there is a significant correlation between horizontal position accuracy performance and the altitude, whereby as the altitude increases, the HPE also increases.

The mean ADS-B horizontal position integrity (NUC) measured for the sample included in this thesis is 5.43, sufficient for the radar and non-radar airspace separation. However, 100% missed detections were identified for three aircraft. Missed detections are critical as the ATC relies on the NUC value to ensure aircraft separation. The identified error is assumed to be due to the decoding process in the ADS-B transmitting subsystem. Therefore, the integrity indicator included in the ADS-B message must be validated at the ground station before it is transmitted to ATC for operational use.

The ADS-B availability analysis indicates 81.78% availability.

The findings from the continuity analysis indicate that, to conduct a continuity analysis, the data have to be recorded for at least 45 minutes to enable the presence of a deterministic pattern to be identified in the data distribution. The analysis shows that there is no consistency in the update rate of ADS-B messages to the ground station. The required update rate between 0.5 to 2 seconds is not met by the aircraft. Therefore, further analysis to identify the factors that contribute to the update rate performance based on various correlation tests and Generalized Linear Model (GLM) show that the aircraft model, GPS model, transponder model, flight level, range from the ground station, ground station and phases of flight, significantly impact the update rate performance.

In summary, this Chapter has presented a comprehensive framework for ADS-B data performance evaluation using a comparison method (with extrapolated GPS horizontal position as the reference). The evaluation was made by analysing recorded data, observing tracks, and measuring accuracy, integrity, latency, availability and update rate. The Chapter also identified various errors in the datasets which limit the performance evaluation. The causes of these errors should be investigated and mitigated before the ADS-B system can be implemented for ATC surveillance and to support enhanced airborne and ground ATC applications. The Chapter provides a method to validate the integrity quality indicator included in the ADS-B message. Finally, the Chapter identifies the factors that contribute to the measured performance and also derives an Update Rate Model. The aircraft used in this analysis are certified to the DO-260 standards. However, the framework proposed in this Chapter is applicable also to the aircraft to be certified in future to the DO-260B standards.

Chapter 7

Fault Based Safety Analysis (FBSA)

In Chapter 6, the performance of ADS-B in terms of accuracy, integrity, availability, latency and continuity was assessed using the Performance Based Safety Assessment Approach (PBSA) proposed in the chapter. The anomalies identified throughout the PBSA process, in the ADS-B and onboard navigation data are used in this Chapter to analyze ADS-B safety.

To quantify system safety, a good understanding of its potential failure modes is vital. ADS-B system failure modes include those from the communication and navigation systems and human and environmental factors, as well as ADS-B specific components. In this Chapter, potential failure modes of the ADS-B system are identified using a systematic approach developed in this Chapter. The approach is customized for the ADS-B system due to its complexity and operational context which includes human and environmental elements. However, the approach is transferable to other ATC surveillance systems. The failures are classified and a mathematical model specified for each class, before analyzing the impact on ATC operations and finally proposing potential mitigations. It is important to note that the work carried out in this Chapter is based on the assumption that the ADS-B operates as the sole surveillance source for the ATC. Finally the Chapter analyses the risks of the failure modes by quantifying the failures using Fault Tree Analysis (FTA). Where relevant, the assumptions and limitations are highlighted.

This Chapter accomplishes the fourth research objective; 'to identity failure modes for ADS-B, develop a failure mode register and failure model and to analyze the risks of the failure modes'.

7.1 Background

Integrity is a crucial parameter to measure system safety. It is defined as the "level of trust that errors will be correctly detected while integrity risk is the probability that an error larger than a given threshold goes undetected for longer than a specified time to alert" (ICAO, 2006b). More specifically, ADS-B position integrity can be defined as the level of trust in the navigation source and the communication system to provide the required input to the ADS-B reported information. The ADS-B positioning data integrity level is represented by the NUC/NIC indicator, derived from the navigation system, included in the ADS-B message. Therefore, the safety of ADS-B depends on the navigation and communication systems.

According to Bhatti and Ochieng (2007), failures can occur from the system components, operational environment and human factors. It is important to note that, for ADS-B, the analysis of failure modes should include failures of the system specific components and also of the integrated architecture that defines the whole system. Prior research has characterised failure modes for ADS-B based applications (Hammer et al., 2007, Walala, 2008), without considering the ADS-B system as a whole. Hammer et al. (2007) provide a method for the analysis of ADS-B based on operational hazard identification and assessment. This method identifies potential hazards and allocates safety requirements to ADS-B ground and airborne functions. However, it is at a relatively high level of detail dealing with systems and applications, and does not address the failure modes of the ADS-B at the component level. Walala (2008) assesses the implementation of ADS-B for ground operations at non-towered airports to prevent runway incursions. The author identifies functional and general component failures that may potentially lead to runway incursions. Walala's (2008) approach focuses on the ADS-B failures that lead to a particular type of incident i.e. runway incursion. Both studies do not address ADS-B failure modes that impact the system performance (particularly integrity and hence safety) for both ground and airborne applications. The various safety cases developed by EUROCONTROL, NATS, FAA and Airservices Australia for the ADS-B system discussed in detail in Chapter 6, are used this Chapter to identify ADS-B failure modes.

This Chapter conducts an exhaustive search for potential failure modes that can affect ADS-B performance using a systematic approach developed in this thesis (described in section 7.2). The approach incorporates the analysis of the impact of the failure modes on ATC operations and aircraft navigation based on the assumption that ADS-B operates as the sole surveillance source. Finally the identified failure modes are classified and a mathematical model specified for each. The Chapter then identifies potential risks/hazards as a result of the failures followed by quantification of the risks using Fault Tree Analysis (FTA).

7.2 ADS-B Failure Mode Identification Approach

A failure mode is a description of a state that disables the performance of a required function due to certain event (Rausand and Høyland, 2004). Due to the complexity and safety critical nature of the ADS-B system, a systematic approach is developed in this thesis to identify its failure modes. The approach focuses on identifying possible failures in the system specific components and its interaction and integration with external systems (e.g. navigation and communication) and external elements such as human (controllers and pilots) and environmental factors. The human element is identified as one of the failure modes, as failures induced by a pilot's action (or inactions) may result in the loss of ADS-B service to controllers. Such failures are analyzed based on the impact of the human actions on the overall system performance. The existence of elements with unpredictable nature such as the human increases the complexity of the system in addition to its highly integrated nature.

The failure identification process is illustrated in Figure 7-1, and consists of the following tasks:

- identify all failure modes of the ADS-B system;
- identify failure mode effects on the ADS-B system;
- determine consequences of the failure effect on the overall ATC surveillance operations;
- determine failure hazards to ATC operations and aircraft navigation;
- categorize failure modes; and
- propose a mitigation approach for each failure mode.

The input to the processes is obtained from:

- an extensive literature review on each ADS-B specific components and the integrated navigation and communication system components;
- a review of safety reports on ADS-B trials from various Air Navigation Service Providers (ANSPs) worldwide including EUROCONTROL, FAA and Air Services Australia;
- analysis of ADS-B reports gathered from ADS-B ground stations and corresponding positioning data from onboard navigation system (GPS) for 57 aircraft through collaboration with NATS CRISTAL Project and British Airways;
- Subject Matter Experts (with more than five years of experience on ADS-B system design and trial implementation) from EUROCONTROL, QinetiQ, Airbus and NATS via structured interviews; and
- an understanding of the overall system architecture and functionalities.

The sub-next section describes in detail the processes, inputs used and outputs.

7.2.1. ADS-B Failure Mode Identification Process

In the first step, various technical documents of the ADS-B system requirements and system descriptions are reviewed to gain a comprehensive understanding of the system architecture, functions and operations.

In the second step, a high level system architecture diagram (Figure 7-2), the ADS-B OUT functional block diagram (Figure 7-3) and ADS-B IN functional block diagram (Figure 7-4) are developed based on inputs from the literature and experts from Airbus, NATS and British Airways. The system architecture in Figure 7-2 is divided into five levels: Level-0 is the GNSS subsystem; Level-1 is the ADS-B avionics, known as the on-board ADS-B OUT subsystem; Level-2 is the ADS-B IN specific subsystem; Level-3 is the ADS-OUT ground station subsystem and Level-4 the controller working positions on the ground. Figure 7-3 illustrates the detailed components of the ADS-B OUT functional block composed of the Message Generation Function which obtains its input from external systems: onboard navigation system, barometric altimeter, pilot interface and Flight Management System (FMS), and then encodes and assembles the message; and the Transmit Message Exchange Function which broadcasts the ADS-B message to the users (other ADS-B equipped aircraft and to ATC on the ground). Figure 7-4 illustrates the detailed components of the ADS-B IN functional block composed of the Receive Message Exchange Function, which receives the encoded message from the Transmit Message Exchange Function (Figure 3); and the Report Assembly Function which decodes and feeds the ADS-B message to client applications: FMS, Traffic Collision Avoidance System (TCAS), Airborne Separation Assistance System (ASAS) and Cockpit Display of Traffic Information (CDTI) for aircraft navigation aid.

In the third step, ADS-B failure modes are identified from safety reports generated by ANSPs following ADS-B trial implementations, literature review of the system components and ADS-B data performance analysis (Chapter 6). The failures identified from the ADS-B data and the corresponding onboard navigation system data are discussed and provided in the next sub-section. The scope of the analysis in this thesis is from Level-0 to Level-3 as shown in Figure 2. Most of the failure modes in Level-0 (GNSS) included in this thesis are adopted from existing research (Bhatti and Ochieng, 2007, Ochieng and Sauer, 2003, The Royal Academy of Engineering, 2011). Failures also result from interfaces between the components, human errors and environmental effects. The failure modes identified are provided in Tables 7-1 to 7-5.

In the fourth step, the effects of each failure mode on the ADS-B system performance are analyzed based on safety reports and understanding of the system component interactions and functionalities. In the fifth step, the consequence of the failure mode effects on ATC surveillance operations and aircraft navigation are analyzed by referring to the Required Surveillance Performance (RSP) and understanding the required surveillance function and level of performance for ATC operations. In the sixth step, specific hazards to ATC operations are determined based on the findings in step five.

In the seventh step, the characteristics of each failure mode are described and categorized based on the failure model: step error, ramp error, random noise, oscillation, or bias error by understanding the nature of the failure modes. In the eighth step, a mitigation for each failure mode identified is derived / proposed based on the understanding of the ADS-B system design and ATC surveillance system requirements.

In the last step, the list of identified failure modes is reviewed in an iterative manner to revise and update the failure mode register. The failure mode register is a living document that can be updated as more failures are discovered in the future.

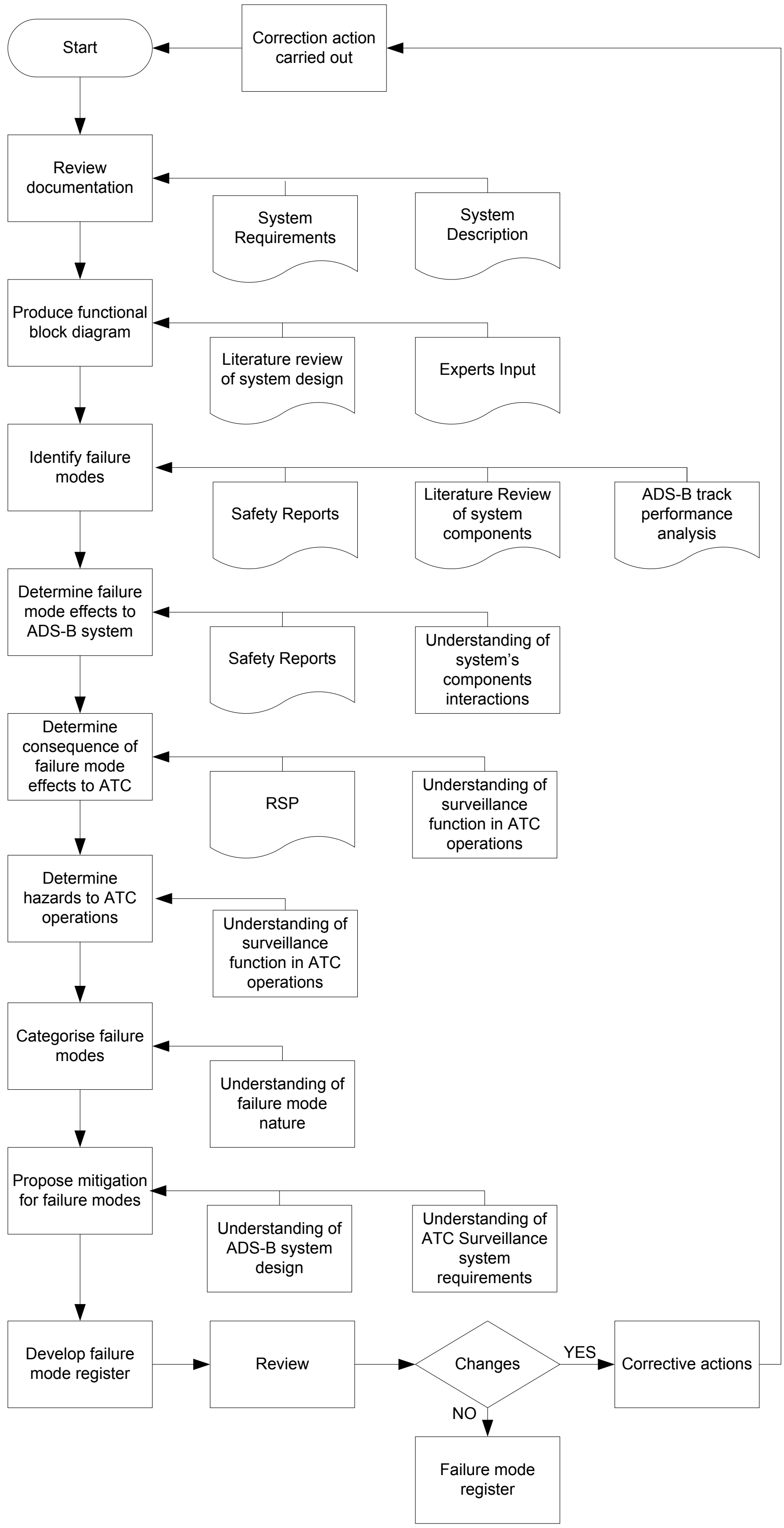


Figure 7-1: ADS-B failure mode identification process

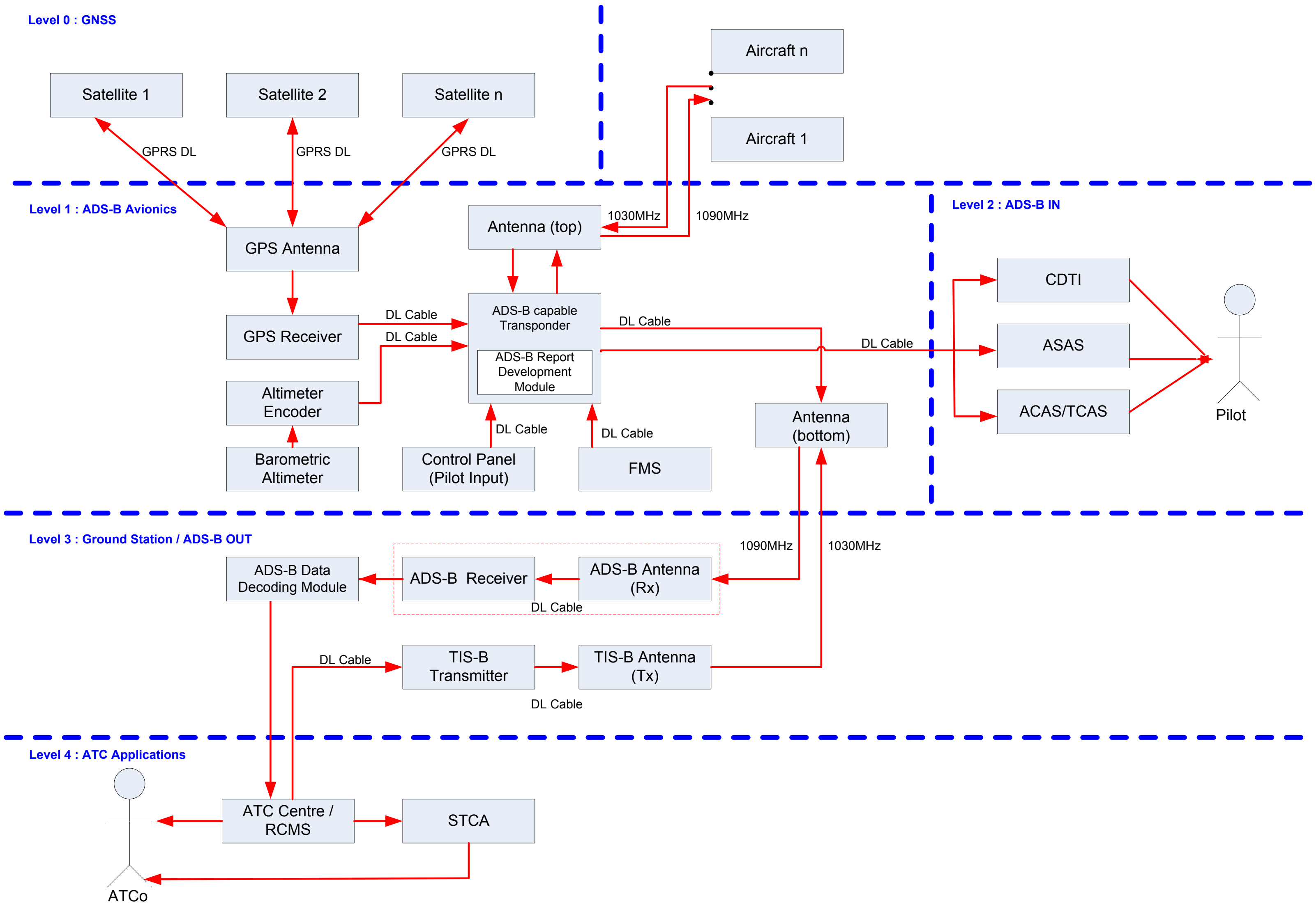


Figure 7-2: ADS-B High Level System Architecture

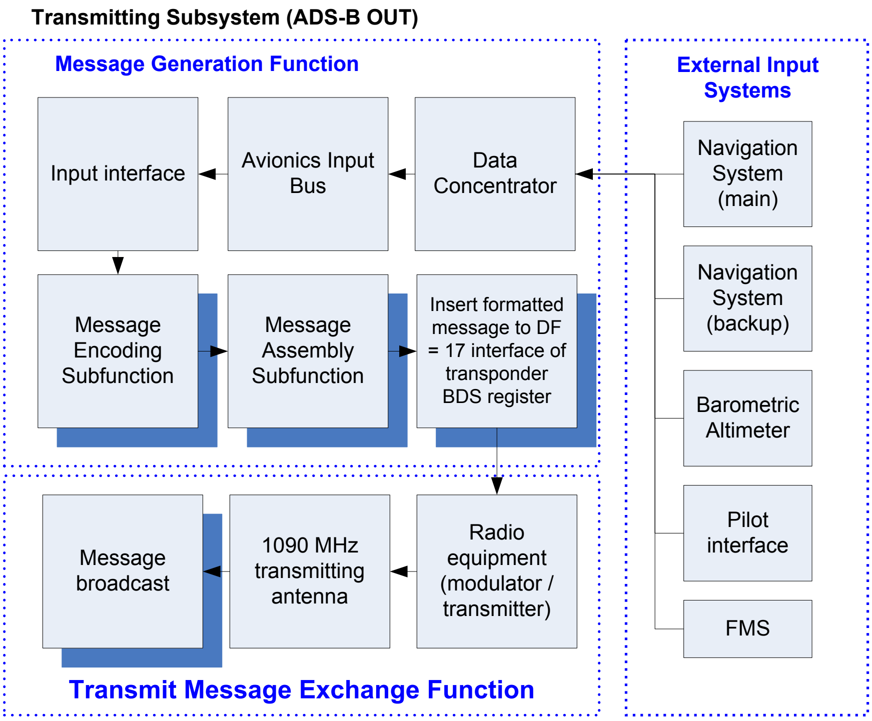


Figure 7-3: ADS-B OUT Functional Block Diagram

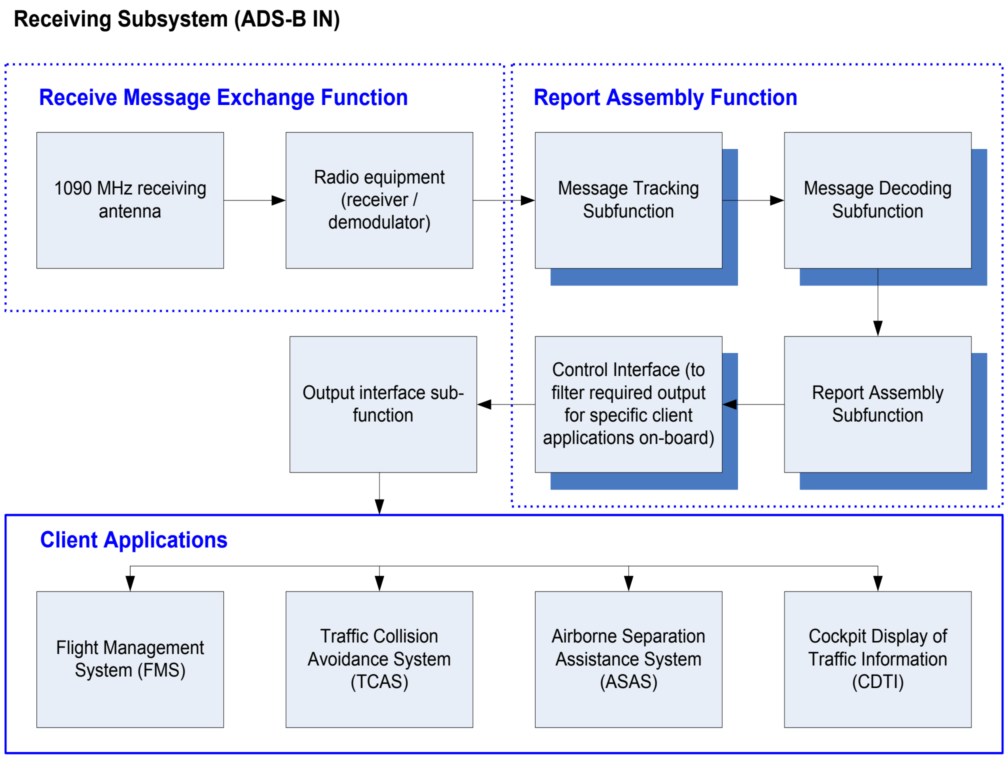


Figure 7-4: ADS-B IN Functional Block Diagram

** Shaded boxes indicate software modules*

7.2.2 Anomalies identified from ADS-B and corresponding onboard navigation system (GPS) data analysis

ADS-B data from the ground station and the corresponding onboard navigation system (GPS) data were collected from opportunity traffic in LTMA for 57 ADS-B equipped aircraft. Various errors were identified in the datasets, some of which were found to be common to the same aircraft type. The common errors identified are summarized according to the aircraft type as follows:

a) GPS Clock Error

- For A319, A320 and A321 aircraft, after the 59th second, the minute did not increase by one, e.g. the epoch after 10:48:59 was 10:48:00, instead of 10:49:00.
- The GPS position update rate was consistent at one second. However, for aircraft B777-200 and B744, duplicate and missing time information without any deterministic pattern were found in the GPS time data.

b) GPS Data Error

- For B744 aircraft, GPS latitude and longitude were provided every four seconds.
- For B767-300, GPS latitude and longitude values were given individually every two seconds.

c) GPS Position Jumps

Latitude and longitude position jumps were found in the GPS data for all B777-200 aircraft. The height of the spikes was approximately 0.1 degrees for both latitude and longitude for all the aircraft. However, the latitude jump was consistent at every 50, 100 or 200 seconds while that for the longitude was random. All of the aircraft used the Honeywell GNSSU GPS receiver. Further investigations on the corresponding ADS-B data show that the position jumps found in the GPS data were discarded by either the ADS-B emitter onboard aircraft or ADS-B ground station. Figures 7-5 to 7-12 illustrate the GPS latitude and longitude position jump and the corresponding ADS-B horizontal position data for four B777-200 aircraft. According to Airservices Australia (2009), for Australian ADS-B ground stations, if the ground station detects unreasonable position jumps in the ADS-B position data, the FOM/NUC value (position integrity quality indicator) for the corresponding position transmitted to ATC is forced to zero (so that the position is not used by the ATC system). However, this was not the case identified in this thesis for the NATS's ADS-B ground stations in the LTMA, in which the whole string of the data was found to be missing from the ADS-B message. The cause for this anomaly is still being investigated with the help of British Airways for the particular aircraft. The position jumps can result from avionics faults and sometimes for unknown reasons at the edge of coverage (NATS, 2002).

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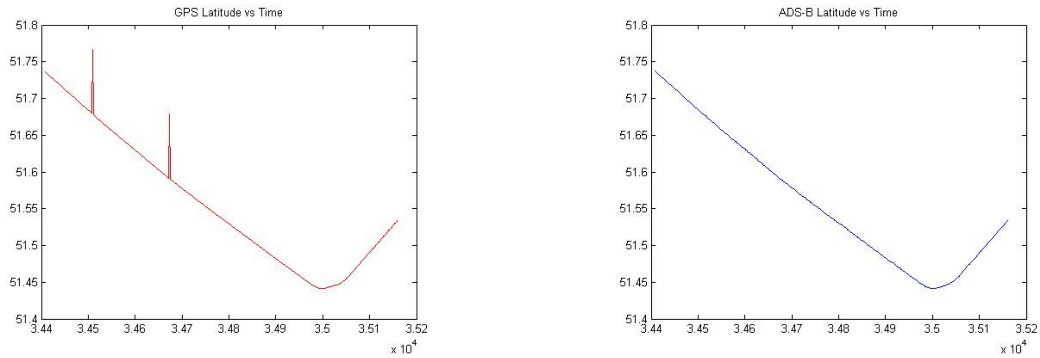

Figure 7-5: GPS latitude indicating position jumps and the corresponding ADS-B latitude

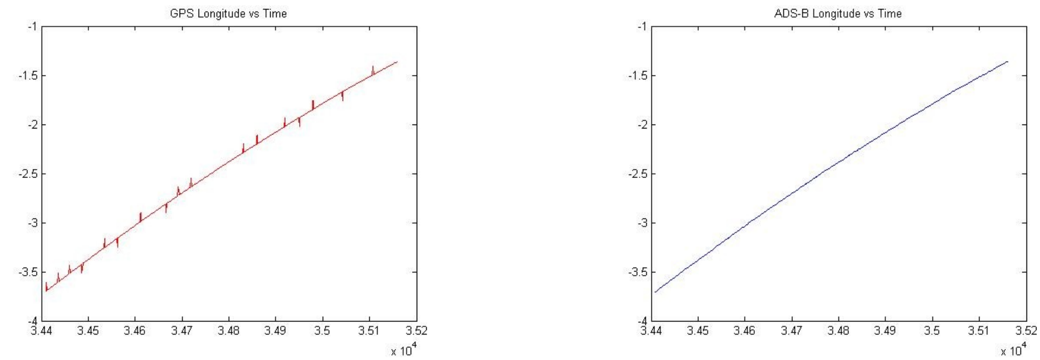

Figure 7-6: GPS longitude indicating position jumps and the corresponding ADS-B longitude

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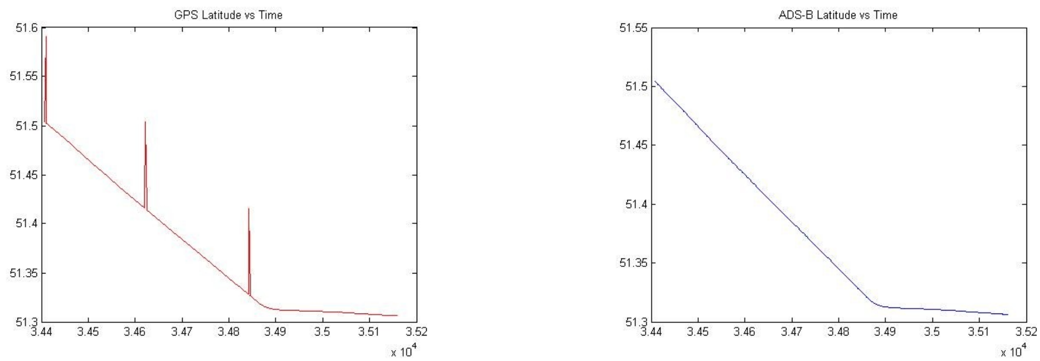

Figure 7-7: GPS latitude indicating position jumps and the corresponding ADS-B latitude

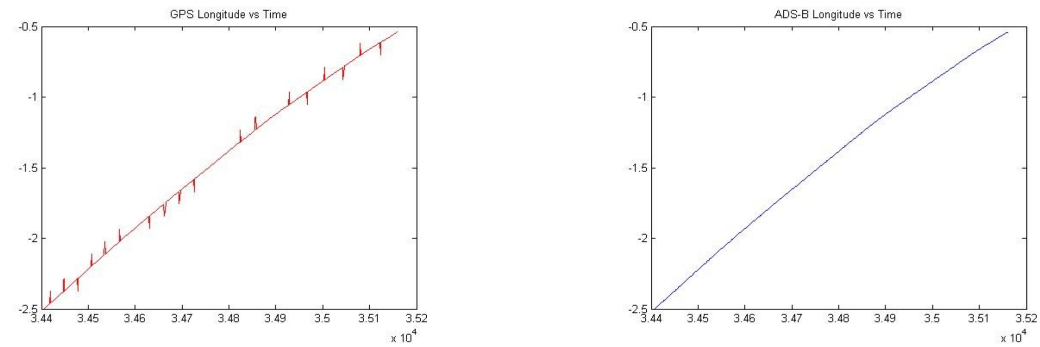

Figure 7-8: GPS longitude indicating position jumps and the corresponding ADS-B longitude

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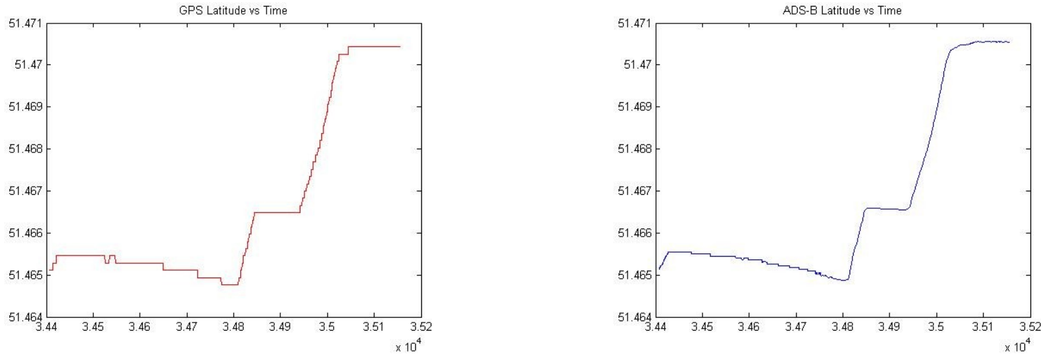

Figure 7-9: GPS latitude indicating position jumps and the corresponding ADS-B latitude

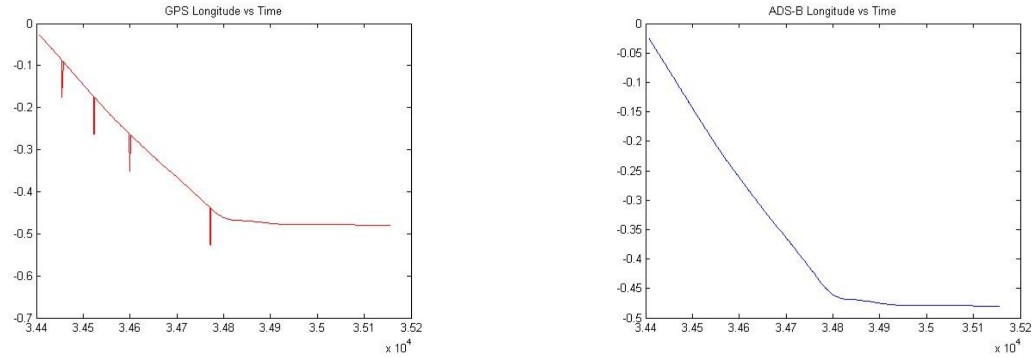

Figure 7-10: GPS longitude indicating position jumps and the corresponding ADS-B longitude

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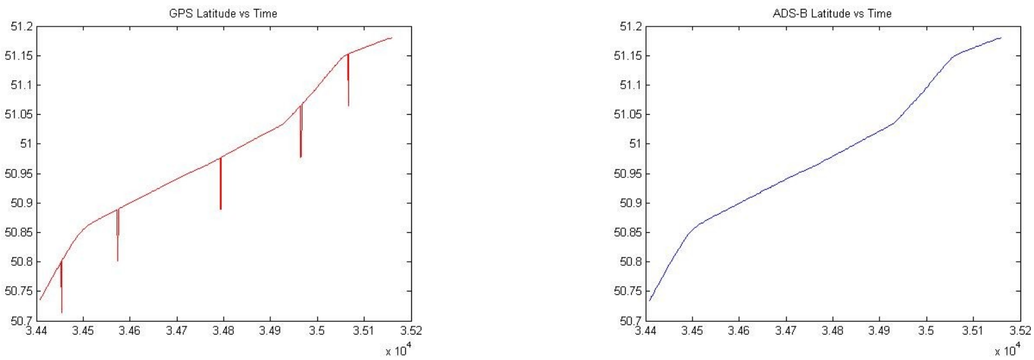


Figure 7-11: GPS latitude indicating position jumps and the corresponding ADS-B latitude

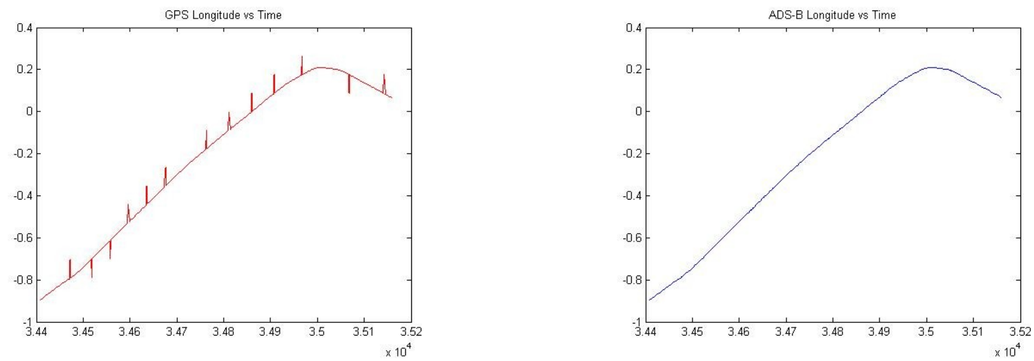


Figure 7-12: GPS longitude indicating position jumps and the corresponding ADS-B longitude

The general errors identified in the datasets are:

a) ***Missing flight level information in the ADS-B message***

In the first set of ADS-B data (Appendix A) collected, three aircraft (two A319 and one B777-200) had no flight level (barometric altitude) information. Instead, only the geometric altitude information was available. However, in the second dataset (Appendix G), none of the 31 aircraft had flight level information. Based on this, it could be concluded that the missing flight level information in the three aircraft in the first dataset could be a fault in either the barometric altimeters or FMS transmission. On the other hand, the unavailability of flight level information in the second dataset could be a problem in the data collection process.

b) ***Duplicate ADS-B messages***

Duplicate ADS-B messages for random aircraft were found. Further investigation showed that the aircraft was detected by more than one ground station within its coverage at the same time. However, the central processing unit for the ground station did not remove the duplicate messages.

c) ***Obvious outliers in the ADS-B message update rate***

An extensive ADS-B update rate analysis was conducted in Chapter 6. The analysis showed that on average, approximately 15% of ADS-B messages were updated in more than two seconds. The factors that influence the outliers were also identified in Chapter 6. The update rate distribution indicating the outliers for 30 aircraft are given in Appendix D.

d) ***ADS-B position jumps***

No position jumps were identified in the ADS-B datasets analyzed due to the jumps being discarded. An analysis by Airservices Australia (2007, 2012) reported jumps in longitude (ADS-B position data) as aircraft cross a transition latitude. The error was justified due to the use of early Compact Position Reporting (CPR) encoding algorithm (Sensis Corporation, 2009). The CPR is used to encode the ADS-B position (latitude and longitude) to reduce the bits to be broadcast. Figure 7-13 illustrates the jump. The FAA also reported on ADS-B position jumps in their early implementation experiences and justified the cause as being a position encoding issue (Federal Aviation Administration, 2011b). Furthermore, Airservices Australia identified backward jumps with some aircraft. The jump was of the order of 0.6 NM in the direction of the aircraft's track. This was attributed to a fault in the extrapolation process of the position between updates from the position source. Airservices Australia has implemented a mechanism called "Reasonableness Test" to detect sudden jumps in position to deal with this problem (Airservices Australia, 2007). However, the mechanism neither identifies the cause nor provides a mitigation. In this thesis, the investigation on the position jumps were conducted one step ahead by analyzing the corresponding position source. It was found that, all the position jumps identified in this thesis are from the onboard navigation system (GPS) that feeds the position information to the ADS-B system.

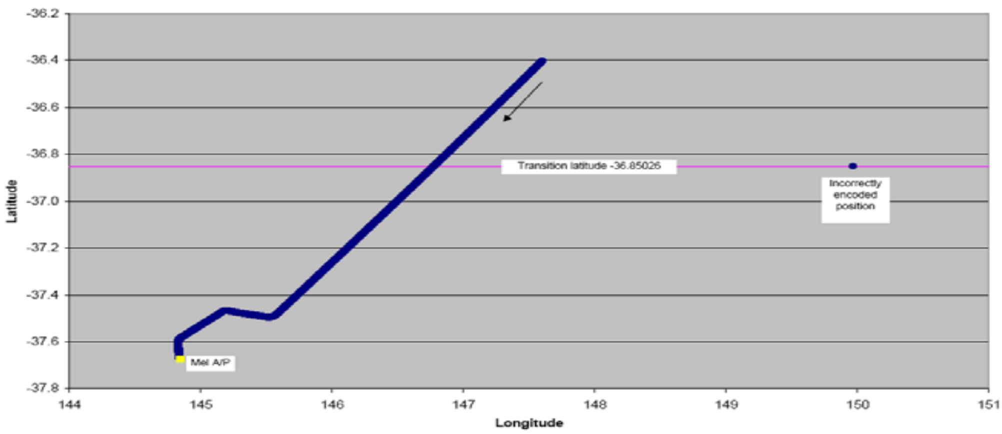


Figure 7- 13: Longitude jump at transition latitude (Airservices Australia, 2007)

e) Position Integrity Indicator Error

Based on the ADS-B position integrity analysis conducted in Chapter 6, it was found that the position integrity indicator, FOM/NUC value, was incorrectly provided for the position of three aircraft; A318, A319 and A320, all using Honeywell TRA-67A transponder. However, the cause of the error is unknown due to several other aircraft using the same transponder and performing well. An analysis by the FAA also identified a similar error without further details on the aircraft type or avionics (Federal Aviation Administration, 2011b). In this thesis (in chapter 6) a mechanism is proposed to be implemented at the ADS-B ground station to detect and isolate the positions with such error. This is crucial for ATC safety.

The detailed error analyses for each of the 57 aircraft are provided in Appendix A and Appendix G.

Table 7-1: ADS-B OUT avionics failure modes

ID	Cause	Characteristics	Impact / Remark	Mitigation	User Detection
AOA1	Deterioration of aircraft equipment accuracy performance	Loss of positional accuracy of reported position. This failure is difficult to detect due to equipment aging and may contribute a small constant error.	Possible error in the displayed position of the aircraft therefore could lead to a breakdown in separation. This will affect particular aircraft.	ADS-B position accuracy quality indicator (NAC) will alert the controller of the hazard. Routine aircraft avionics maintenance and testing is required.	No
AOA2	Fault in GPS receiver unit	Corrupted position data sent to ADS-B emitter. This failure can propagate over a long period due to lack of calibration / maintenance.	Possible error in the displayed position of the aircraft could lead to a breakdown in separation. This will affect particular aircraft.	Provision of redundant GPS receiver as a back-up, in the case of single receiver failure.	No
AOA3	Failure of GPS Time system	Failure of GPS time input to ADS-B track processor will cause loss of time synchronisation unexpectedly without notification.	Could lead to incorrect intent data without the controller being aware. This will affect all aircraft.	Intent data verification mechanism needs to be implemented.	No
AOA4	ADS-B OUT antenna deterioration	Incorrect data broadcast. This failure is difficult to detect due to equipment aging and may contribute a small constant error.	Error in the reported data without controller awareness could lead to a breakdown in separation. This will only affect particular aircraft.	ADS-B data integrity validation mechanism required at the ADS-B ground station / onboard receiving equipment. Flight plan can be utilized to conduct the verification in the ground and TCAS data for onboard verification.	No
AOA5	Incorrect data broadcast due to data corruption during transmission	Significant random error in the displayed aircraft position.	Could lead to a breakdown in separation without controller awareness. This will affect all aircraft in the region.	ADS-B data integrity validation mechanism required at the ADS-B ground station / onboard receiving equipment.	No
AOA6	Intentional or unintentional RF interference	Signal interruption and noise may cause data distortion.	Error in the reported position without controller / pilot awareness could lead to a breakdown in separation. This affects all aircraft in the region.	ADS-B data integrity validation mechanism required at the ADS-B ground station / onboard receiving equipment.	No
AOA7	Fault in ADS-B emitter/ transponder	Significant error in the displayed position of the aircraft. This failure can propagate over a long period due to lack of calibration /	Could lead to a breakdown in separation without controller awareness. This affects particular aircraft.	ADS-B data integrity validation mechanism required at the ADS-B ground station / onboard receiving equipment.	No

ID	Cause	Characteristics	Impact / Remark	Mitigation	User Detection
		maintenance.			
AOA8	Error in Figure of Merit (FOM) transmitted by ADS-B emitter	ADS-B data with incorrect integrity level will be broadcast to ATC or other aircrafts. This failure can last for a long period if undetected.	Could lead to a breakdown in separation without controller awareness. This affects particular aircraft.	ADS-B data integrity validation mechanism required at the ADS-B ground station / onboard receiving equipment.	No
AOA9	Failure of altitude sensing	Corrupted altitude data transmitted to ADS-B emitter. This failure can propagate over a long period due to lack of calibration / maintenance.	Could lead to a breakdown in separation without controller awareness. This affects particular aircraft.	Altitude quality indicator will alert the controller of the hazard. Routine aircraft avionics maintenance required.	No
AOA10	Altitude encoder malfunction	Incorrect altitude data transmitted to ADS-B emitter. The system attitude instability may introduce significant random error to the altitude data.	Could lead to a breakdown in separation without controller awareness. This affects particular aircraft.	Altitude quality indicator will alert the controller of the hazard. Routine aircraft avionics maintenance and testing is required.	No
AOA11	Altimetry System Error	-Blocked static port - Damage to port and pitot tube -Pressure leaks in pitot/static pipes -Air Data computer out of tolerance -Poor paint finish static port sensitive areas. This failure can propagate over a long period due to lack of calibration / maintenance.	Incorrect altitude data transmitted to ADS-B emitter. This affects particular aircraft.	Altitude quality indicator will alert the controller of the hazard. Routine aircraft avionics maintenance and testing is required.	No
AOA12	Stuck bit in altitude encoder	Incorrect altitude data transmitted to ADS-B emitter due to stuck bit in altitude encoder. This failure leads to unexpected error without notification.	Could lead to a breakdown in separation without controller awareness. This only affects particular aircraft.	Altitude quality indicator will alert the controller of the hazard. Routine aircraft avionics maintenance and testing is required.	No
AOA13	Error in the data encoding process in the ADS-B emitter	Incorrect data broadcast by the ADS-B emitter due to data corruption. The error is difficult to detect.	Could lead to a breakdown in separation without controller awareness. This only affects particular aircraft.	ADS-B software module testing and debugging to identify and resolve bug causing data error.	No

ID	Cause	Characteristics	Impact / Remark	Mitigation	User Detection
AOA14	Jamming of GPS transmission from the satellite due to deliberate or non-deliberate actions	Loss of ADS-B position data to ADS-B emitter. Emitter will stop squitting ADS-B data. This may impact all aircraft within the region. The failure is abrupt without notification.	Loss of situational awareness. Increase in workload due to requirement to transition back to procedural control	Provision of backup navigation system onboard -e.g. Inertial Navigation System (INS)	Yes
AOA15	Loss of geometry from the satellite	Possible loss of ADS-B service. The failure is abrupt without notification.	Loss of situational awareness. Increase in workload due to transitioning back to procedural control and reassessment of traffic. This will affect particular aircraft.	Provision of backup navigation system onboard -e.g. Inertial Navigation System (INS)	Yes
AOA16	Satellite Failure - Predicted (NANU)	Possible loss of ADS-B service. The failure is abrupt.	ADS-B tracks will not be displayed on the ATC console therefore will cause an increase in workload due to the requirement to transition back to procedural control. This will affect all aircraft in the region.	Provision of backup navigation system onboard -e.g. Inertial Navigation System (INS)	Yes
AOA17	Satellite Failure - Unpredicted-Yes	Possible loss of ADS-B service. The failure is abrupt without notification.	Loss of situational awareness. Increase in workload due to transitioning back to procedural control and reassessment of traffic. This will affect all aircraft in the region.	Provision of backup navigation system onboard -e.g. Inertial Navigation System (INS)	Yes
AOA18	Satellite Failure - Unpredicted-No	Possible loss of ADS-B service. The failure is abrupt.	Loss of situational awareness. Increase in workload due to transitioning back to procedural control and reassessment of traffic. This will affect all aircraft in the region.	Common Failure mode -no mitigation	Yes
AOA19	Satellite Failure - Unpredicted-Undeclared	Possible loss of ADS-B service. The failure is abrupt without notification.	Loss of situational awareness. Increase in workload due to transitioning back to procedural control and reassessment of traffic. This will affect all aircraft.	Common Failure mode -no mitigation	Yes

ID	Cause	Characteristics	Impact / Remark	Mitigation	User Detection
AOA20	GPS receiver malfunction	No position data sent to ADS-B emitter. The failure is abrupt without notification.	Loss of situational awareness. Increase in workload due to transitioning back to procedural control and reassessment of traffic. This will affect particular aircraft.	Provision of backup navigation system onboard -e.g. Inertial Navigation System (INS) or redundant GNSS receiver	Yes
AOA21	SBAS inaccuracy	Reduced accuracy position sent to ADS-B emitter. This failure can propagate over a long period due to lack of calibration / maintenance.	Possible error in the displayed position of the aircraft could lead to a breakdown in separation. This will affect all aircraft in the region.	ADS-B emitter will reject corrupted position data based on position accuracy indicator (HFOM) from GNSS	Yes
AOA22	SBAS failure	Reduced accuracy & integrity position sent to ADS-B emitter. The error is difficult to detect.	Possible error in the displayed position of the aircraft could lead to a breakdown in separation. This will affect all aircraft in the region.	GNSS receiver autonomous integrity monitoring (RAIM) with fault detection and exclusion (FDE) is required for all IFR aircraft.	Yes
AOA23	Failure to detect aircraft in manoeuvring	Sudden delayed aircraft position updates without any notification.	If the position error between updates is larger than the separation standard, this could lead to a breakdown in separation. This will affect particular aircraft.	Need to check and verify GPS antenna sensitivity	Yes
AOA24	GPS antenna failure causing the transponder to stop squitting when data is not refreshed every 2 seconds.	Loss of ADS-B position data affecting the controller. The error slope is large enough to be detected.	Loss of situational awareness. Increase in workload due to transitioning back to procedural control and reassessment of traffic. This will affect particular aircraft.	Provision of backup navigation system onboard -e.g. Inertial Navigation System (INS)	Yes
AOA25	ADS-B OUT antenna malfunction	Loss of ADS-B data affecting controller .The error slope is large enough to be detected.	Loss of situational awareness. Increase in workload due to transitioning back to procedural control and reassessment of traffic. This will affect particular aircraft.	Enable antenna sharing with TCAS antenna as a backup	Yes
AOA26	RF jamming of ADS-B transmissions due to deliberate or	Sudden loss of ADS-B data to controller without notification.	Loss of situational awareness. Increase in workload due to requirement to transition back to procedural control. This affects all aircraft within the	This is a security concern that needs to be addressed before fully implementing the system.	Yes

ID	Cause	Characteristics	Impact / Remark	Mitigation	User Detection
	non-deliberate actions		specific airspace.		
AOA27	Failure of ADS-B transponder /emitter on the aircraft	Loss of ADS-B data affecting controller. The error slope is large enough to be detected.	Loss of situational awareness. Increase in controller workload due to requirement to revert back to procedural control. This affects particular aircraft.	Provision of redundant ADS-B transponder or emitter	Yes
AOA28	Altimeter malfunction	No altitude data transmitted to ADS-B emitter. The failure is abrupt without notification.	No altitude transmitted. ATC should fall back to procedural control. This affects particular aircraft.	Geometric height from GPS can be used as backup information.	Yes
AOA29	Failure of connection between navigation source and Mode-S ES transponder/UAT box	Loss of ADS-B positional data to ADS-B emitter. Emitter will stop squitting ADS-B data. The failure is abrupt without notification.	Loss of situational awareness. Increase in workload due to transitioning back to procedural control and reassessment of traffic. This only affects particular aircraft.	Routine aircraft avionics maintenance and testing is required.	Yes

Table 7-2: ADS-B OUT ground station failure modes

ID	Cause	Characteristics	Impact / Remark	Mitigation	User Detection
AOG1	Fault in the ADS-B receiver at the ground station.	Incorrect data displayed to controller due to corruption of data by the ground station. The errors last over a long period.	Could lead to a breakdown in separation without controller awareness. This may affect all aircraft tracked by the station.	Routine ADS-B ground station maintenance and testing is required.	No
AOG2	Unstable sensitivity of the ground sensor.	Tracks dropping in and out of coverage in the control area. The error portrays the system instability.	Loss of situational awareness. Increase in workload due to transitioning back to procedural control and reassessment of traffic. This may affect all aircraft.	Routine antenna maintenance and calibration are required.	Yes
AOG3	Failure of ADS-B ground station power supply.	Unexpected loss of ADS-B data affecting the controller.	Loss of situational awareness. Increase in workload due to transitioning back to procedural control and	Provision of backup Uninterrupted Power Supply (UPS).	Yes

ID	Cause	Characteristics	Impact / Remark	Mitigation	User Detection
			reassessment of traffic		
AOG4	Failure of data links between ADS-B ground stations and Controller Working Position (CWP).	Sudden loss of ADS-B data affecting the controller.	Loss of situational awareness. Increase in workload due to transitioning back to procedural control and reassessment of traffic.	Provision of redundant data link of different nature, for example fibre optic or lease line.	Yes
AOG5	Error in the ground station data links.	Incorrect data displayed to controller due to corruption of data by the instable attitude of ground station data links.	Could lead to a breakdown in separation without controller awareness. This may affect all aircraft.	Routine data link testing and maintenance required.	No
AOG6	Error in the data decoding process (report assembly module) at the ground station.	Position of aircraft may be incorrect when the range exceeds a certain distance due to the decoding process.	Could lead to a breakdown in separation without controller awareness. This may affect all aircraft.	ADS-B software module testing and debugging to identify and resolve bug causing data error.	No

Table 7-3: ADS-B IN failure modes

ID	Cause	Characteristics	Impact / Remark	Mitigation	User Detection
AI1	ADS-B IN (receiving) antenna deterioration.	Position of aircraft may be in incorrect. The error is a small constant and difficult to detect.	False situational awareness and error in the navigational aids provided by the ADS-B IN application.	Routine maintenance and calibration is required.	No
AI2	Error in the ADS-B report assembly module.	Position of aircraft may be incorrect due to the error in the assembly process. The error may last over long period.	False situational awareness and error in the navigational aids provided by the ADS-B IN application.	ADS-B software module testing and debugging to identify and resolve bug causing data error.	No
AI3	Connection failure between ADS-B receiver box and the application systems (e.g. CDTI, ASAS).	No aircraft track will be displayed to the pilot. This will affect particular aircraft. The error is abrupt without notification.	Reduced situational awareness affecting pilot.	Routine aircraft avionics maintenance and testing is required.	Yes

ID	Cause	Characteristics	Impact / Remark	Mitigation	User Detection
AI4	CDTI display failure.	System hang due to insufficient memory to accommodate incoming data. The failure is of sudden nature.	Reduced situational awareness affecting pilot.	Restart system. Increase system memory capacity.	Yes
AI5	Inadequate pilot knowledge / experience about the system functionalities, HMI, new procedures (e.g. CDTI, ASAS).	Ineffective use of the ADS-B IN application systems. The failure is associated with human error.	Can lead to undesirable events.	Provide comprehensive training to flight crew.	Yes
AI6	ADS-B IN (receiving) antenna malfunction.	Sudden loss of ADS-B data to ADS-B IN application.	Reduced situational awareness.	Routine aircraft avionics maintenance and testing is required.	Yes
AI7	Failure of ADS-B receiver on the aircraft	Sudden loss of ADS-B data affecting ADS-B IN application.	Reduced situational awareness.	Provision of redundant ADS-B receiver on-board.	Yes

Table 7-4: Human error

ID	Cause	Characteristics	Impact / Remark	Mitigation	User Detection
H1	Transponder on wrong mode - Pilot	No data broadcast from aircraft. The failure will remain until the pilot notices or informed by the ATC.	Loss of situational awareness. Increase in workload due to transitioning back to procedural control and reassessment of traffic	Provision of reminder on aircraft navigation document by co-pilot	No
H2	Altitude incorrect and not checked	Different altitude displayed in the cockpit and on the ATC screen whenever the aircraft initially enters either ADS-B or radar airspace. The failure will remain until the pilot notices or informed by the ATC.	If separate pressure settings are used for the ADS-B and SSR transponders, the aircraft altitude source depends on type of surveillance being used	Standardise aircraft avionics and procedures	No
H3	Wrong pressure adjust value given by ATC	Pilot will key in wrong pressure adjust on the altimeter before take-off. The failure will remain until the	Loss of track of the actual aircraft flight level. May lead to collision either in the air or on the ground.	The error can be mitigated if the pilot repeats the value to the controller and with experience the	No

ID	Cause	Characteristics	Impact / Remark	Mitigation	User Detection
		aircraft enters another transition altitude.		controller may realize the mistake.	
H4	Error in altimeter setting by pilot	Pilot keys in wrong pressure adjust on the altimeter before take-off. The failure will remain until the pilot notices or informed by the ATC.	Loss of track of the actual aircraft flight level. May lead to collision either in the air or on the ground.	Re-checking the altimeter setting should be a practise for the cockpit crew.	No
H5	Mishear the pressure adjust value from ATC during radio-communication	Pilot keys in wrong pressure adjust on the altimeter before take-off. The failure will remain until the aircraft enters another transition altitude.	Loss of track of the actual aircraft flight level. May lead to collision either in the air or on the ground.	The error can be mitigated if the pilot repeats the value to the controller.	No
H6	Inadequate knowledge about the ADS-B system functionalities, HMI and new procedures (Pilot and Controllers)	Introduces a hazard to the operations. The same failure may be repeated on every flight until the knowledge is upgraded via attending courses or on job training. Hence the nature of the failure will not increase or reduce over time.	Increases the probability of loss of separation	Provision of training on the new systems	Yes
H7	Incorrect Callsign in FMS –input by Pilot	Incorrect coupling with Flight Plan. The failure will remain until notified by ATC.	May lead to incorrect data broadcast by ADS-B emitter	Provision of reminder on aircraft navigation document / by co-pilot	Yes
H8	Incorrect 24 bit in Flight Plan-input by ATC	Label will be attached to the wrong aircraft. The failure will remain until notified by pilot.	Incorrect coupling will increase the controller workload	Counter check flight plan data by controller	Yes
H9	Coupling and decoupling parameters	Coupling and decoupling occur differently from radar and may confuse controllers. The failure will remain until the knowledge is upgraded on the new system graphical user interface (GUI).	There is a difference in coupling requirements between ADS-B and radar	Training on ADS-B system functionality and display features	Yes
H10	Mixed operating environment-ADS-B and Radar tracks	The system will introduce an additional track (ADS-B) to the current environment which will introduce a risk that the controller	Potential for incorrect separation standard applied to the Flight Plan track	ADS-B mandate and training on ADS-B system functionality and display features	Yes

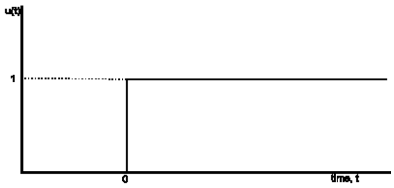
ID	Cause	Characteristics	Impact / Remark	Mitigation	User Detection
		may inadvertently apply radar or ADS-B separation standard to the Flight Plan track. The failure will remain until the knowledge is upgraded on the new system graphical user interface (GUI).			
H11	Confusion affecting controller due to different altitude source display (barometric and geometric levels)	Possibility of controllers confusing barometric and geometric levels on display. The failure will remain until the knowledge is upgraded on the new system graphical user interface (GUI).	Geometric level is displayed if the aircraft is at or below the transition altitude AND either barometric level is not or the aircraft is not in a QNH defined area	ADS-B mandate and training on ADS-B system functionality and display features	Yes
H12	Track couples to wrong Flight Plan	An aircraft's ADS-B track may couple to the wrong flight plan. The failure will remain until noticed by ATC.	Could be a result of an aircraft substitution that is not followed by cancellation and re-issue of flight plan	Counter check flight plan data by controller	Yes

Table 7-5: Environmental effects

ID	Cause	Characteristics	Impact / Remark	Mitigation	User Detection
E1	Deterioration of ground outdoor and aircraft external equipment	Corrupted ADS-B data transmitted to controllers or other ADS-B equipped aircraft. The error may propagate over a long period.	Possible error in the displayed data of the aircraft could lead to a loss of separation or navigation	Routine maintenance and calibration is required.	No

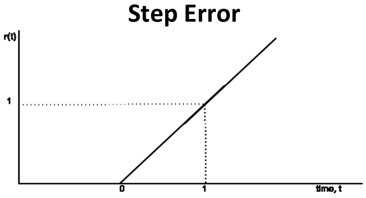
7.2.3 Failure models

To assess the system integrity performance, the failure modes are modeled mathematically. The first step in the modeling process is to analyze the error type based on the failure mode characteristics in the third column of Tables 7-1 to 7-5. The second step is to group the failure modes based on the error nature; the error groups are then mapped to their corresponding mathematical function. Table 7-6 summarizes the failure mode classification based on the error type and corresponding failure model. The error type classification is adopted from Bhatti and Ochieng (2007) on the classification of GPS and INS failure modes. This classification approach is adopted for the work in this thesis, for two main reasons: the characteristics of ADS-B system failure modes are found to be similar to the GPS failure modes; and the GPS system feeds the ADS-B system with the aircraft positioning information; and hence contributes to the ADS-B failures. Based on the failure mode analysis, five types of errors were identified: step, ramp, random noise, oscillation and bias. A description of each error type including nature of the occurrence and possible causes are given below:



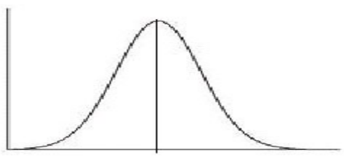
Step Error

This type of error includes an abrupt change without notification, when there is a sudden failure associated with an indicator, a sudden jump in the signal, unavailability of the data link connection and human errors.



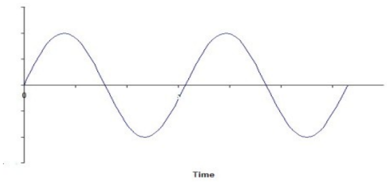
Ramp Error

This type of error is the most difficult to detect when the slope is small (Bhatti and Ochieng, 2007).This category covers aging of equipment, motion and low availability of signal. The error increases with time.



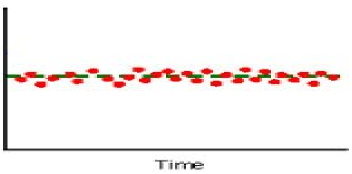
Random Noise

This error is a random fluctuation in an electrical signal. It may be caused by external interruptions such as interference, multipath, signal jamming, and system attitude instability.



Oscillation Error

In navigation equation , oscillatory behaviour results from the modelling of the Earth's dynamics, reaction effect of initial conditions and calibration errors (Bhatti and Ochieng, 2007). The error propagates over a long period of time.



Bias Error

Bias is a small constant error, less than the threshold. Therefore it cannot be detected unless simultaneous multiple failures occur. Ageing of equipment can contribute to this type of failure (Bhatti and Ochieng, 2007).

Table 7-6: Failure mode classification, groups and models

Error Type	Related Codes	Failure Model
Step Error	AOA14, AOA3, AOA16, AOA17, AOA18, AOA19, AOA20, AOA23, AOA12, AOA26, AOA28, AOA29, AOG3, AOG4, AI3, AI4, AI5,AI6, AI7, H1-H12	$f(t)=A\,\mu(t-t_0)$ where A is the magnitude of the fault, $\mu(t)$ is the unit step function and t_0 is the onset time of the failure.
Ramp Error	AOA15, AOA22, AOA24, AOA25, AOA27, AOA13,	$f(t)=R(t-t_0)\,\mu(t-t_0)$ where R is the slope of the fault, $\mu(t)$ is the unit step function and t_0 is the onset time of the failure.
Random Noise	AOA5, AOA6, AOA10, AOG2, AOG5, AOG6,	$f(t)=A_k\,\mu(t-t_0)$ where $A_k \sim \begin{cases} N(0, \Sigma_k) & k<t_0 \\ N(\eta(k, t_o), \Sigma_k) & k \geq t_0 \end{cases}$ where $N(m,V)$ describes a Gaussian distribution with mean m, η is the mean value of the fault, V the variance, $\mu(t)$ is the unit step function and t_0 is the onset time of the failure.
Oscillation	AOA2, AOA21, AOA7, AOA8, AOA9, AOA11, AOG1,AOG2, AI2	$f(t)=A\sin(t-\vartheta)\,\mu(t-t_0)$ A is the magnitude of the fault, ϑ is the phase difference, $\mu(t)$ is the unit step function and t_0 is the onset time of the failure.
Bias	AOA1, AOA4, AI1, E1	$f(t)=B\,\mu(t-t_0)$ where B is the magnitude of the fault, $\mu(t)$ is the unit step function and t_0 is the onset time of the failure.

7.3 Fault Tree Analysis (FTA)

Fault tree analysis (FTA) is a well standardized and documented technique (Henley and Kumamoto, 1981). A fault tree is a logic diagram that displays the interrelationships between a potential hazard (top event) in a system and the reasons for this event. The reasons may be environmental conditions, human errors, normal events (events which are expected to occur during the life span of the system) and specific component failures. A properly constructed fault tree provides a good illustration of the various combinations of failures and other events which can lead to a specified hazard.

FTA may be qualitative, quantitative or both, depending on the objectives of the analysis. Possible results from the analysis may be:

- A listing of the possible combinations of environmental factors, human errors, normal events and component failures that can result in a critical event in the system (minimal cut sets); and
- The probability that the critical event will occur during a specified time interval (risk measure).

In this thesis, both qualitative and quantitative FTA analysis methods are used. In the first part of the analysis (qualitative analysis), cut sets for the potential hazards are identified. In the second part, quantitative evaluation of fault tree is carried out using reliability data of each basic event that leads to the potential hazard. The FTA is conducted with the assumption that the ADS-B system is operates as the sole surveillance system to support ATC operations. The FTA conducted in this Chapter aims to:

- identify the combination of basic events (minimal cut sets) that leads to the potential hazards of the ADS-B system;
- measure the risk of the potential hazards of the ADS-B system; and
- identify the events that contribute the most to the occurrence of the hazards (importance/sensitivity analysis).

It is important to note that, input from Original Equipment Manufacturers (OEM) of subsystem components of ADS-B, on the subsystem component performance (reliability data) is vital in the FTA process. This is the most difficult part of the FTA quantification process, as most of the information were not easily obtained. Without this reliability data, it is not possible to conduct the risk measurement of the potential hazards. As described in Chapter 5, the ADS-B system is composed of navigation, communication and ADS-B specific components. In addition, the system includes human and environmental components that contribute to the system performance. Reliability data for the components in each of the external system is obtained from the literature and OEM.

7.3.1 Fault Tree Construction

The fault trees in this thesis are developed using RiskSpectrum PSA version 1.0 (Scandpower, 2008) developed by Scandpower. RiskSpectrum PSA is an advanced fault tree and event tree software tool used widely to conduct Probabilistic Safety Assessment (PSA) for half of the world's nuclear power plants (Scandpower, 2008).

Based on the output from the Failure Mode Identification approach conducted in section 7.2, six potential hazards of the ADS-B system are identified and defined as follows:

- ***Corruption of data for all aircraft***
  Incorrect ADS-B surveillance data (including position data) broadcast to ATC on the ground or to other ADS-B equipped aircraft within a specified range by all ADS-B equipped aircraft in the airspace.
- ***Corruption of data for one aircraft***
  Incorrect ADS-B surveillance data (including position data) broadcast to ATC on the ground or to other ADS-B equipped aircraft within a specified range by one ADS-B equipped aircraft in the airspace.
- ***Corruption of position data for one aircraft***
  Incorrect position data transmitted (in the ADS-B message) to ATC on the ground or to other ADS-B equipped aircraft by one ADS-B equipped aircraft in the airspace.
- ***Loss of data for all aircraft***
  Unavailability of ADS-B surveillance data (including position data) broadcast to ATC on the ground or to other ADS-B equipped aircraft within a specified range by all ADS-B equipped aircraft in the airspace.
- ***Loss of data for one aircraft***
  Unavailability of ADS-B surveillance data (including position data) broadcast to ATC on the ground or to other ADS-B equipped aircraft within a specified range by one ADS-B equipped aircraft in the airspace.
- ***Failure of 'ADS-B In'***
  Loss of ADS-B data from other ADS-B equipped aircraft within a specified range which results in the failure of airborne applications that use the data.

A fault tree for each of the six potential system hazards (top event) is constructed based on the connection between the hazard (top event) and the failure modes (basic events) identified in section 7.2. The basic events can be interpreted as the reason for the occurrence of the top event. The connection between the top event and basic events are illustrated using logic gates (Henley and Kumamoto, 1981). Tables 7-7 and 7-8 show and describe the basic symbols of the events and gates respectively, used in the construction of the fault trees in this thesis.

Table 7-7: Event Symbols

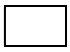
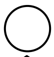
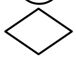
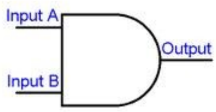
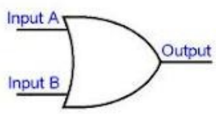
Event Symbol		Description
	Fault event	Input / output event of a logic gate
	Basic event	Basic inherent failure of a system
	Undeveloped event	Failure event that is not developed further

Table 7-8: Symbols for fundamental logic gates

Logic Gate	Description
 AND Gate	Output event will exist if both input events coexist.
 OR Gate	Output event will exist if one or more of the input events exist.

Before constructing the fault trees, a detailed understanding of the ADS-B In and ADS-B Out system architecture and functionalities was gained from the literature and subject matter experts from NATS and British Airways (Section 7.2.1 and Chapter 3).

Figures 7-14 to 7-19 illustrate the fault trees constructed for the potential hazards for the ADS-B system. The fault tree in Figure 7-14 for 'Corruption of ADS-B data for all aircraft' mainly includes the degradation and reduced integrity of ADS-B ground and airborne equipment, while that for 'Corruption of ADS-B data for one aircraft' in Figure 7-15 includes only degradation and reduced integrity of airborne equipments of a particular aircraft. The fault tree for 'Corruption of position data for one aircraft' 7-16 is constructed with the failure modes of degradation and reduced integrity of the onboard navigation system which feeds the aircraft position information to the ADS-B transponder. The ground equipment are categorized as a common failure mode which impacts all aircraft. The fault tree in Figure 7-17 for 'Loss of ADS-B data from all aircraft' includes failure of ADS-B ground equipments, failure of ground datalink between the ground stations and the controller working positions (CWP) and failure of airborne ADS-B system due to common failure modes such as satellite failure, Mode-S datalink failure and signal jamming within the airspace. Fault tree for 'Loss of ADS-B data from one aircraft' in Figure 7-18, is constructed based on human errors (by pilot) and failure of onboard ADS-B equipments. Finally the fault tree for 'Failure of ADS-B In' in Figure 7-19 includes the failure of ADS-B In applications and failure of ADS-B Out service from other aircraft. The next section identifies minimal cut sets for each of the fault trees.

7.3.2 Minimal Cut Sets (MCS) Identification

A cut set in a fault tree is a set of basic events whose simultaneous occurrence causes the occurrence of the top event. A cut set is said to be minimal if the set cannot be reduced without losing its status as a cut set (Vatn, 2001). The cut set derivation depends on the logic gates applied to construct the fault tree; an AND gate increases the size of the cut set while an OR gate increases the number of cut sets. For small and simple fault trees, it is easy to identify the minimal cut sets (MCS) by inspection without any formal algorithm. However, for large and complex fault trees an efficient algorithm is needed. The MOCUS algorithm (Method for obtaining cut sets) is described in standard FTA textbooks, and an efficient improvement of the algorithm is described by Vatn (1992). Table 7-9 provides the minimal cut sets identified for each of the fault tree developed for the potential hazards of the ADS-B system in this thesis, using the MOCUS algorithm.

Table 7-9: Minimal Cut Sets (MCS)

Fault Tree	Minimal Cut Sets
Corruption of data for all aircraft *(Figure 7-13)*	{CAA-6}, {CAA-7}, {CAA-8}, {CAA-9}, {CAA-10}, {CAA-11}, {CAA-14}, {CAA-15}, {CAA-16}, {CAA-17}, {CAA-18}, {CAA-19}
Corruption of data for one aircraft *(Figure 7-14)*	{COA-5}, {COA-6}, {COA-7}, {COA-8}, {COA-10}, {COA-11}, {COA-12}, {COA-13}
Corruption of position data for one aircraft *(Figure 7-15)*	{COAP-5}, {COAP-7}, {COAP-8}, {COAP-9}, {COAP-10, COAP-11, COAP-12}
Loss of data from all aircraft *(Figure 7-16)*	{LAA-2}, {LAA-4}, {LAA-5}, {LAA-7}, {LAA-8}, {LAA-9}, {LAA-10}, {LAA-11}
Loss of data from one aircraft *(Figure 7-17)*	{LOA-4}, {LOA-5}, {LOA-6}, {LOA-7}, {LOA-8, LOA-9}, {LOA-10}, {LOA-12}, {LOA-13}, {LOA-14}, {LOA-15}, {LOA-16}
Failure of 'ADS-B In' *(Figure 7-18)*	{LOA-0}, {FOAI-2}, {FOAI-4}, {FOAI-5}, {FOAI-6}, {FOAI-8}, {FOAI-9}

In reliability and safety analysis, it is crucial to know which failure modes must occur to create a hazard. Therefore, the concept of MCS clearly defines these failure modes. The next section measures the probability of occurrence (risk) of the potential hazards (top events) of the ADS-B system using Probabilistic Safety Assessment (PSA).

7.3.3 Risk measurement of the potential hazards of ADS-B system

The probabilistic safety assessment (PSA) using FTA uses various reliability models for the basic events that lead to the top event. Examples of the basic event reliability models are:

a) Repairable

This model applies for components in operation. Failure of a component is detected immediately and can be repaired. The component is unavailable during repair time. A typical failure mode here is spurious stop.

- Required parameters: Failure rate, Mean time to repair (MTTR)
- Optional parameters: Fixed probability

b) Tested

This is a standard model for components in stand-by. Failure of a component is detected only during component test. The component is unavailable during repair time. A typical failure mode here is failure to start.

- Required parameters: Failure rate, Test interval
- Optional parameters: Fixed probability, MTTR, Time to first test (TF)

c) Probability

This is a general model. Failure probability for the component does not depend on the time the component is in operation. Typically used for passive components or human errors.

- Required parameter: Fixed probability

d) Mission time

A component must work during a fixed time period and is non-repairable during this time. A typical failure mode here is spurious stop.

- Required parameters: Failure rate, Mission rate
- Optional parameters: Fixed probability

e) Frequency

This model requires a constant failure rate. It is applied for initiating events.

- Required parameters: Frequency

f) ***Non-repairable***

This model is used for components which are not repairable during their operation. It is used in availability analysis and especially in time-dependent analysis.

- Required parameters: Failure rate
- Optional parameters: Fixed probability

In this thesis, the Probability Reliability Model is used for all the basic events included to measure the probability of occurrence of the top events. The model is represented as:

$$Q_{0(t)} = q_{0(t)}$$

Where $Q_0(t)$ is the probability that the top event occurs at time *t and* $q_{0(t)}$ is the probability a basic event that leads to the top event. If the state of each component in the fault tree is known at time *t*, then the state of the top event can also be determined regardless of what has happened up to time *t*. Hence $Q_0(t)$ is uniquely determined by the $q_i(t)$'s.

The failure probabilities (q) of the basic events included in the FTA in this thesis are adopted from EUROCONTROL (EUROCONTROL, 2008b), Capstone Project (Walala, 2008), Federal Aviation Administration (2008) and the software related events from (McDermid, 2001). The probability of a failure occurring is assumed to be distributed equally over all elements that can cause the failure (e.g. the probability of a failure onboard an aircraft is equally likely for all aircraft type in the airspace). Table 7-10 provides the (q) values used for the basic events included in all the FTA in this thesis. Some of the basic events are used to construct more than one fault tree. Therefore, the 'Reference Column' in Table 7-10 contains more than one reference code for one basic event referring its use to the different fault trees.

Table 7-10: Failure probabilities for the basic events

Reference to Fault tree	Basic Event Description	Failure Probability (q)
FOAI-2	Failure connection between ADS-B receiver and ADS-B In application	1E-1
FOAI-4	System hang due to insufficient memory	1E-7
FOAI-5	Inadequate knowledge/experience on the system functionalities (HMI)	1E-3
CAA-19/COA-13/FOA-6	Bug in module	1E-7
FOAI-8	Failure of report assembly module	1E-7
FOAI-9	Failure of onboard ADS-B receiver	1E-4
LOA-4	ADS-B Out antenna failure	1E-4
LOA-6	Pilot forgot to turn on ADS-B transponder	1E-3
LOA-7	Pilot turned on ADS-B transponder on wrong mode	1E-3

Reference to Fault tree	Basic Event Description	Failure Probability (q)
LOA-10	Failure of connection between GPS receiver and ADS-B transponder	1E-1
LOA-8	Main transponder failure	1E-4
LOA-9	Backup transponder failure	1E-4
COAP-10/LOA-12	Loss of geometry from satellite	1E-8
LOA-13	Onboard GPS receiver malfunction	1E-4
COAP-12/LOA-14	GPS antenna failure	1E-4
CAA-8/LAA-9/LOA-15	Jamming of GPS transmission for satellite	1E-13
COAP-11/LAA-10/LOA-16	Satellite failure	1E-13
CAA-6/LAA-2	Failure of ground comm. link between ground station and Controller Working Position (CWP)	1E-4
LAA-4	Failure of ground station power supply	1E-5
CAA-17/LAA-5	Data decoding error	1E-13
LAA-11	Failure of ground processing unit	1E-5
LAA-6	Failure of ADS-B ground receiver	1E-5
LAA-7	Failure of ADS-B ground receiving antenna	1E-4
COA-5	Incorrect 24 bit-code	1E-4
COAP-8/COA-6/CAA-15	Lack of maintenance	1E-3
COAP-9/COA-7/CAA-16	Environmental impact	2E-4
COA-8	Fault in signal	2.6E-6
COA-10	Fault in ADS-B transponder	1E-4
COA-11	Data encoding error	1E-13
COA-12/CAA-18	Data processing error	1E-13
CAA-7	Error in GPS Time system	1E-4
CAA-9	Interference	1E-2
CAA-11	ADS-B ground receiver degradation	1E-3
CAA-14	Fault in ground ADS-B receiver equipment	1E-5
COAP-5	WAAS inaccuracy	5E-2
COAP-7	Signal processing error	1E-13

The results of FTA for all the ADS-B system hazards identified in this thesis are provided in Figures 7-14 to 7-19. Table 7-11 summarizes the FTA results for the top events.

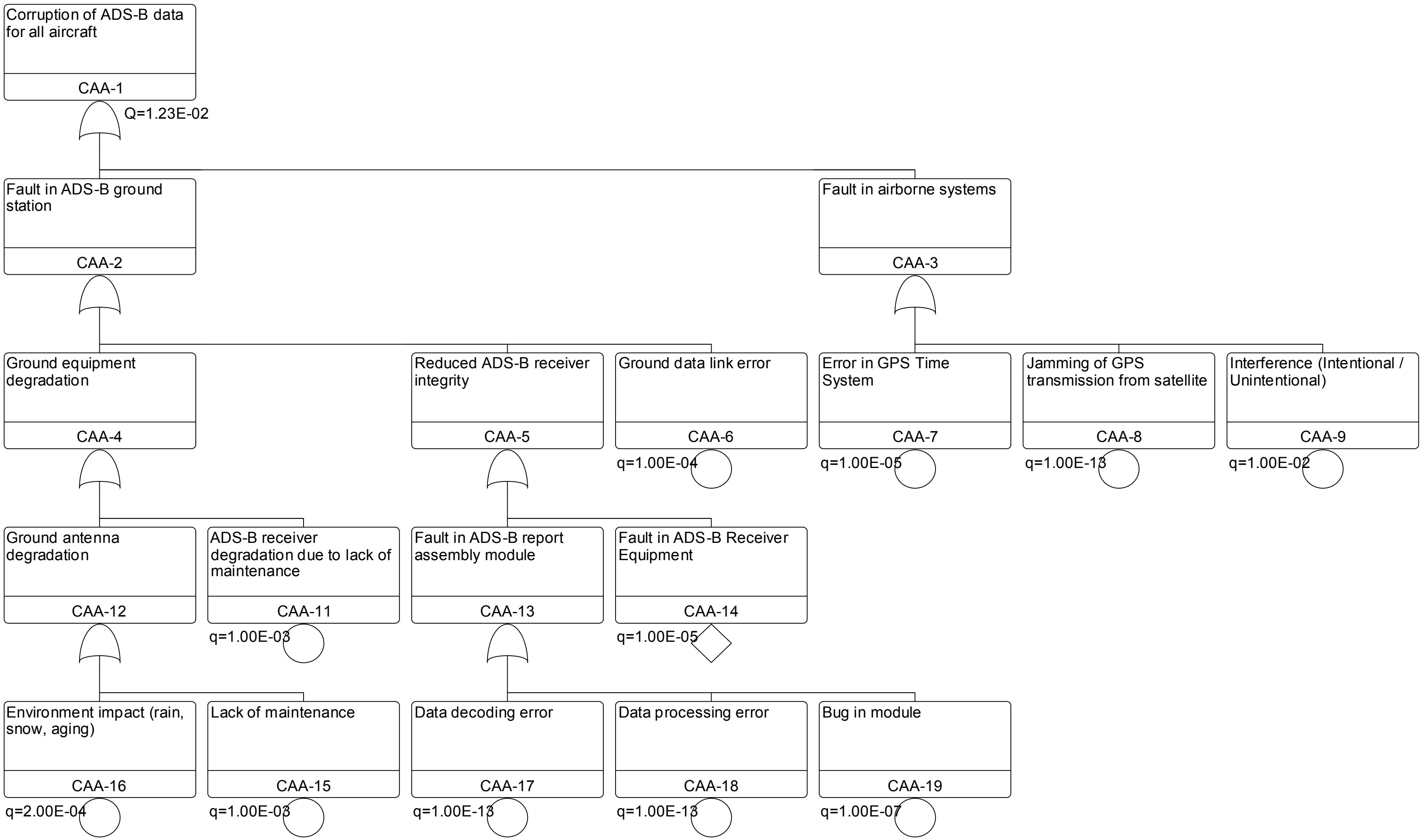


Figure 7-14: Fault tree analysis for 'Corruption of ADS-B data for all aircraft'

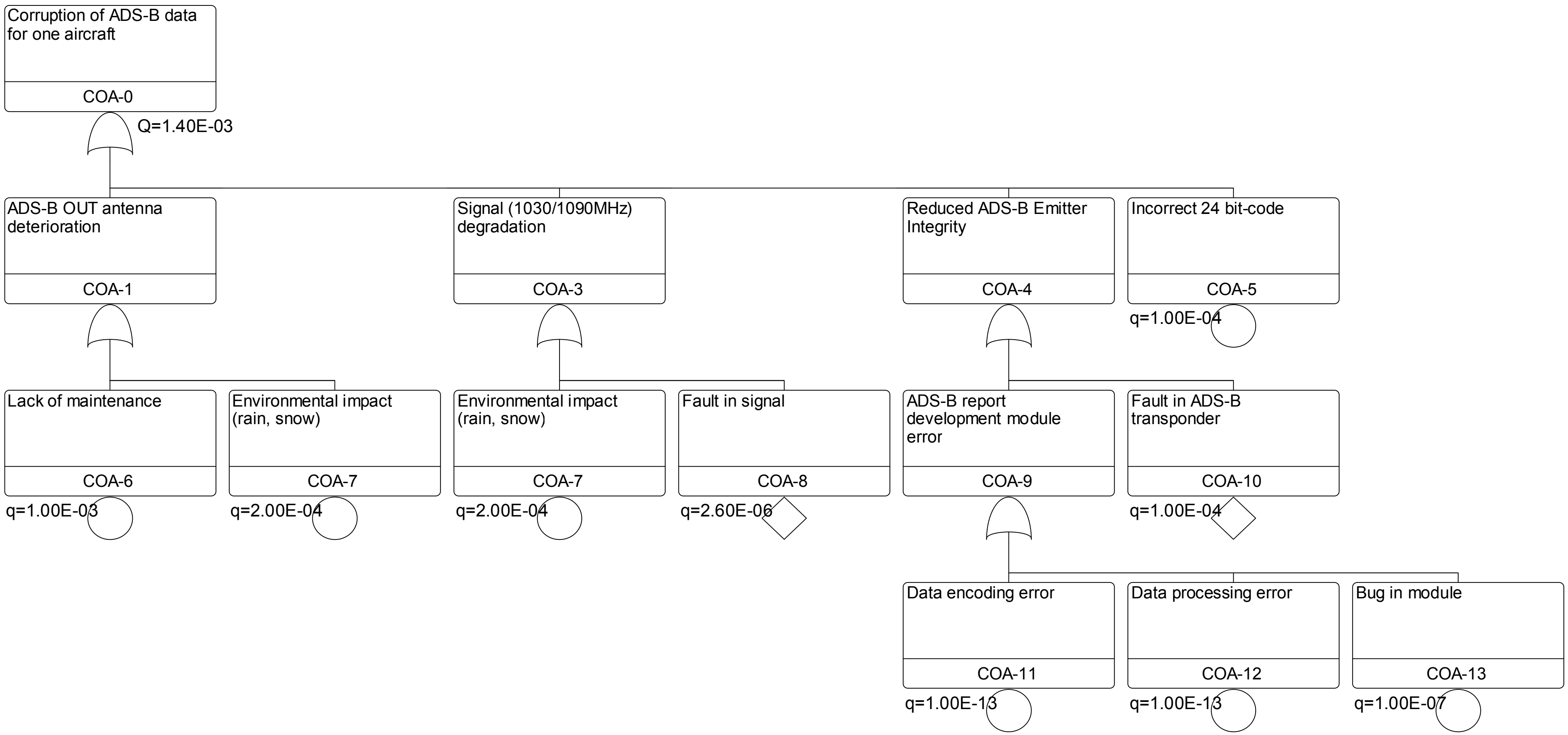


Figure 7-15: Fault tree analysis for 'Corruption of ADS-B data for one aircraft'

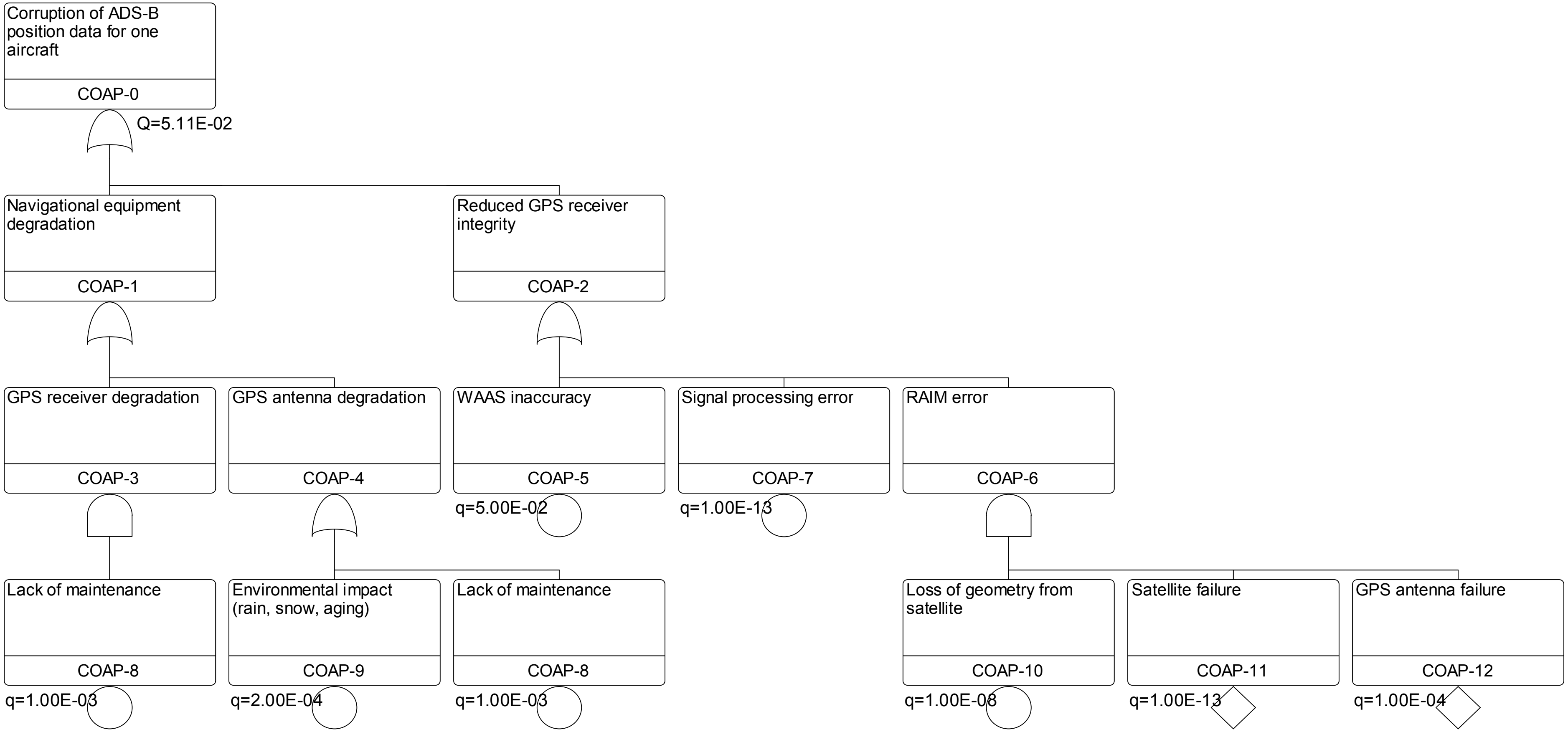


Figure 7-16: Fault tree analysis for 'Corruption of ADS-B position data for one aircraft'

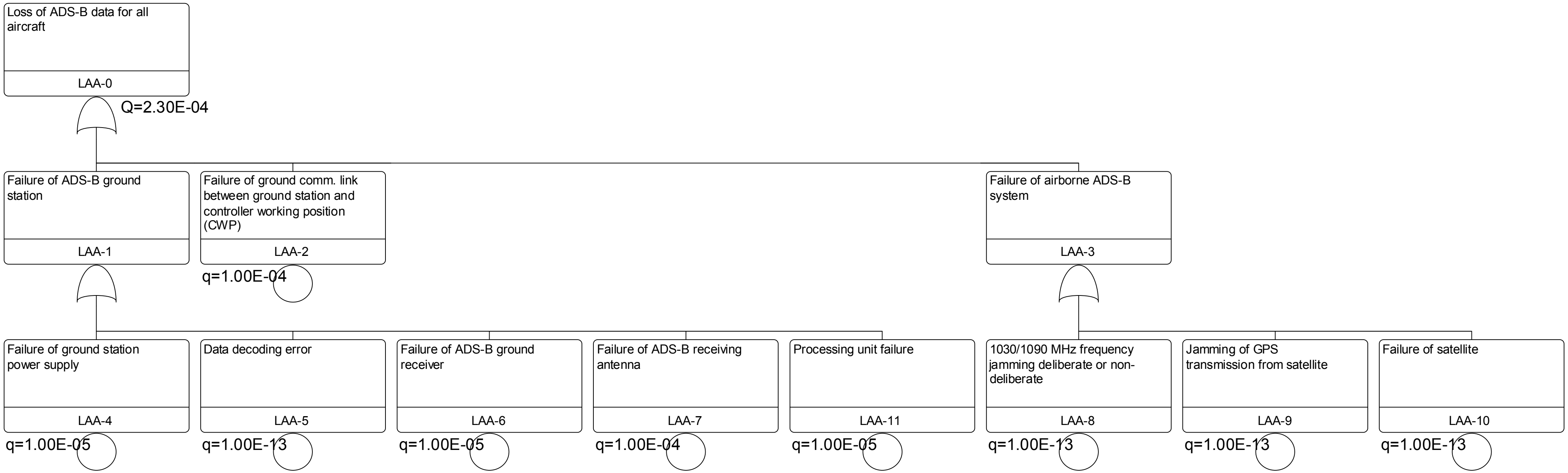


Figure 7-17: Fault tree analysis for 'Loss of ADS-B data from all aircraft'

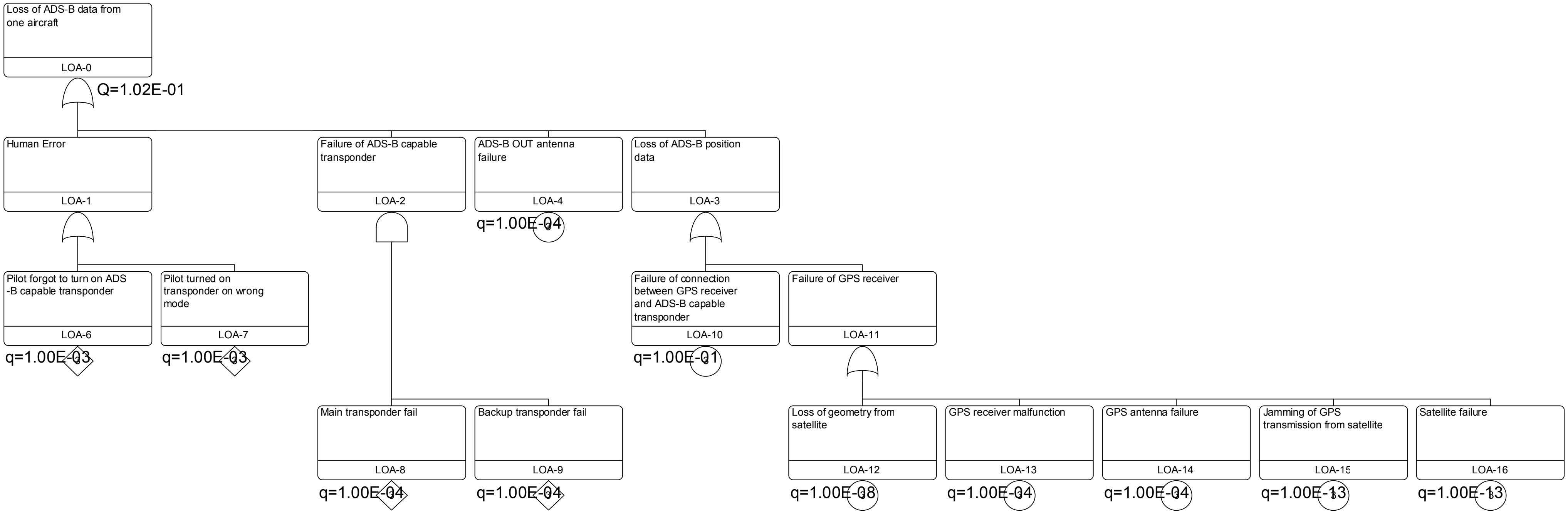


Figure 7-18: Fault tree analysis for 'Loss of ADS-B data from one aircraft'

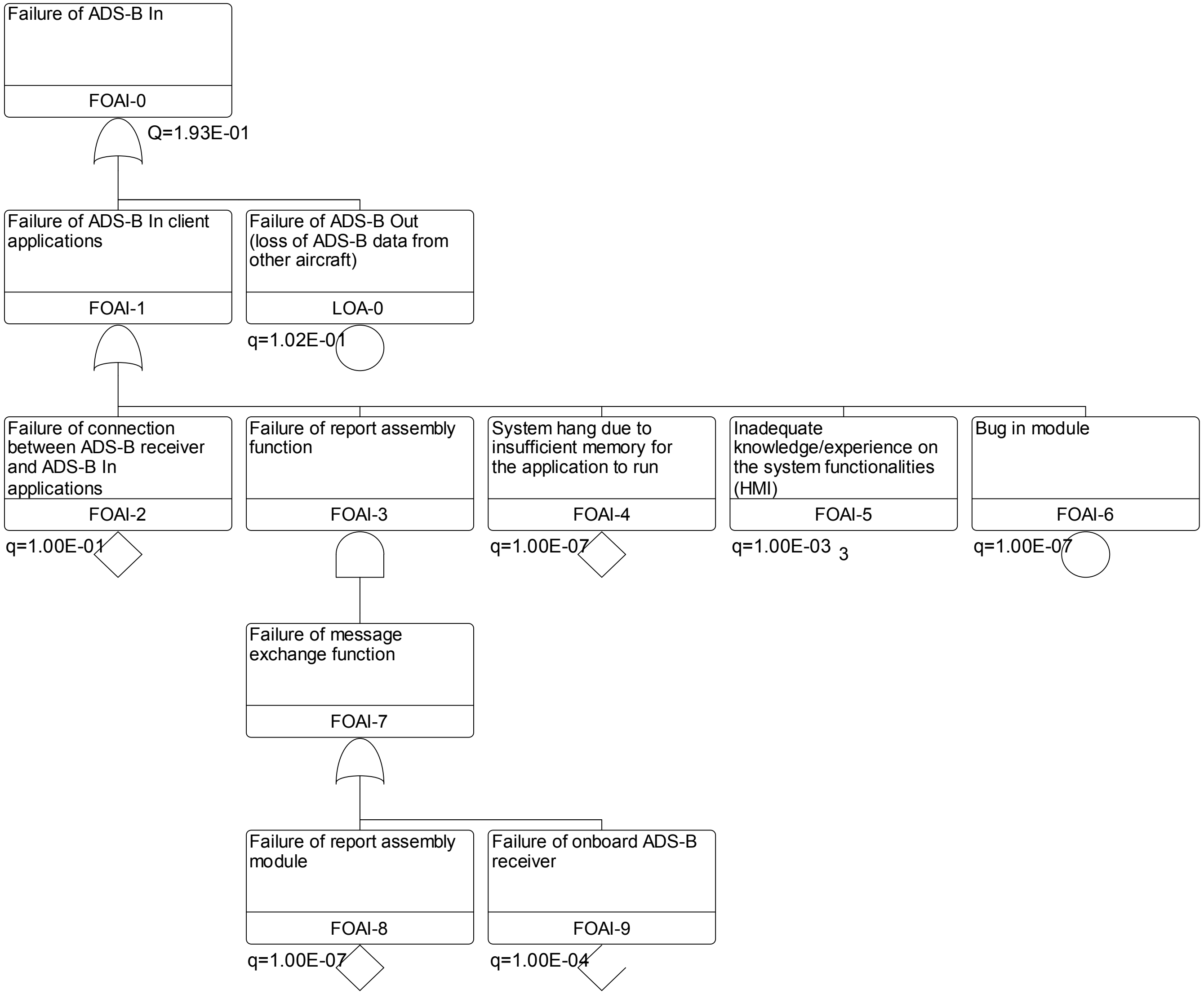


Figure 7-19: Fault tree analysis for 'Failure of ADS-B In'

Table 7-11: Summary of FTA results for the top events.

Top event (ADS-B system hazard)	Risk Measure (Q)	Availability (1-Q)
Corruption of ADS-B data for all aircraft	1.23E-02	0.9877
Corruption of ADS-B data for one aircraft	1.40E-03	0.9960
Corruption of ADS-B position data for one aircraft	5.11E-02	0.9489
Loss of ADS-B data from all aircraft	2.30E-04	0.9997
Loss of ADS-B data from one aircraft	1.02E-01	0.8980
Failure of 'ADS-B In'	1.93E-01	0.8070

The risk measure or the probability of the hazard/top event occurrence is also known as unavailability (EUROCONTROL, 2008b). Therefore, the ADS-B system availability is defined as:

Availability ***= 1 – (probability of the hazard/top event occurrence)***

= 1 – Q

According to the Minimum Aviation System Performance Standards for ADS-B (RTCA, 2002), if the ADS-B system were to be used the a sole means of surveillance, the system availability would be calculated using only ADS-B, aircraft sources and applications. In this thesis, the FTA is conducted with the assumption that ADS-B operates as the sole means of surveillance. The availability of ADS-B as supplemental or as a primary means of surveillance is specified as 95% and 99.9% respectively, for all operations (DO-242A). If ADS-B is used as a supplemental means of surveillance during the transition period to full ADS-B equipage, then the ADS-B system adds availability within a larger surveillance system. While if ADS-B is used as a primary means of surveillance, then a supplemental surveillance system (other mean of surveillance) independent of the navigation system is expected to be available. To date, there is no quantified requirement for availability of ADS-B as sole means of surveillance. However, based on the stipulated availability requirements for other ADS-B operational modes discussed above, it can be assumed that the availability of ADS-B as the sole mean of surveillance will be smaller than 95% as it will not include availability of any supplemental system and it is also bound to the failure of the onboard navigation system.

Table 7-11 presents the FTA results from this thesis. The results show that the availability of ADS-B system based on one aircraft is 89.8%. However, the availability of ADS-B system based on all aircraft in the airspace is higher at 99.9%. This is because the latter is measured based on common failure modes that impacts airborne ADS-B equipment (eg. satellite failure, signal jamming and interference) and also failure modes of ADS-B ground equipment (e.g. ground station failure, ground data link failure) which are common to all aircraft within the airspace. While the former (i.e. based on one aircraft) is measured based localized failure modes (airborne ADS-B equipments and supporting avionic systems) which directly impact the particular aircraft. It is also important to note that ADS-B is a surveillance system that critically relies on the aircraft equipage. The FTA in this thesis is conducted based on the assumption that the failure modes are equally distributed despite the aircraft avionics make model. However, the analysis in Chapter 6 and section 7.2 of this Chapter, showed that ADS-B performance and some of the failure modes do vary based on the aircraft avionics make-model. This is particularly relevant to the onboard positioning source, ADS-B transponder and ADS-B system configuration onboard.

The FTA (in Table 7-11) indicates that the probability of 'Corruption of ADS-B position data for one aircraft' is higher than the probability of 'Corruption of all ADS-B data for one aircraft' at 5.11E-02 and 1.4E-03 respectively. The former hazard is mainly due to onboard navigation system integrity reduction and equipment degradation. While, the latter hazard is due to ADS-B specific onboard equipment degradation and data processing/encoding errors. The probability of 'corruption of ADS-B for all aircraft' is measured as 1.23-02. Finally the availability of ADS-B In service is measured as 0.807. Unavailability of ADS-B In includes failure of onboard ADS-B receiving equipment, onboard ADS-B In applications such as CDTI and ASAS and also unavailability of ADS-B Out service from other aircraft.

The next sub-section identifies which basic event contributes the most to the occurrence of the hazards (top event) using importance analysis method (Henley and Kumamoto, 1981).

7.3.4 Importance Analysis

A component or cut set's contribution to the top event occurrence is termed *importance.* The importance analysis is useful for system design, diagnosis and optimization (Henley and Kumamoto, 1981). Possible variation of the system availability caused by uncertainty in components reliability parameters can be estimated through the analysis. As a result, inspection, maintenance and failure detection can be carried out based on the order of the *importance* of the components. Hence, the system can be upgraded by improving the components with relatively high *importance* (Henley and Kumamoto, 1981).

Importance measures of the basic events are associated with the risk-significance and safety-significance of the related components. In particular, they are normally used to rank the system's components with respect to their contribution to the reliability and availability of the overall system.

Thus they provide an important indication about the components to be improved in order to increase the reliability and the availability of the system (Sergio Contini et al., 2009). The reliability importance of a component in a system generally depends on the location of the component in the system and the reliability of the component itself (Vatn, 2001). The *importance* is quantified using the following importance measures and its corresponding probabilistic expressions (Henley and Kumamoto, 1981):

a) ***Fussel Vessely factor (FV)***

This measure is used to quantify the contribution of the basic event (*i*) to the top event with the present failure probability of *i*. The measure is calculated as:

$$I_i^{FV} = \frac{Q_{TOP}(MCS\ including\ i)}{Q_{TOP}}$$

b) ***Risk Decrease Factor (RDF)***

This measure presents the maximum decrease in the risk for an improvement to the reliability (failure probability) of the basic event (i). $Q_{TOP}\ (q_i = 0)$ indicates the decrease in the risk level with basic event (i) optimised or assumed to be perfectly reliable. The measure is calculated as:

$$I_i^R = \frac{Q_{TOP}}{Q_{TOP}\ (q_i = 0)}$$

c) ***Risk Increase Factor (RIF)***

This measure presents the worth of the basic event (i) in achieving the present level of risk and indicates the importance of maintaining the current level of reliability (failure probability) for the basic event. $Q_{TOP}(q_i = 1)$ indicates the increase in the risk level without basic event (i) or with basic event (i) assumed to be failed. The measure is calculated as:

$$I_i^I = \frac{Q_{TOP}(q_i = 1)}{Q_{TOP}}$$

The importance measures above contain different information and thus have their own use. For most applications, the combination of two importance measures is needed while for some other applications, one importance measure could be enough. The Fussel Vessely factor (FV) is often used as a measure of risk-significance and the Risk Increase Factor (RIF) as a measure of safety-significance. However, the FV importance alone is sufficient to identify potential components for safety improvement based on the ranking of the basic event's contribution to the occurrence of the risk (top event) (M. Van der Borst and H. Schoonakker, 2001).

The results of the importance analysis conducted for the ADS-B hazards (top events) are provided in Table 7-12 to 7-17, which include the three importance measures FV, RDF and RIF. The results show the ranks of the basic events that give the greatest contribution to the likelihood of occurrence of the top event with the FV measure. In addition, in this thesis the risk significance (with the FV measure) and safety significance (with the RIF measure) are regarded as a complementary way to identify the role of basic events in the risks of the ADS-B system.

The importance analysis results for 'Corruption of ADS-B data for all aircraft' are provided in Table 7-12. The FV measure results show that the basic event with the highest rank that contribute to the risk is basic event CAA-9 referring to signal interference with FV = 8.13E-01. Thus, when the probability of the present signal interference (1.00E-02) is improved, the maximum decrease in the risk is 5.30E (RDF). The results further show that all the basic events have the same RIF value at 8.13E+01 indicating equal safety-importance to the system hazard. In other words, any change in the probability of the basic events will result in an increase in the risk level.

Table 7-12: Importance analysis for Corruption of ADS-B data for all aircraft (refer Figure 7-14)

Basic Event	Fussel Vessely factor (FV)	Risk Decrease Factor (RDF)	Risk Increase Factor (RIF)
CAA-9	8.13E-01	5.30E+00	8.13E+01
CAA-11	8.13E-02	1.09E+00	8.13E+01
CAA-15	8.13E-02	1.09E+00	8.13E+01
CAA-16	1.63E-02	1.02E+00	8.13E+01
CAA-6	8.13E-03	1.01E+00	8.13E+01
CAA-7	8.13E-04	1.00E+00	8.13E+01
CAA-14	8.13E-04	1.00E+00	8.13E+01
CAA-19	8.13E-06	1.00E+00	8.13E+01
CAA-17	8.13E-12	1.00E+00	8.13E+01
CAA-18	8.13E-12	1.00E+00	8.13E+01
CAA-8	8.13E-12	1.00E+00	8.13E+01

Table 7-13 provides importance analysis results for 'Corruption of ADS-B data for one aircraft'. Based on the FV measure results, basic event COA-6 (referring to ADS-B Out antenna degradation due to lack of maintenance - this event is also considered as human error) is identified as the main contributing element to the occurrence of the risk. An improvement on it results in a maximum decrease of the risk level with RDF = 3.48E. The safety-importance measure (RIF) of the basic events shows that all events have the same effect on the risk level measured in Figure 7-14 with RIF = 7.13E+02.

Table 7-13: Importance analysis for Corruption of ADS-B data for one aircraft (refer Figure 7-15)

Basic Event	Fussel Vessely factor (FV)	Risk Decrease Factor (RDF)	Risk Increase Factor (RIF)
COA-6	7.13E-01	3.48E+00	7.13E+02
COA-7	1.43E-01	1.17E+00	7.13E+02
COA-5	7.13E-02	1.08E+00	7.13E+02
COA-10	7.13E-02	1.08E+00	7.13E+02
COA-8	1.85E-03	1.00E+00	7.13E+02
COA-13	7.13E-05	1.00E+00	7.13E+02
COA-11	7.13E-11	1.00E+00	7.13E+02
COA-12	7.13E-11	1.00E+00	7.13E+02

Based on the importance analysis results in Table 7-14, the FV measure indicates basic event COAP-5 (WAAS inaccuracy) has the highest contribution to 'Corruption of ADS-B position information for one aircraft' with FV = 9.78E-01. An improvement in the reliability of this basic event results in a maximum decrease in the risk with RDF = 4.26E+01. Further analysis based on the RIF indicates that basic events: COAP-5, COAP-8, COAP-9 and COAP-7 have higher safety significance with RIF =1.96E+01 than basic events: COAP-12, COAP-11 and COAP-10 with RIF= 1.00E+00.

.

Table 7-14: Importance analysis for Corruption of ADS-B position information for one aircraft (refer Figure 7-16)

Basic Event	FV	RDF	RIF
COAP-5	9.78E-01	4.26E+01	1.96E+01
COAP-8	1.96E-02	1.02E+00	1.96E+01
COAP-9	3.91E-03	1.00E+00	1.96E+01
COAP-7	1.96E-12	1.00E+00	1.96E+01
COAP-12	1.96E-24	1.00E+00	1.00E+00
COAP-11	1.96E-24	1.00E+00	1.00E+00
COAP-10	1.96E-24	1.00E+00	1.00E+00

Table 7-15 shows the importance analysis results for Loss of ADS-B data from all aircraft. There are two basic events that have the highest contribution to the risk; LAA-7 (Failure of ADS-B receiving antenna) and LAA-2 (Failure of ground communication link between ground station and controller working position (CWP)) with same FV measure at 4.35E-01. Improvement in the reliability of these basic event results in a maximum decrease in the risk with RDF = 1.77E+00. The results further show that all the basic events have the same RIF value at 4.35E+03 indicating equal safety-importance to the system hazard.

Table 7-15: Importance analysis for Loss of ADS-B data from all aircraft (refer Figure 7-17)

Basic Event	FV	RDF	RIF
LAA-7	4.35E-01	1.77E+00	4.35E+03
LAA-2	4.35E-01	1.77E+00	4.35E+03
LAA-6	4.35E-02	1.05E+00	4.35E+03
LAA-4	4.35E-02	1.05E+00	4.35E+03
LAA-11	4.35E-02	1.05E+00	4.35E+03
LAA-10	4.35E-10	1.00E+00	4.35E+03
LAA-5	4.35E-10	1.00E+00	4.35E+03
LAA-8	4.35E-10	1.00E+00	4.35E+03
LAA-9	4.35E-10	1.00E+00	4.35E+03

The importance analysis results for Loss of ADS-B data from one aircraft are provided in Table 7-16. The highest contributing basic event to the risk is LOA-10 (Failure of connection between GPS receiver and ADS-B capable transponder) with FV = 9.80E-01. An improvement in the reliability of the basic event results in a maximum decrease in the risk level with RDF = 4.44E+01. Further analysis based on the RIF indicates that basic events: LOA-10, LOA-6, LOA-7, LOA-13, LOA-14, LOA-4, LOA-12, LOA-16 and LOA-15 have higher safety significance with RIF = 9.80E+00 than basic events: LOA-9and LOA-8 with RIF= 1.00E+00

Table 7-16: Importance analysis for Loss of ADS-B data from one aircraft (refer Figure 7-18)

Basic Event	FV	RDF	RIF
LOA-10	9.80E-01	4.44E+01	9.80E+00
LOA-6	9.80E-03	1.01E+00	9.80E+00
LOA-7	9.80E-03	1.01E+00	9.80E+00
LOA-13	9.80E-04	1.00E+00	9.80E+00
LOA-14	9.80E-04	1.00E+00	9.80E+00
LOA-4	9.80E-04	1.00E+00	9.80E+00
LOA-12	9.80E-08	1.00E+00	9.80E+00
LOA-9	9.80E-08	1.00E+00	1.00E+00
LOA-8	9.80E-08	1.00E+00	1.00E+00
LOA-16	9.80E-13	1.00E+00	9.80E+00
LOA-15	9.80E-13	1.00E+00	9.80E+00

Table 7-17 shows the importance analysis results for Failure of ADS-B In. The FV measure indicates basic event LOA-0 referring to Failure of ADS-B Out (loss of ADS-B data from other aircraft) with FV = 5.29E-01. An improvement in the basic event leads to a maximum decrease in the risk with RDF = 1.91E+00. The safety-importance measure (RIF) of the basic events shows that all events have the same effect on the risk level measured in Figure 7-19 at with RIF = 5.19E+00.

Table 7-17: Importance analysis for Failure of ADS-B In (refer Figure 7-19)

Basic Event	FV	RDF	RIF
LOA-0	5.29E-01	1.91E+00	5.19E+00
FOAI-2	5.19E-01	1.87E+00	5.19E+00
FOAI-5	5.19E-03	1.00E+00	5.19E+00
FOAI-9	5.19E-04	1.00E+00	5.19E+00
FOAI-6	5.19E-07	1.00E+00	5.19E+00
FOAI-4	5.19E-07	1.00E+00	5.19E+00
FOAI-8	5.19E-07	1.00E+00	5.19E+00

7.4 Summary

The main novelties in this Chapter are a comprehensive failure mode register for ADS-B, a systematic approach for ADS-B failure mode identification and Probabilistic Safety Assessment (PSA) using Fault Tree Analysis (FTA). The failure mode register is a living document which can be populated to assist system maintenance; docket logging and most importantly to support incident/accident investigations. The approach includes various types of data sources including literature, safety reports, subject matter experts input and ADS-B track analysis. In addition, it also takes into account failure modes induced by the human element and environmental factors.

Based on the findings in this Chapter, a safety advantage over the radar system is that, failures of the ADS-B system on-board an aircraft does not affect the whole ATC surveillance services based on the ADS-B system. Hence, failures are typically more localized. In addition, the availability of several ADS-B ground stations reduces the probability of failure of ground-based ADS-B systems to capture ADS-B data from aircraft. On the other hand, failure of a radar system causes complete surveillance failure in the particular airspace within its coverage, forcing controllers and flight crew to engage in procedural control for ATC operations (ICAO, 2007c) and (ICAO, 2006d) for all aircraft within the sector.

The findings also indicate that some of the failure modes only affect one aircraft. However, loss of ADS-B data from one aircraft impacts the reliability of ADS-B In service and the various future air navigation applications, such as situational awareness, conflict detection, conflict resolution, separation assistance or trajectory prediction. In the case where the failure modes are not detected, this may lead to safety risks.

Based on the finding from the failure modes, six potential hazards of the ADS-B system are identified. FTA is used to develop and quantify the occurrence of the potential hazards (risk). The findings indicate that the availability for the ADS-B system as a sole surveillance mean is low at 0.898 in comparison to the availability of ADS-B system as supplemental or as primary means of surveillance at 0.95 and 0.999 respectively. The latter availability values are obtained from DO-242A.

Further analysis identified minimal cut sets in the fault tree of each potential hazard. The minimal cut sets indicate the simultaneous occurrence of the basic events (which cannot be reduced) that ensures the occurrence of the hazards. Finally, importance analysis is conducted to rank the risk of basic events that lead to the ADS-B hazards indentified in this thesis. The risk significance and safety significance of each basic event are also identified. These will aid in the ADS-B system safety improvements.

The next chapter maps the ADS-B performance identified in this thesis to the envisioned future airborne surveillance applications.

Chapter 8

ADS-B for Enhanced Surveillance Applications

ADS-B Out supports various ground applications including ATC surveillance in radar airspace, non-radar airspace and on the airport surface. In addition, the feasibility of enhanced airborne surveillance applications requires the capability of aircraft to receive ADS-B Out messages from other aircraft within their coverage (ADS-B In).

This Chapter reviews the various enhanced airborne surveillance applications and the required ADS-B information to support them. A mapping exercise is undertaken to assess the credibility of the ADS-B system performance quantified in Chapter 6 and Chapter 7 to support the functionalities of the various enhanced airborne surveillance applications envisioned as part of the future ATM modernisation.

8.1 Background

The evolution of navigation and surveillance technologies is a key element of the modernisation of ATM, to enable better planning and thereby increasing capacity and efficiency without jeopardizing safety and the environment. The Single-European-Sky ATM Research (SESAR, 2012) and Next Generation Air Transportation System (FAA, 2010, FAA, 2012) initiatives recognize that at the core of a more efficient navigation is the need to integrate aircraft operations as a seamless continuum and to involve all relevant stakeholders, including airspace users, air navigation service providers, airport operators and the military, in the decision making process. This requires the capability to provide shared Air Traffic Situational AWareness (ATSAW) with high accuracy and integrity aircraft state information. This capability is envisioned through the ADS-B system. High-performance surveillance systems have the potential to increase both airspace efficiency (and thereby capacity) and safety, by improving the capability to perform the necessary synchronisation and separation activities in advance, making it possible to use an optimised strategic approach to the integration of traffic instead of the current inefficient tactical process. Therefore, performance and reliability of the ADS-B system will be a major factor in the future ATM performance. Optimal integration of air traffic will be achieved on the basis of various ConOps elements (i.e. applications) that each require surveillance information with specific levels of performance.

8.2 ADS-B for the future ATM system modernisation

At the core of the future SESAR and NextGen ATM are advanced automation systems based on the ADS-B. These must progressively fulfill a number of functions, as summarised in Figure 8-1.

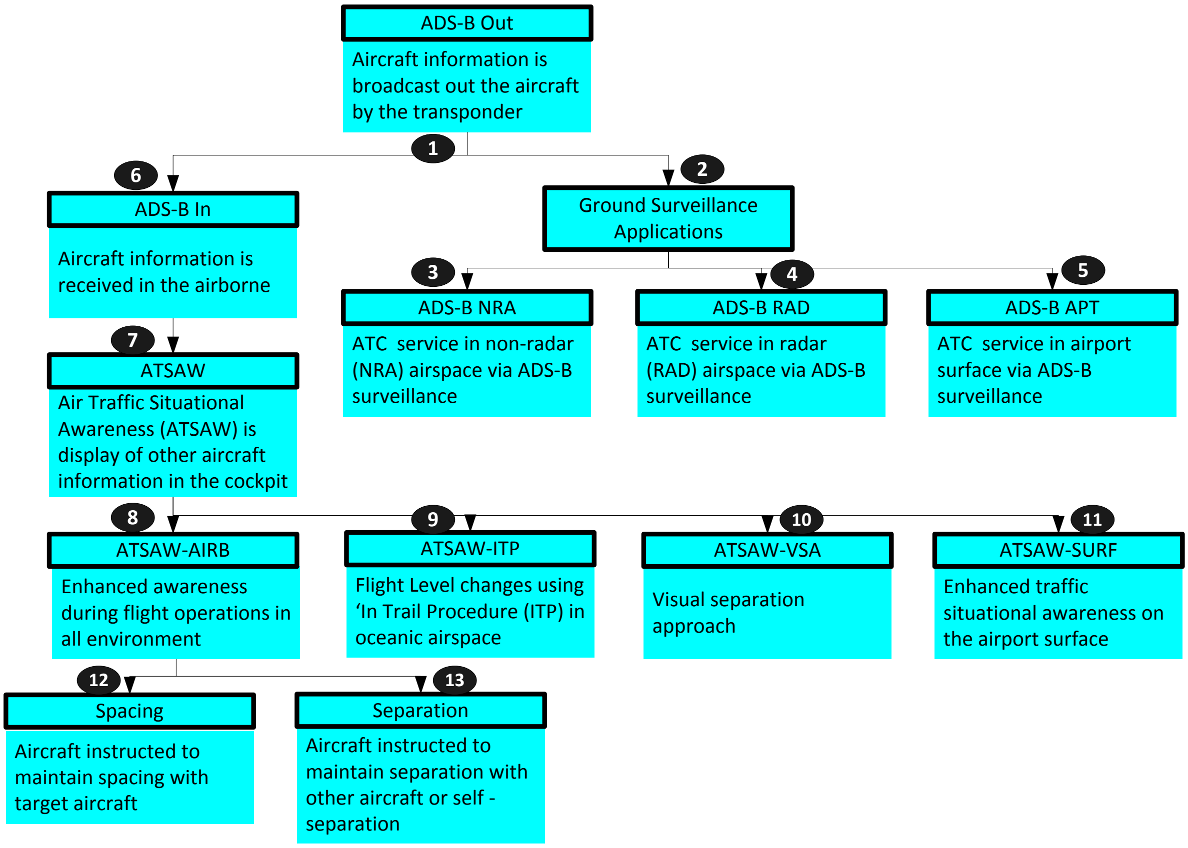


Figure 8-1: ADS-B system evolution

The first step requires the aircraft to be equipped with ADS-B Out (as discussed in detail in Chapter 3). The second step involves the implementation of ground surveillance applications for ATC; followed by ADS-B NRA (step 3), ADS-B RAD (step 4) and ADS-B APT (step 5). The implementation is conducted in a sequence, based on the criticality of the current limitations in the radar system to support ATC to provide surveillance services to the aircraft. ADS-NRA has been fully implemented and is operational in various regions such as Australia while ADS-B RAD and ADS-B APT are still currently under trial, as discussed in Chapters 3 and 5. These ground applications are meant to provide radar like services where the radar is either unavailable or to supplement the reduced radar services in a particular operational environment or airspace. Future applications envision providing enhanced surveillance services (e.g. reduced separation to aircraft) by exploiting the higher performance from ADS-B. However, these are still to be implemented due to a lack of confidence in the system performance and aircraft equipage.

The sixth step is the implementation of ADS-B In, which requires ADS-B In equipage to enable aircraft to receive ADS-B Out messages from other aircraft within its specified range. ADS-B In is a means to enable various airborne surveillance applications including providing ATSAW via display of other aircraft information to flight crew. At present, pilots build traffic situational awareness by integrating information from two main sources: visual observation and radio communication with ATC. The radio communication includes traffic information provided to flight crew by a controller, transmission from a controller to other aircraft, and responses from other aircraft, and air-to-air radio communication in uncontrolled airspace. Additionally, to enhance situational awareness, pilots of suitably equipped aircraft may use their TCAS traffic display to supplement the available traffic information. Even though the TCAS traffic display is meant to support visual acquisition when TCAS logic generates a Traffic Advisory (TA), in some cases it has confused the pilot's perception of the traffic situation (CASCADE Operational Focus Group, 2009). This causes unsynchronized situational awareness between pilots and ATC which may lead to undesirable incidents, as discussed in Chapter 4. According to EUROCONTROL (CASCADE Operational Focus Group, 2009), this particular situation has been one of the drivers of the development of airborne surveillance applications.

ATSAW has led to the development and implementation of various surveillance applications: enhanced traffic situational awareness in all environments (ATSA-AIRB), flight level changes using 'In Trail Procedure (ITP) in oceanic airspace (ATSA-ITP), visual separation approach (ATSA-VSA) and enhanced traffic situational awareness on the airport surface.

Feasibility of the ground surveillance and airborne surveillance applications are underpinned by the ADS-B Out data performance. These applications were introduced in Chapter 3 and the specific information in the ADS-B message required for each identified. The next section describes each of the enhanced airborne applications, its operational environment and requirements. This is followed in the last section, by the validation of real time ADS-B data performance to support the applications.

8.3 Airborne surveillance applications using ADS-B

This section reviews and discusses the various airborne surveillance applications shown in Figure 8-1, envisioned with the ADS-B system.

8.3.1 Air Traffic Situational Awareness during flight operations (ATSAW-AIRB)

The ATSAW-AIRB is defined as the enhancement of a flight crew's knowledge of the surrounding traffic situation in all environments. It is meant to improve flight safety and operations by assisting flight crews in building their traffic situational awareness through the provision of an appropriate on-board traffic display (CASCADE Operational Focus Group, 2009). This is achieved by retrieving ADS-B information transmitted by other aircraft transponders via Mode S 1090MHz. The information is then fed to the Cockpit Display of Traffic Information (CDTI) tool to provide instantaneous and up-to-date traffic information (including aircraft identification, position, direction, ground speed, vertical tendency, relative altitude and wake vortex category). A functional diagram of the CDTI is shown in Figure 8-2. The display determines the "own-aircraft" position through the use of a directly connected GPS receiver onboard the aircraft. The ADS-B receiver (1090 MHz Rx) detects ADS-B Out signals from other aircraft within its range, and presents raw messages to the CDTI for further processing. The CDTI processor decodes the raw messages to determine the identity, position (latitude, longitude), altitude, and velocity of detected aircraft. It then presents symbols on the display depicting other aircraft in relation to the "own-aircraft" (Owusu, 2005). Figure 8-3 shows the onboard CDTI display.

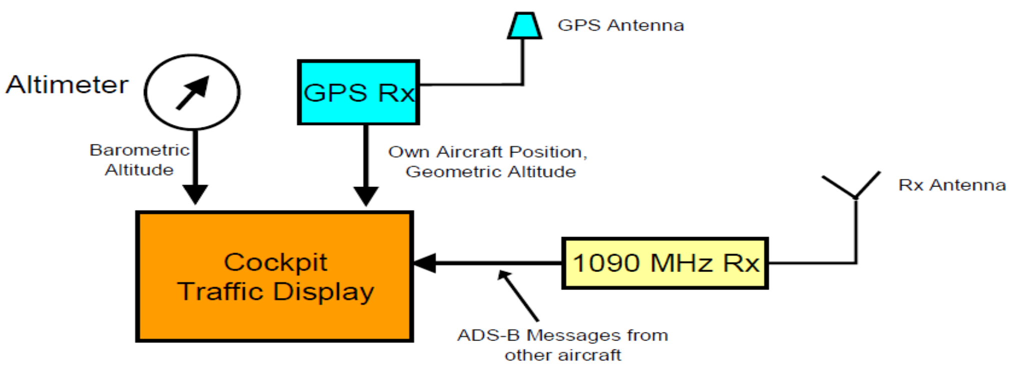


Figure 8-2: CDTI functional diagram (Owusu, 2005)

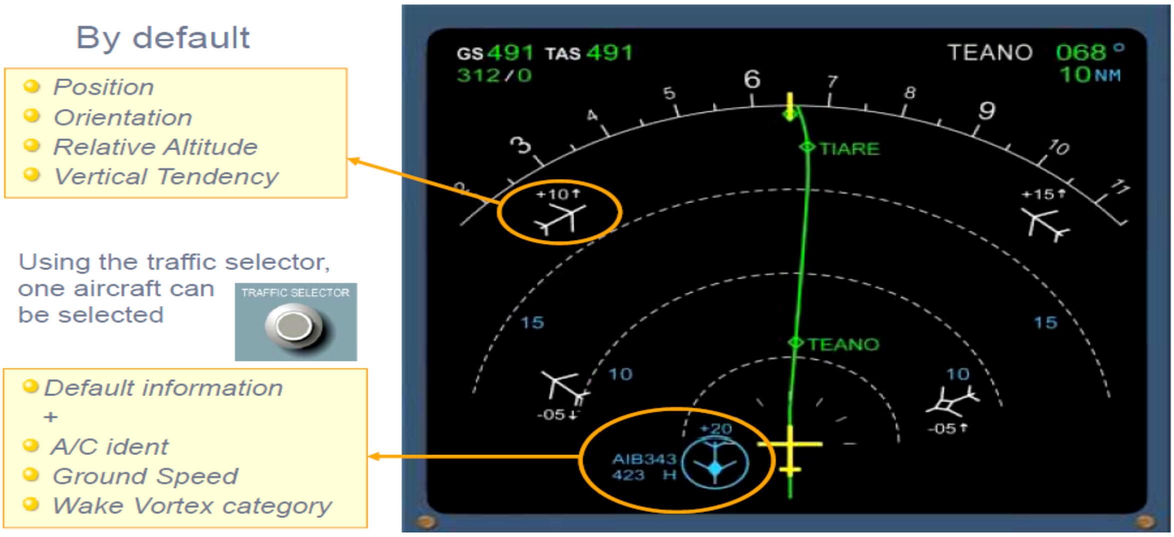


Figure 8-3: CDTI display onboard (Vidal, 2012)

In the latest TCAS technology, the ATSAW-AIRB and TCAS software are integrated within the TCAS equipment, whereby the ATSAW-AIRB (using ADS-B) information is correlated with the TCAS information to enhance the TCAS function. The ATSAW (via CDTI) provides additional information over the TCAS traffic display for example the aircraft intent information. It also provides a longer range (up to 150 NM) than current TCAS (40 to 80 NM). A unique traffic symbol is presented on the system display to the pilot when the merged TCAS and ADS-B information is available as shown in Figure 8-4.

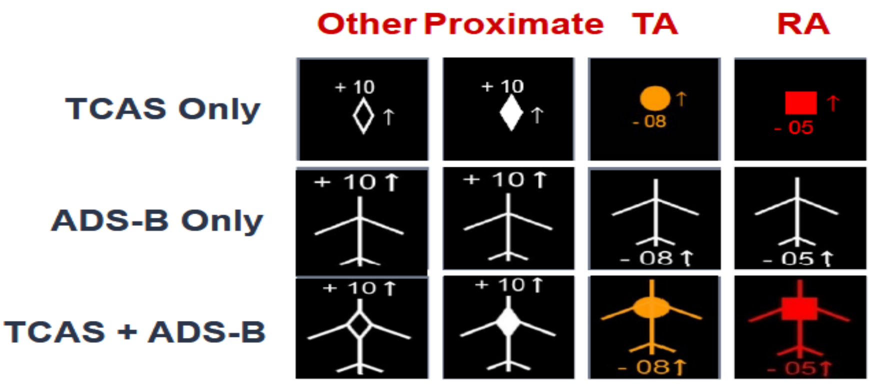


Figure 8-4: Merged TCAS and ADS-B traffic symbols (Vidal, 2012)

If no correlation is detected between the TCAS and ADS-B positioning information, only the TCAS symbol is displayed to the users. In addition, the ADS-B (ATSAW) symbols are not displayed if:

- The ADS-B data is out of date by 3 seconds; compared to the TCAS information

- The integrity and accuracy of the ADS-B data are invalid;
- The tracks or positions from other aircraft are missing; or
- The GPS position of the own aircraft is lost for more than 5 minutes or downgraded.

8.3.1.1 Operational Environment

The ATSAW-AIRB is applicable in both controlled and uncontrolled airspace. It is likely to produce more benefits from a safety perspective in airspace where separation is not provided by ATC. It can be used from prior to take-off, through in-flight operations, to landing, by aircraft operating under Instrument Flight Rules (IFR) and Visual Flight Rules (VFR) and by all types of aircraft. In Visual Meteorological Conditions (VMC), a routine out of the window scan remains key to safety. In Instrument Meteorological Conditions (IMC), the ATSAW-AIRB will supplement existing available surveillance information from ATC and aircraft radio communication. In terms of traffic density, ATSAW-AIRB is applicable in low to very high density.

The use of ATSAW-AIRB does not require any changes to the ATS infrastructure, systems and ATC procedures. Therefore, application can be used in the exact same environments as the current operations from the communications, navigation and surveillance perspective (CASCADE Operational Focus Group, 2009).

8.3.1.2 Requirements

The ATSAW-AIRB application requires all the aircraft within the airspace to be capable of transmitting ADS-B Out messages and the “owner aircraft” to be equipped with a traffic display (e.g CDTI or merged TCAS/ADS-B traffic display). Standardisation for the implementation of the application is developed jointly by EUROCAE and the RTCA (EUROCAE and RTCA, 2010a). EUROCONTROL has developed a Preliminary Safety Case for ATSAW-AIRB. To date more than 3000, ATSAW-AIRB equipped flights have been performed in Europe (Rekkas, 2013). However, the relevant safety case is not in the public domain.

According to Airbus (Lelievrep, 2005), the ATSAW-AIRB application itself is less demanding in terms of certification level and ADS-B data performance, than spacing or separation applications. This may be due to the unavailability of ADS-B information quality assessment mechanisms in the CDTI.

Nevertheless, without ensuring the certification and ADS-B performance level, the safety and efficiency of the ATSAW application will not be achieved. This is confirmed by EUROCONTROL stressing that ADS-B systems used in the provision of the ATSAW-AIRB shall be of a very high level of reliability, availability and integrity (CASCADE Operational Focus Group, 2009). Furthermore, ATSAW paves the way for enhanced airborne surveillance applications; ATSAW-ITP, ATSAW-VSA, ATSAW-SURF and, also spacing and separation. The required ADS-B information elements to support ATSAW-AIRB are:

- Aircraft 24 bit address;
- Horizontal Position;
- Vertical Position;
- Horizontal Velocity;
- Vertical Velocity;
- Emergency/Priority Status;
- Position Accuracy (NAC_P); and
- System Design Assurance (SDA).

The minimum required ADS-B performances for ATSAW-AIRB application are:

- $NAC_P = 5$;
- $NAC_V = 1$; and
- SDA = 1.

8.3.2 Air Traffic Situational Awareness In-Trail Procedure in oceanic airspace (ATSAW ITP)

Currently, aircraft operating in procedural airspace (oceanic or remote) are constrained to fly at the same flight level, and thus do not necessarily fly at an optimum flight level. ATSAW-ITP using ADS-B is meant to enable altitude changes. The ITP is achieved with the combination of ATSAW and CPDLC. The ATSAW display allows the pilot to detect a climb/descend opportunity. The clearance exchange for the altitude change is then requested via CPDLC. The shared situational awareness between pilot and the ATC enabled by ADS-B will provide confidence to ATC to grant the clearance requested. This will also lead to reduced separation between aircraft in these airspaces. The current standard longitudinal separation requirement is 80NM (ICAO, 2007c), while with ATSAW- ITP, a reduced longitudinal separation of 15NM (Vidal, 2012) will be achieved. The vertical separation minimum is 1000ft in a RVSM airspace (below FL290) and 2000ft in non RVSM airspace (above FL290).

Flight level changes can significantly improve flight efficiency by reducing fuel use. This is because there is no single flight level that provides an optimum cruising flight level over the substantial period of time that aircraft spend in procedural airspace. As the optimum flight level increases throughout the flight (as fuel is burned and aircraft weight is reduced), the aircraft would need to climb to maintain optimum cruise efficiency. Additionally, higher or lower flight levels may be more efficient because of more favorable winds (ICAO, 2012b). ATSAW-ITP is therefore, expected to contribute to a reduction in CO_2 emissions (Vidal, 2012). These benefits were assessed by EUROCONTROL in the CRISTAL ITP project (Martensson and Rekkas, 2009). The study found that ITP is capable of approximately 1% fuel burn reduction resulting in a saving € 108 million (€ 124K per aircraft) annually and a reduction in CO_2 emission of 344000 tonnes annually.

In addition to capacity, efficiency and cost improvements, flight level changes can increase safety when turbulent conditions exist at the current flight level. A flight level change for this reason would reduce the risk of injury to passengers and cabin crew, and increase passenger comfort (ICAO, 2012b).

8.3.2.1 Operational Environment

The ATSAW-ITP, is designed for en-route non-surveillance environments in which the airspace system is composed of fixed routes, flexible tracks, and random routes, where separation is procedural and supported by periodic position reports via radio communication (EUROCAE and RTCA, 2008a). Random routes may cross each other at a variety of angles depending on city pairs served by the flights and on forecast winds. Random routes may also merge with each other. Random routes include user preferred routes (UPR) and the Dynamic Aircraft Route Planning (DARP) system used in the Pacific region. To date, ATSAW-ITP is only certified in the North Atlantic region.

8.3.2.2 Requirements

In order to enable the ATSAW-ITP application, the following criteria have to be met:

- A maximum of two reference (target) aircraft; +/- 2000 feet from ITP aircraft altitude;
- The reference aircraft can be any combination of ahead of or behind the ITP aircraft;
- The ITP aircraft must be able to climb or descend at no less than 300 feet per minute;

- ITP may be initiated at distances between aircraft no closer than 15 NM and no more than 20 knots of closure;
- The closing Mach number difference must be less than or equal to a Mach Number of 0.06;
- The ITP aircraft must maintain the Mach number in climb;
- The reference aircraft must be level-flight and non-manoeuvring;
- The ITP aircraft must have certified ITP equipment onboard as well as CPDLC; and
- The reference aircraft must have a valid ADS-B Out signal.

The required ADS-B information elements to support ATSAW-ITP are:

- Aircraft 24 bit address;
- Horizontal Position;
- Vertical Position;
- Horizontal Velocity;
- Vertical Velocity;
- Emergency/Priority Status;
- Velocity Accuracy;
- Source Integrity Level (SIL);
- Navigation Integrity Category (NIC);
- Position Accuracy (NAC_P); and
- System Design Assurance (SDA).

The minimum required ADS-B performances for the ATSAW-ITP application are:

- $NAC_P = 5$;
- NIC = 5;
- $NAC_V = 1$;
- SIL = 2; and
- SDA = 2.

8.3.3 Air Traffic Situational Awareness Visual Separation in Approach (ATSAW-VSA)

Operations at some airports are based on pilots maintaining visual separation from the preceding aircraft to increase runway capacity. ATSAW-VSA is meant to support this type of operation. The objective of this application is to safely execute approach procedures using “own separation” from the preceding aircraft more efficiently and more regularly (CASCADE Operational Focus Group, 2008). The procedure aids the pilot to acquire and maintain visual contact with the preceding aircraft. More importantly it supports safe operations in extended meteorological conditions. The ATSAW-VSA improves efficiency by increasing the runway capacity, and also improves safety by providing enhanced situational awareness and enhanced identification of the target aircraft (Vidal, 2010). The ATSAW-VSA paves the way for future spacing applications.

8.3.3.1 Operational Environment

The ATSAW-VSA application, defined in (EUROCAE and RTCA, 2008b), is designed to support aircraft performing approach and landing operations in VMC. It is applicable to all types of runway configuration: single runway, independent parallel runways, dependent parallel runways and closely-spaced parallel runways. It is also applicable to airspace of any traffic density (ICAO, 2012b).

8.3.3.2 Requirements

To enable the ATSAW-VSA, the aircraft has to be equipped with ADS-B In equipment, appropriate flight deck tools, and a traffic display tool (e.g. CDTI). Most importantly the application is only feasible with full mandate of ADS-Out, ensuring all the surrounding aircraft are equipped with ADS-B Out capability. Partial equipage of surrounding aircraft is not sufficient to use the ATSAW-VSA application. However, the use of ATSAW-VSA is not a substitute to visual information. Instead the pilot has to maintain visual contact with the preceding aircraft throughout the ATSAW-VSA.

Apart from the above, there are no new requirements on ground systems when ATSAW-VSA is used. Therefore, from communication, navigation and surveillance perspectives, the application can be used in the same environments as existing operations.

The required ADS-B information elements to support ATSAW-VSA are:

- Aircraft 24 bit address;
- Horizontal Position;
- Vertical Position;
- Horizontal Velocity;
- Vertical Velocity;
- Emergency/Priority Status;
- Velocity Accuracy;

- Source Integrity Level (SIL);
- Navigation Integrity Category (NIC)
- Position Accuracy (NAC_P); and
- System Design Assurance (SDA).

The minimum required ADS-B performances for the ATSAW-VSA application are:

- $NAC_P = 6$;
- NIC = 6;
- $NAC_V = 1$;
- SIL = 1; and
- SDA = 1.

8.3.4 Air Traffic Situational Awareness on the Airport Surface (ATSAW-SURF)

The ATSAW-SURF is intended to improve situational awareness of surrounding aircraft and ground vehicles operating in the vicinity of the aerodrome, when operating on the aerodrome surface during final approach, landing and take-off. This is achieved by providing the pilot with a display of the surrounding traffic position and identity, together with the "own aircraft" position overlaid on a map of the aerodrome. The enhanced situational awareness provided by the ATSAW-SURF application will improve the safety of aerodrome surface operations, in particular at taxiway and runway intersections, and for aircraft landing and taking off. A secondary outcome is to enhance taxi efficiency through improved traffic situational awareness during operations such as conditional taxi clearances, especially during low visibility conditions, night operations and at airports unfamiliar to flight crews. The application is also expected to decrease pilot and controller workload by reducing requests for repeat information with respect to surrounding traffic (ICAO, 2012b).

8.3.4.1 Operational Environment

The ATSAW-SURF application defined in (EUROCAE and RTCA, 2010b) is designed to be used by aircraft conducting operations on or near the aerodrome surface, at both controlled and uncontrolled airports. It may be introduced in a partial or mixed equipage environment in which some aircraft and ground vehicles are equipped only with ADS-B Out. It is also applicable to be used in all visibility conditions without modifying controller/pilot responsibilities and procedures compared to current operations.

8.3.4.2 Requirements

To enable the ATSAW-SURF application, the aircraft has to be equipped with ADS-B In equipment, a traffic display tool and must have access to the airport map database. There are no further specific requirements for communication and surface ground surveillance capability when SURF is used. The ATSAW-SURF application does not modify current pilot and controller responsibilities or the use of visual information as the primary basis of airport surface operations. The pilot must continue to maintain visual contact with other traffic, and should not rely solely on the ATSAW-SURF. Surface navigation and own separation must still be based on visual information and radio communications (ICAO, 2012b).

The required ADS-B information elements to support ATSAW-SURF are:

- Aircraft 24 bit address;
- Call sign;
- Category;
- Horizontal Position;
- Surface Heading;
- Ground Speed;
- Capability Codes;
- Operational Modes;
- Velocity Accuracy (NAC_V)
- Position Accuracy (NAC_P); and
- System Design Assurance (SDA).

The minimum required ADS-B performances for ATSAW-SURF application are:

- NAC_P = 7 or 9;
- NAC_V = 2; and
- SDA = 1 or 2.

8.3.5 Spacing / Interval Management (IM)

The step following the introduction of ATSAW applications is the introduction of spacing applications (Vidal, 2012). This is also known as Interval Management (IM). According to the ICAO, IM provides improved means for managing traffic flows and aircraft spacing. This includes both the use of ground and airborne tools as follows (ICAO, 2012b):

- Ground tools that assist the controller in evaluating the traffic scenario and determining appropriate clearances to merge and space aircraft efficiently and safely, and allow the controller to issue an IM clearance; and
- Airborne tools that allow the pilot to conform to the IM clearance. These airborne capabilities are referred to as the Flight-deck based Interval Management (FIM) capabilities. The requirements for the FIM are provided in Safety Performance and Interoperability Requirements for Flight Deck Interval Management (ASPA-FIM) (EUROCAE, 2011).

Under the IM, the equipped aircraft is instructed to merge behind and maintain a given time spacing from another aircraft. Three types of manoeuvers are supported by the IM application:

- Remain in trail;
- Merge in trail; and
- Radar vector then merge in trail.

This is illustrated in Figure 8-5. Compared with current operations, the controller is relieved of the provision of speed and turn clearance to manage traffic by assigning an interval to the pilot. However, during the IM operations, the controller still retains responsibility for separation.

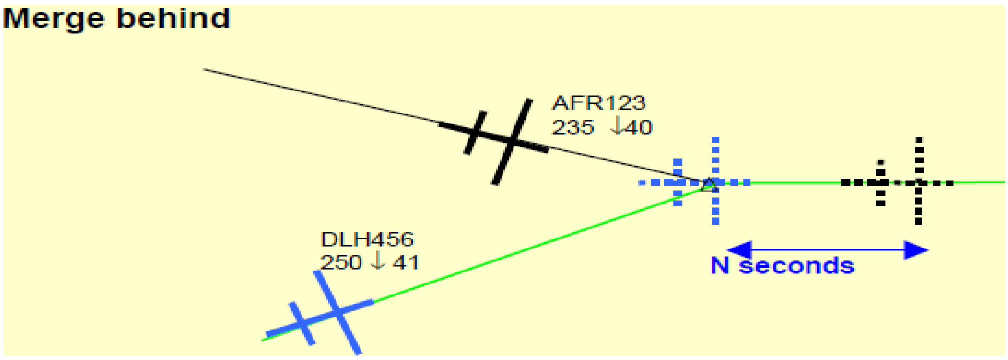


Figure 8-5: Manoeuvres supported by the Interval Management application

In terms of operational benefit, the IM application may enhance traffic regularity during the approach to dense airports to increase airport capacity. Apart from this, the ICAO has identified a number of potential benefits:

- Early speed advisories removing requirements for subsequent path-lengthening;

- Consistent and low variance spacing between paired aircraft (e.g., at the entry to an arrival procedure and on final approach). More precise spacing can allow for higher throughput and more efficient aircraft operations;
- Continuous Descent Operations (CDO) in higher density environments than in current operations;
- Reduced ATC instructions due to the need to communicate fewer speed and vector instructions; and
- When an Arrival MANager (AMAN) is used, the IM procedure will support more efficient aircraft operations for FIM-equipped aircraft.

8.3.5.1 Operational Environment

The IM application is used in a variety of environments and situations and during all phases of flight (i.e. departure, en-route and arrival phases).

8.3.5.2 Requirements

Technology requirements for the aircraft performing IM operation include: ADS-B IN capability, avionics components (FIM equipment /spacing functions with advisories) that provide IM capabilities (i.e. to provide IM speed and IM Turn), and a cockpit based CDTI. For the reference/target aircraft: ADS-B OUT capability and other requirements similar to ITP compliance. A direct communication link is also required between pilotS and controllers (e.g. radio communication or CPDLC). Ground automation to support the interval management application is also required. This will most likely be customised based on the set of interval management procedures allowed in a given terminal area. This may include the implementation of additional CPDLC messages. The AMAN tool is recommended for arrival operations (ICAO, 2012c).

The IM application implementation will impact the ATC system in terms of additional ground systems and new procedures. According to Airbus, in Europe, these impacts are to be addressed in parallel by ANSPs within SESAR (Vidal, 2012). The ICAO adds that, controllers and pilots will be provided with new procedures and a new phraseology for IM operations, to be developed after the IM application is fully defined (ICAO, 2012b).

The required ADS-B information elements to support IM are:

- Aircraft 24 bit address;
- Horizontal Position;
- Vertical Position;
- Horizontal Velocity;
- Vertical Velocity;
- Emergency/Priority Status;
- Position Accuracy (NAC_P); and
- System Design Assurance (SDA).
- Capability Codes
- Operational Modes
- Navigational Integrity Category (NIC)
- Velocity Accuracy
- Source Integrity Level (SIL)

The minimum required ADS-B performances for the IM application are:

- NAC_P = 6 (En-route) and 7 (TMA);
- NIC = 5 (En-route) and 7 (TMA);
- NAC_V = 1 (En-route) and 2 (TMA);
- SIL = 2; and
- SDA = 1×10^{-6} per flight hour.

8.3.6 Separation

The separation application in this section refers to Airborne SEParation (ASEP) and Airborne Self-SEParation (SSEP). According to the ICAO (2012b), delegation of separation responsibility to flight crew is foreseen in the future. The pilot will be responsible to ensure separation from designated aircraft as communicated in the future clearance, thereby relieving the controller from the responsibility for separation between these aircraft. Typical airborne separation applications include (ICAO, 2012c):

- interval management with delegation of separation: the flight crew maintains a time-based separation behind designated aircraft;

- lateral crossing and passing: the flight crew adjusts the lateral flight path to ensure that horizontal separation with designated aircraft is larger than the applicable airborne separation minimum;

- vertical crossing: the flight crew adjusts the vertical flight path to ensure that vertical separation with designated aircraft is larger than the applicable airborne separation minimum;

- paired approaches in which the flight crew maintains separation on final approach to parallel runways; and

- in oceanic airspace, improved procedures of ITP using new airborne separation minima: ASEP-ITF In-trail follow; ASEP-ITP In-trail procedure; and ASEP-ITM In-trail merge.

Airborne self-separation occurs when the pilot ensures separation of their aircraft from all surrounding traffic. Hence the controller has no responsibility for separation. Typical airborne self-separation applications include (ICAO, 2012c):

- airborne self-separation in ATC-controlled airspace;
- airborne self-separation in segregated en-route airspace;
- airborne self-separation in mixed-equipage en-route airspace; and
- airborne self-separation –free flight on an oceanic track.

An early implementation of the ASEP and SSEP applications is anticipated in oceanic and low density airspace. ASSTAR (2005-2007) initiated the work on ASEP and SSEP applications in Europe which has been supported by the following SESAR projects:

- SESAR Project 04.07.04.b ASAS-ASEP Oceanic Applications.
  The airborne separation in-trail follow (ASEP-ITF) and in-trail merge (ASEP-ITM) applications have been designed for use in oceanic and other non-radar airspace.

- SESAR Project 04.07.06 En Route Trajectory and Separation Management – ASAS Separation (Cooperative Separation).
  The main objective of this project is to assess the introduction of the ASAS separation application in the SESAR context (taking into account all platforms, including military and Unmanned Aerial System (UAS)).

The ASEP and SSEP applications will require airborne separation minima to be defined which in turn will require very high performance navigation and surveillance functions onboard. In addition, due to the impact of these applications on the controller and pilot responsibilities, provisions for these applications are expected to require modification of the ICAO annexes. Currently, no RTCA/EUROCAE documents exists to support these applications (ICAO, 2012b). They are still under research and development.

All of the airborne surveillance applications discussed above rely on the capability of ADS-B Out to provide the required information elements.

8.4 ADS-B Out Capabilities versus the Airborne Surveillance Applications Requirements

There are currently three different versions of ADS-B Out and hence ADS-B avionics with different levels of performance: DO-260, DO-260A and DO-260B. The differences between the three versions are discussed in detail in Chapter 3 and summarised below:

a) Version 0 (DO-260) provides a basic ADS-B capability, with position integrity provided by the NUC parameter. This was the initial version of ADS-B and there are a variety of Version 0 installations; typically only those ADS-B version 0 installations complying with EASA AMC 20-24 are approved for use in ATC separation applications;

b) Version 1 (DO-260A) provides, amongst others, separate accuracy and integrity parameters which replace the NUC – NAC and NIC and SIL; also, a new message provides Target State and Status data; and

c) Version 2 (DO-260B) provides, amongst others, a renaming and new definition for SIL; includes several new fields, such as the system design assurance (SDA) and Geometric Vertical Accuracy; removes vertical information from the NIC, NAC, and SIL parameters; provides improved support of surface operations through changes to the NIC encoding; supports non-diversity antenna options for smaller (general aviation) aircraft in addition to various other fixes/improvements as discussed in Chapter 3.

The differences between the versions is in the amount of information (particularly the quality indicators for the aircraft state information) transmitted in the ADS-B messages. However, the performance of the aircraft state information is not affected by the different versions. The additional information in the last version increases the user's confidence level on the aircraft state information broadcast by the ADS-B system. To date, most of the aircraft flying are equipped with DO-260 avionics on a voluntary basis. The aircraft analysed in this thesis are certified to DO-260 standards. This section analyses the credibility and level of ADS-B Out performance identified and analysed in Chapter 6 and Chapter 7 to support the ADS-B ground and airborne surveillance applications. Table 8-1 presents the results of the mapping exercise between the specific information in the ADS-B message required for each of the applications and the availability of this information in real time.

Table 8-1: Required Information Elements to Support ADS-B Applications vs. Available Information in the ADS-B Message (certified with DO-260)

Information Element	Required								Available	Comments
	ATSAW-AIRB	ATSAW-VSA	ATSAW-ITP	Spacing	Airborne Separation (ASEP)	Self – separation (SSEP)	ATSAW-SURF &ADS-B APT	ATS Surveillance		
Identification										
Call Sign				✓	✓	✓	✓	✓	✓	
Address	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Category					✓	✓	✓	✓	✓	
Mode A Code								✓	✓	
State Vector										
Horizontal Position	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Vertical Position	✓	✓	✓	✓	✓	✓		✓	✓	
Horizontal Velocity	✓	✓	✓	✓	✓	✓		✓	✓	
Vertical Velocity	✓	✓	✓	✓	✓	✓		✓	✓	
Surface Heading							✓		✓	
Ground Speed							✓		✓	
Mode Status										
Emergency/ Priority Status	✓	✓	✓	✓				✓	✓	
Capability Codes				✓	✓	✓	✓	✓		No Capability Codes available in the ADS-B message
Operational Modes				✓	✓	✓	✓	✓		No Operational Modes available in the ADS-B message
State Vector Quality Indicator										
NIC		✓	✓	✓	✓	✓	✓	✓		NIC value is presented as NUC representing horizontal position accuracy and integrity in the ADS-B message
NAC_P	✓	✓	✓	✓	✓	✓	✓	✓		No specific position accuracy

	Required								Available	Comments
Information Element	**ATSAW-AIRB**	**ATSAW-VSA**	**ATSAW-ITP**	**Spacing**	**Airborne Separation (ASEP)**	**Self – separation (SSEP)**	**ATSAW-SURF &ADS-B APT**	**ATS Surveillance**		
										available in the ADS-B message
NAC_V		✓	✓	✓	✓	✓	✓	✓	✓	
SIL		✓	✓	✓	✓	✓	✓	✓		No SIL information available in the ADS-B message
SDA	✓	✓	✓	✓	✓	✓	✓	✓		No SDA value available in the ADS-B message
Air-Reference Vector					✓					No Air-Reference Vector available in the ADS-B message
Intent Data					✓	✓				No intent information available in the ADS-B message

The ADS-B data included in the mapping exercise in Table 8-1 are from aircraft with avionics certified to DO-260 standards and compliant with EASA AMC 20-24. Based on the mapping exercise, the required Identification Information and State Vector Information are available in the real time ADS-B message to support all the applications in Table 8-1. The only Mode Status Information available in the ADS-B message required to support the ATSAW-AIRB/VSA/ITP, Spacing and ATS Surveillance is the Emergency/Priority Status Information. Apart from the Velocity Accuracy (NAC_V), none of the State Vector Quality Indicator information required by the applications is available in the ADS-B message. However, the NUC information in the ADS-B message is a substitute for the NIC and NAC_P information, indicating the quality of the transmitted aircraft position information. The Air-Reference Vector information required for the ASEP application is not available in the ADS-B message. Intent Data required for the ASEP and SSEP are also not available in the ADS-B message.

Based on the assessment in Chapter 6, the ADS-B performance between aircraft is variable. Therefore, it is currently not possible to derive a representative ADS-B performance. Hence, in order to validate the ADS-B performance to support the airborne surveillance applications in this Chapter, the best and worst aircraft performances are mapped to the minimum required ADS-B performance to support these applications. The applications include ATSAW-AIRB, ATSAW-VSA, ATSAW-SURF, Oceanic-ITP, as well as Interval-Management/Spacing and Airborne Separation delegation (ASEP) for en-route/terminal phases of operation. Self-Separation (SSEP) is not included as the requirements for this application are not established yet. In fact, most of the applications envisioned to use the information provided by ADS-B are not established fully.

The requirements for each of the airborne applications included in the mapping exercise in Table 8-4 and Table 8-5 are obtained from Safety Performance and Interoperability Requirements for ATSAW during light operations (ATSAW-AIRB) (DO-319), Safety Performance and Interoperability Requirements for ATSAW Visual Separation in Approach (ATSAW VSA) (DO-314), Safety Performance and Interoperability Requirements for ATSAW on the Airport Surface (ATSAW SURF) (DO-322), Safety Performance and Interoperability Requirements for ATSAW In-Trail Procedure in oceanic airspace (ATSAW ITP) (DO-312), and Minimum Aviation System Performance Standards (MASPS) for Aircraft Surveillance Applications (ASA) (DO-289).

The required ADS-B position accuracy is represented by the NAC_P value, as discussed in Chapter 3. This value is translated as a 95% Horizontal Accuracy Bound or measured as a Horizontal Position Error (HPE). The required ADS-B integrity is indicated as the NIC value, representing an integrity containment radius around an aircraft's reported position. The required ADS-B velocity accuracy is presented as NAC_V. Onboard navigation sources such as GNSS provide a direct measure of velocity to the ADS-B system. The navigation data source 95% accuracy for the Horizontal ($HFOM_V$) and Vertical Figures Of Merit Vertical ($VFOM_V$) components are summarised in Table 8-2.

Table 8-2: Position Velocity Accuracy (NAC_V)

NAC_V	HFOMV Value $VFOM_V$ Value
0	HFOMV ≥ 10 m/s or VFOMV ≥ 15.2 m/s or unknown
1	HFOMV < 10 m/s and VFOMV < 15.2 m/s
2	HFOMV < 3m/s and VFOMV < 4.6 m/s
3	HFOMV < 1m/s and VFOMV < 1.5 m/s
4	HFOMV < 0.3 m/s and VFOMV < 0.46 m/s

Another required ADS-B performance indicator is the System Design Assurance (SDA). The SDA defines the failure conditions that the position transmission chain is designed to support, as defined in Table 8-3. The supported failure conditions will indicate the probability of a fault in the position transmission chain which would cause false or misleading position information to be transmitted.

Table 8-3: System Design Assurance (SDA)

SDA	Probability of Undetected Fault causing transmission of false or misleading information
0	$>1 \times 10^{-3}$ per flight hour or unknown
1	$\leq 1 \times 10^{-3}$ per flight hour
2	$\leq 1 \times 10^{-5}$ per flight hour
3	$\leq 1 \times 10^{-7}$ per flight hour

Table 8-4: Minimum Required ADS-B Performance for Airborne Surveillance Application vs Actual ADS-B Performances (best performing aircraft)

Performance Metric	Required ADS-B Performance						Measured ADS-B System Performance (Best performing aircraft from Chapter 6 analysis)
	Situational Awareness Applications (ATSAW)				IM/Spacing (EnRoute/Terminal)	Airborne Separation (ASEP) (EnRoute/Terminal)	
	AIRB	VSA	SURF	ITP			
Accuracy (NAC$_P$)	5	6	7/9 [1]	5	6/7	9	26 meters
Integrity (NIC)	N/A [2]	6	N/A	5	5/7	9	NUC$_P$ = 6.4
Velocity Accuracy (NAC$_V$)	1	1	2	1	1 / 2	3	Unknown
Source Integrity Level (SIL)	N/A	1	N/A	2	2	2	Not Available
System Design Assurance (SDA)	1	1	1/2 [3]	2	< 1x10^{-6} / flight hour	TBD	Not Available
Update Rate (seconds)	3	N/A	≤ 2	≤ 5 to ≤ 24	* [4]	TBD	2.3
Latency (seconds)	< 1.5	< 1.6	< 0.5 (onboard)	≤ 4.575	*	TBD	0.6

Table 8-5: Minimum Required ADS-B Performance for Airborne Surveillance Application vs Actual ADS-B Performances (worst performing aircraft)

Performance Metric	Required ADS-B Performance						Measured ADS-B System Performance (Worst performing aircraft from Chapter 6 analysis)
	Situational Awareness Applications (ATSAW)				IM/Spacing (EnRoute/Terminal)	Airborne Separation (ASEP) (EnRoute/Terminal)	
	AIRB	VSA	SURF	ITP			
Accuracy (NAC$_P$)	5	6	7/9	5	6/7	9	553 meters
Integrity (NIC)	N/A	6	N/A	5	5/7	9	NUC$_P$ = 5
Velocity Accuracy (NAC$_V$)	1	1	2	1	1 / 2	3	0
Source Integrity Level (SIL)	N/A	1	N/A	2	2	2	Not Available
System Design Assurance (SDA)	1	1	1/2	2	< 1x10^{-6} / flight hour	TBD	Not Available
Update Rate (seconds)	3	N/A	≤ 2	≤ 5 to ≤ 24	*	TBD	1.4
Latency (seconds)	< 1.5	< 1.6	< 0.5 (onboard)	≤ 4.575	*	TBD	1.9

[1] SURF surface targets require NACP >=9
SURF airborne targets require NACP = 7 or 9 depending on parallel runway spacing
[2] N/A – Not Applicable
[3] Hazard level for ownship when airborne or on surface >80 knots =Major (SDA=2)
Hazard level for ownship when airborne or on surface <80 knots =Minor (SDA=1)
[4] Not available at the time of writing

Table 8-4 maps the performance of the best performing aircraft analysed in this thesis to the minimum required ADS-B performance for future applications. The best ADS-B position accuracy of 26 metres, corresponding to NAC_P = 9, is better than the required accuracy performance for all airborne applications. The measured NUC_P = 6.4 corresponds to a HPL < 0.2 NM. Based on the specifications, ADS-B position integrity is not required for the ATSAW-AIRB and ATSAW-SURF. The required position integrity for ATSAW-VSA is NIC = 6 (HPL < 0.5 NM), and Oceanic-ITP is NIC = 5 (HPL < 1.0 NM). The Interval-Management en-route also requires a NIC = 5 and Interval-Management TMA a NIC = 7 (HPL < 0.2 NM) and ASEP a NIC = 9 (HPL < 25 meters). Therefore the ADS-B system integrity is sufficient to support all of the applications except for the ASEP application. The required SIL and SDA parameters are not available from the aircraft certified with DO-260 avionics. The required NAC_V value is missing from the ADS-B message collected for the particular aircraft. This reduces the credibility of the ADS-B system in the particular aircraft to support the envisioned applications. The measured update rate = 2.3 seconds, is sufficient for all airborne applications except for the ATSAW-SURF. The latency performance of 0.6 seconds is better than the required latency for all of the airborne applications. The required latency for ATSAW-SURF is based on the onboard latency of < 500 milliseconds, while the measured latency of 0.6 seconds is based on the total latency. However, the onboard latency for the aircraft is assumed to be consistent with the established ADS-B RAD aircraft requirements of 200 milliseconds, and hence, sufficient for the ATSAW-SURF.

Table 8-5 maps the performance of the worst performing aircraft analysed to the minimum required ADS-B performance for the airborne applications. 553 meters ADS-B position accuracy corresponds to a NAC_P = 6, which is only sufficient to support ATSAW-AIRB, ATSAW-VSA, Oceanic-ITP and Interval-Management en-route. The ADS-B position integrity NUC_P = 5 corresponds to HPL < 0.5 NM, which is equivalent to NIC = 6 and hence only sufficient to support the ATSAW-VSA, Oceanic-ITP and Interval-Management en-route. ADS-B velocity accuracy NAC_V = 0 indicates that the system is unable to support the required velocity accuracy for any of the applications. The measured update rate = 1.4 seconds, is sufficient for all airborne applications. The latency performance of 1.9 seconds is only sufficient to support ATSAW-ITP.

8.5 Summary

From the mapping exercise conducted to validate the credibility of the ADS-B Out messages analysed in this thesis to support the ground and airborne surveillance applications, it is found that all of the applications require some of the Mode Status and State Vector Quality Indicator information, which are currently lacking in the ADS-B message. Hence, in order to support the relevant applications, aircraft must be certified to DO-260B standards. In addition, continuous ADS-B system monitoring is crucial to ensure safety. The analysis in Chapter 6 indicates that some of the certified aircraft have missing data elements, corresponding to a performance inferior to their level of certification. The mapping exercise performed to assess the capability of the ADS-B system (analysed in Chapter 6) indicates that ADS-B accuracy from the best performing aircraft is sufficient for all foreseen applications while the worst performing aircraft only supports ATSAW-AIRB, ATSAW-VSA, Oceanic-ITP and Interval-Management en-route. ADS-B integrity from both aircraft is sufficient to support all applications except the most stringent application: ASEP. ADS-B velocity accuracy values from both aircraft are insufficient to support any application. ADS-B update rate from the best performing aircraft is sufficient for all applications except for the ATSAW-SURF, while the worst performing aircraft supports all applications. The best performing aircraft latency is sufficient for all applications while the worst performing aircraft latency is only sufficient for the ATSAW-ITP. In addition, the remaining required performance parameters SIL and SDA are unavailable from aircraft certified to DO-260 standards. Therefore, aircraft must be certified to DO-260B to support the applications with continuous monitoring to ensure the required system performance.

Chapter 9

Conclusions, Recommendations and Future Works

9.1 Conclusions

The objectives of the thesis were to:

- Identify the deficiencies of current surveillance systems in supporting increasing air travel demand;
- Identify the capabilities of ADS-B to address the limitations of the current surveillance systems;
- Develop a comprehensive, rigorous and reliable safety assessment framework for ADS-B;
- Identify the failure modes of the ADS-B, establish a failure mode register and specify failure models;
- Assess and quantify ADS-B performance in an operational environment; and
- Derive a mapping between ADS-B performance measured and the required performance of the various applications to be supported by ADS-B.

Based on the research undertaken and presented in this thesis, the following conclusions are drawn.

- From an extensive literature review in Chapter 2, and safety data analysis and input from subject matter experts in Chapter 4, the limitations of the current surveillance systems are identified as important to increasing air traffic.
    - Lack of situational awareness for pilot and controllers
    - Limited surveillance coverage
    - Inaccurate aircraft positioning information
    - Low position update rate
    - Unsynchronized surveillance information between pilot and controllers
    - Unavailability of services in oceanic and remote areas
    - Limited services during extreme weather conditions
    - Limited availability of spare parts to support system operations

- A detailed review of ADS-B functionalities and capabilities in Chapter 3 and mapping exercise in Chapter 4, conclude that ADS-B has the potential to overcome all the limitations identified in the current surveillance systems.

- The main contribution of this thesis is the development of a comprehensive framework for ADS-B safety assessment, in a systematic manner. The framework incorporates a novel approach to validate ADS-B data performance using onboard GPS positioning information as the reference system. This outperforms the existing ADS-B assessment methods which use radar as the reference system, which has a lower performance than the ADS-B system. The framework has been used to assess ADS-B performance in the dense airspace of LTMA, resulting in the quantification of the ADS-B system performance in terms of accuracy, integrity, continuity, availability, latency and reliability.

- The basis for the performance evaluation includes novel methods for ADS-B data and reference data correlation, ADS-B horizontal position error measure (accuracy), latency measure and ADS-B integrity quality indicator validation. The performance evaluation has shown that there is inconsistency in ADS-B system performance of the same aircraft during two different flights. The ADS-B message update rate of all the aircraft to the ground stations neither has a constant value nor a deterministic pattern. Three of the aircraft data had 100% misdetection of the actual system performance. This is a safety threat to the system users and may lead to undesirable incidents.

- The basis for ADS-B system reliability analysis is thorough and novel search of ADS-B failure modes. The notion of the failure modes has been explored and a register developed which incorporates the characteristics and impact of the failure in its operational environment. The hazards derived as a result of the failures were quantified. It concludes that probability of availability of ADS-B as sole surveillance system is lower (0.898) than the availability figures proposed by RTCA (2002) for ADS-B as primary (0.999) and ADS-B as supplemental (0.95). Throughout the process of the performance evaluation, anomalies were not only found in the ADS-B system itself but also in the onboard GPS system that feeds the aircraft position and state vector information to the ADS-B system.

- The mapping exercise performed between ADS-B performance quantified and the required performance of airborne surveillance applications, indicates that ADS-B accuracy from the best performing aircraft is sufficient for the all applications while the worst performing aircraft only supports ATSAW-AIRB, ATSAW-VSA, Oceanic-ITP and Interval-Management en-route. ADS-B integrity from both aircraft is sufficient to support all applications except the most stringent application, ASEP. However, some of the required data elements such as SIL and SDA are not available in the DO-260 ADS-B messages. Therefore, it can be concluded that all aircraft must be certified to DO-260B to support the applications. In addition, continuous monitoring is vital to ensure consistency in system performance of each aircraft.

9.2 Recommendations

A number of recommendations are proposed based on the findings in this thesis to improve ADS-B system implementation:

- ADS-B and radar are inherently different surveillance systems. Whilst radar is a surveillance system independent of aircraft equipage, ADS-B is not. Each aircraft may therefore, exhibit different performance due to the type of avionics or state of the communication link service. The main problem with the ADS-B communication link is signal jamming. For example, Mode S 1090 MHz Extended Squitter (1090ES) is utilized not only by ADS-B, but also by Secondary Surveillance Radar (SSR) and Traffic Collision Avoidance Systems (TCAS). In dense airspace this may affect ADS-B system reliability and availability, a problem that remains to be addressed.

- ADS-B performance is impacted by system-wide, regional and local failures. For example, system-wide failure may be due to GNSS satellite outage or ADS-B ground station failure. Regional failures may be the result of space weather and local, may be the result of faulty avionics. A redundant navigation source with a flag, for example Inertial Navigation System (INS) integrated to the ADS-B system, may be a good idea to resolve the GNSS outage issue.

- In order to evaluate the performance of the ground station, a ground station identifier should be included in the ADS-B message processed at the ground station.

- The quality indicator validation mechanism developed in this thesis should be implemented at the ground station to validate the ADS-B position integrity, and hence ensure safety. Even though the mechanism is tested on aircraft certified towards DO-260 standard in this thesis, the same method can be used for the DO-260B standard.

- The onboard GPS time stamp should be included in the ADS-B message to extrapolate the ADS-B position to the time it was received at the ground station or other aircraft. This will eliminate the total latency.

- Due to the inconsistency identified in the performance of the same aircraft in two different flights in the same airspace, it is recommended that the each aircraft performance is monitored on a periodic basis.

- Apart from monitoring the onboard and ground ADS-B system performance, the performance of the onboard navigation system should be monitored and validated before being used as the aircraft state source for the ADS-B system.

- Collaboration between the ANSP and airline operators is crucial to successfully monitor the ADS-B system performance as a whole.

9.3 Future Work

This thesis has contributed to the safety assessment of ADS-B system, ADS-B failure modes knowledge base, and validation of ADS-B capabilities to support future airborne surveillance applications. Within these applications, further studies are proposed below in order to ensure and enhance ADS-B system operational use in the current operational environment and future enhanced surveillance operations:

- Assessment of ADS-B data from aircraft certified to the DO-260B standards using the Safety Assessment Framework developed in this thesis. This thesis has only used ADS-B data from aircraft certified to the DO-260 standards due to unavailability of the DO-260B data.

- Development of data fusion algorithm to fuse ADS-B position with radar position and/or WAM position to support the transition period before full implementation of ADS-B in the future.

- Development of safety cases using the safety assessment framework for the following scenarios:
    - ADS-B fused with radar operating in LTMA
    - ADS-B fused with MLAT operating in LTMA
    - ADS-B fused with radar and MLAT operating in LTMA

  This thesis focused on ADS-B operating alone in LTMA.

- Development of a method to verify the integrity of the vertical positions transmitted in the ADS-B message. The NIC_{BARO} indicator in DO-260B only indicates if the vertical position value is crosschecked with other sources of pressure altitude. Hence to date, there is no defensible method available for this purpose. This thesis only focused on the horizontal position.

- Investigation of the validation of the NIC value in DO-260B ADS-B data using the algorithm developed in this thesis. This thesis applied the algorithm for validation of the NUC value from DO-260 ADS-B data.

- Improvement of the ADS-B safety assessment framework developed in this thesis by incorporating the advantages of Safety-II approach into the framework.

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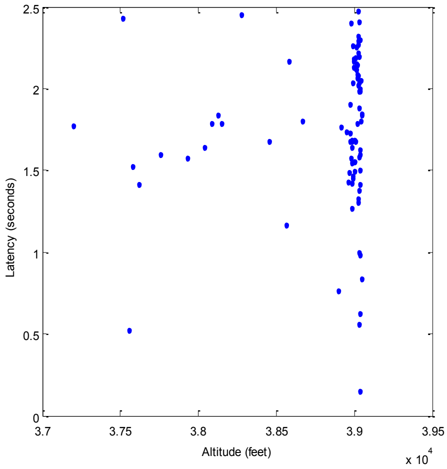
Appendix A

Aircraft ID	Aircraft Make-model	Flight Level Data Availability	GPS Receiver	ADS-B Transponder	Findings	Performance (accuracy, integrity, latency) Analysis
40608F	A318	YES	Thales TLS755 MMR	Honeywell TRA-67A	Duplicate ADS-B messages in the data set. GPS Clock error- no data on the 59th second in the time set. It appears as 00.	Feasible after correcting the clock error and removing the duplicate messages.
405A48	A320	YES	Thales TLS755 MMR	Honeywell TRA-67A	No peculiarities.	Feasible
400A26	A320	YES	Thales TLS755 MMR	Honeywell TRA-67A	Duplicate ADS-B messages in the data set.	Feasible.
40093D	A319	NO	Thales TLS755 MMR	Honeywell TRA-67A	GPS Clock error- time 'minute' does not add after the '59th' second.	Not Feasible due to insufficient data.
400877	A319	YES	Thales TLS755 MMR	Honeywell TRA-67A	GPS Clock error- time 'minute' does not add after the '59th' second.	Feasible after correcting the clock error.
400878	A319	YES	Thales TLS755 MMR	Honeywell TRA-67A	Duplicate ADS-B messages in the data set.	Feasible after filtering out duplicate messages.
40087B	A319	YES	Thales TLS755 MMR	Honeywell TRA-67A	Duplicate ADS-B messages in the data set. GPS Clock error- time 'minute' does not add after the '59th' second.	Feasible after correcting the clock error and removing the duplicate messages.
4008B4	A319	YES	Thales TLS755 MMR	Honeywell TRA-67A	GPS Clock error – time list does not include second '00'. Duplicate time values.	Feasible after correcting the clock error.
4008F2	A319	NO	Thales TLS755 MMR	Honeywell TRA-67A	Duplicate ADS-B messages in the data set.	Feasible after removing the duplicate messages.
400935	A319	YES	Thales TLS755 MMR	Honeywell TRA-67A	No peculiarities.	Feasible
All 6	B747-400		Rockwell Collins GLU920 MMR	ACSS XS-950	GPS horizontal position given every 4 seconds.	Not Feasible due to unreliable GPS data to generate TRUE

All 4	B767-300		Honeywell Mercury Card equipped EGPWC MkV	ACSS XS-950	GPS latitude and longitude values are given individually at different time update-every 2 seconds. Data is assumed to be corrupted.	Not Feasible due to unreliable GPS data to generate TRUE
4005C1	B777-200	NO	Honeywell GNSSU	Honeywell TRA-67A	GPS data and ADS-B data time interval does not correlate	Not Feasible due to uncorrelated timing information
4005BC	B777-200	YES	Honeywell GNSSU	Honeywell TRA-67A	GPS latitude and longitude position jumping.	Not Feasible due to unreliable GPS data to generate TRUE
4005BE	B777-200	YES	Honeywell GNSSU	Honeywell TRA-67A	GPS latitude and longitude position jumping.	Not Feasible due to unreliable GPS data to generate TRUE
400610	B777-200	YES	Honeywell GNSSU	Honeywell TRA-67A	GPS latitude and longitude position jumping.	Not Feasible due to unreliable GPS data to generate TRUE
4006C2	B777-200	YES	Rockwell Collins GLU920 MMR	Honeywell TRA-67A	GPS latitude and longitude position jumping.	Not Feasible due to unreliable GPS data to generate TRUE
4007F7	B777-200	YES	Rockwell Collins GLU920 MMR	Honeywell TRA-67A	GPS latitude and longitude position jumping.	Not Feasible due to unreliable GPS data to generate TRUE

Appendix B

Latency performance across flight altitude



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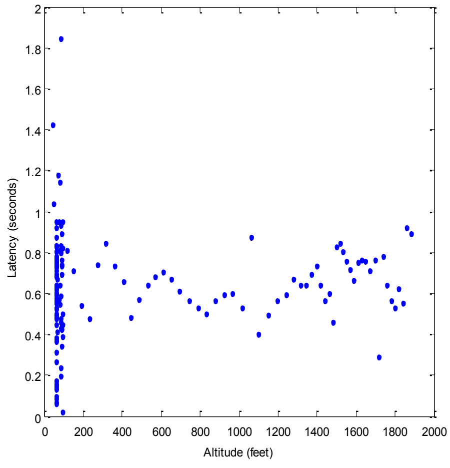

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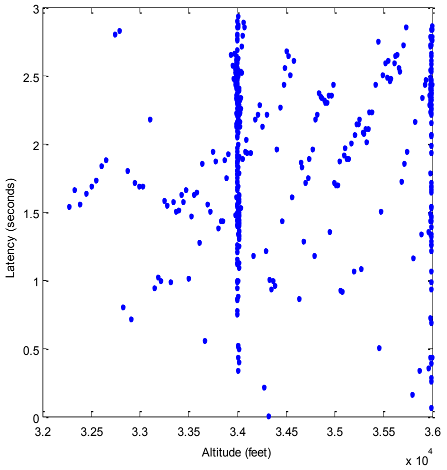

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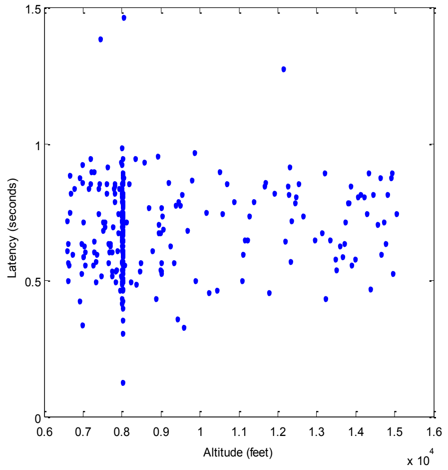

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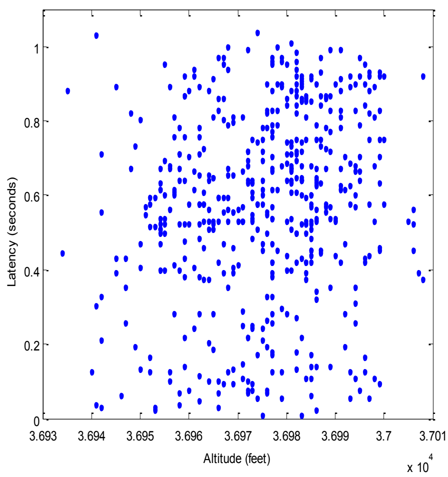

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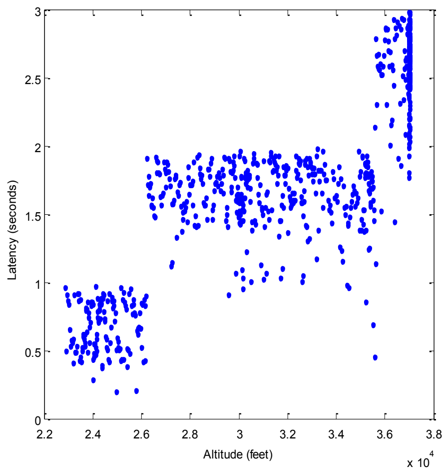

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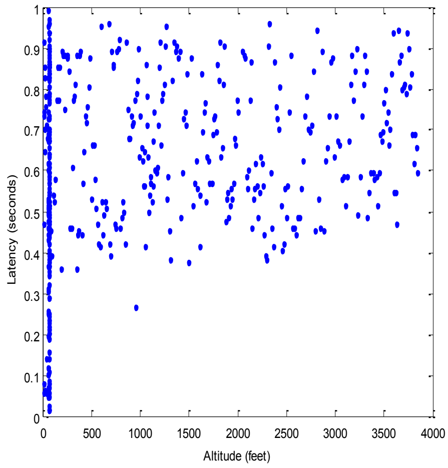
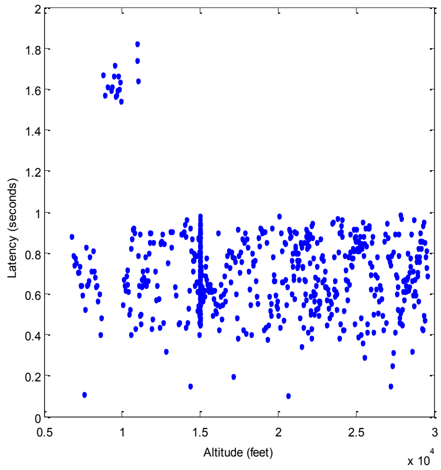


4008F2



400935

Appendix C

Aircraft avionics information and descriptive statistic of ADS-B message update rate

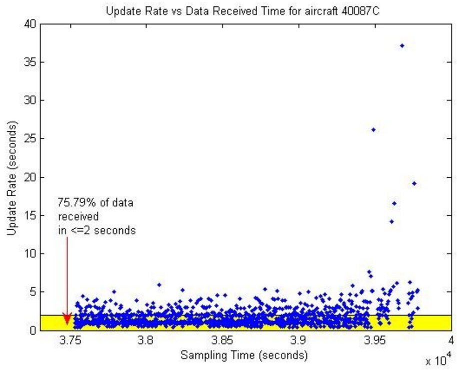
Aircraft ID	Aircraft make-model	GPS receiver model	Transponder model	N	Mean	Std. Dev	Min	Max
A319								
40087C	A319	Thales TLS755 MMR	Honeywell TRA	1355	1.65	1.70	0.40	37.11
400936	A319	Thales TLS755 MMR	Honeywell TRA	3197	1.10	3.09	0.40	173.84
4008AD	A319	Thales TLS755 MMR	Honeywell TRA	3097	1.11	0.77	0.40	23.98
400940	A319	Thales TLS755 MMR	Honeywell TRA	2666	1.04	0.35	0.40	4.96
4008B4	A319	Thales TLS755 MMR	Honeywell TRA	1606	1.13	0.80	0.40	15.64
400802	A319	Thales TLS755 MMR	Honeywell TRA	3126	1.10	0.60	0.40	12.07
4008B5	A319	Thales TLS755 MMR	Honeywell TRA	1263	1.53	0.96	0.40	7.80
400942	A319	Thales TLS755 MMR	Honeywell TRA	3033	1.14	0.85	0.40	18.18
A320								
406250	A320	Thales TLS755 MMR	Honeywell TRA	1210	1.62	1.39	0.41	27.09
40097D	A320	Thales TLS755 MMR	Honeywell TRA	1076	1.72	1.38	0.41	17.49
4009DA	A320	Thales TLS755 MMR	Honeywell TRA	2755	1.09	0.51	0.40	9.92
4009C7	A320	Thales TLS755 MMR	Honeywell TRA	1394	1.72	2.00	0.40	39.81
405EE0	A320	Thales TLS755 MMR	Honeywell TRA	1475	1.64	1.19	0.40	12.80
400CEB	A321	Thales TLS755 MMR	Honeywell TRA	2159	1.28	0.81	0.40	15.52
4010DB	A321	Thales TLS755 MMR	Honeywell TRA	2244	1.56	1.08	1.56	14.34
B744								
40054D	B744	Rockwell Collins GLU920 MMR	ACSS XS	1071	1.93	5.84	0.40	169.84
40040D	B744	Rockwell Collins GLU920 MMR	ACSS XS	1017	1.57	1.14	0.40	12.43
4005E3	B744	Rockwell Collins GLU920 MMR	ACSS XS	2587	1.10	0.64	0.40	18.89
4006AD	B744	Rockwell Collins GLU920 MMR	ACSS XS	1287	1.53	4.75	0.40	163.41
4005E2	B744	Rockwell Collins GLU920 MMR	ACSS XS	1730	1.50	1.25	0.40	28.32
4006B3	B744	Rockwell Collins GLU920 MMR	ACSS XS	1066	1.29	0.94	0.40	10.36
4006AB	B744	Rockwell Collins GLU920 MMR	ACSS XS	1308	1.28	0.96	0.40	17.27
4006B0	B744	Rockwell Collins GLU920 MMR	ACSS XS	2026	1.58	2.51	0.41	104.38
B777-200								
4007F0	B777-200	Rockwell Collins GLU920 MMR	Honeywell TRA	2421	1.45	0.99	0.40	14.74
4005BB	B777-200	Honeywell GNSSU	Honeywell TRA	2371	1.52	1.21	0.40	25.99
400771	B777-200	Rockwell Collins GLU920 MMR	Honeywell TRA	1140	1.82	2.23	0.40	41.91
4007F3	B777-200	Rockwell Collins GLU920 MMR	Honeywell TRA	1603	1.22	2.65	0.40	98.40
400774	B777-200	Rockwell Collins GLU920 MMR	Honeywell	1728	1.17	0.87	0.40	19.77

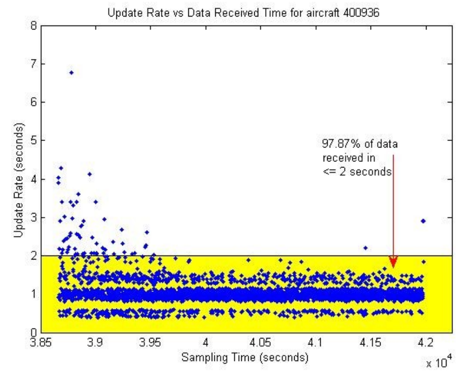
Aircraft ID	Aircraft make-model	GPS receiver model	Transponder model	N	Mean	Std. Dev	Min	Max
			TRA					
400683	B777-200	Rockwell Collins GLU920 MMR	Honeywell TRA	2747	1.14	2.46	0.40	127.05
4007F9	B777-200	Rockwell Collins GLU920 MMR	Honeywell TRA	2316	1.60	1.19	0.40	26.51
4005BE	B777-200	Honeywell GNSSU	Honeywell TRA	1257	1.59	2.08	0.40	47.11

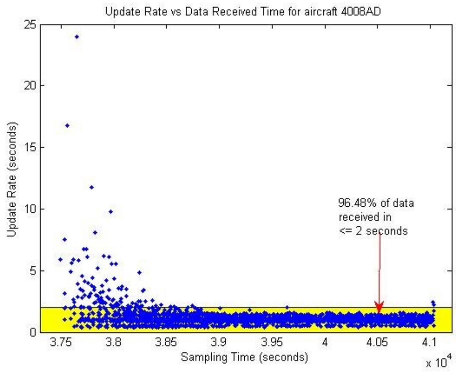
Appendix D

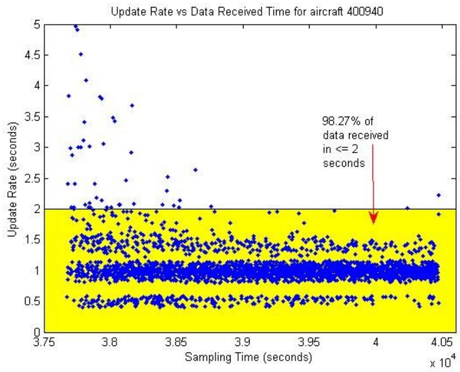
Update rate vs. Flight time

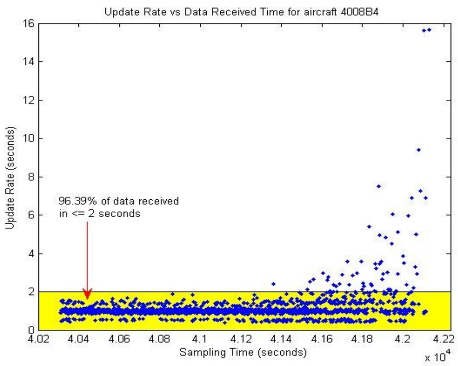
A319

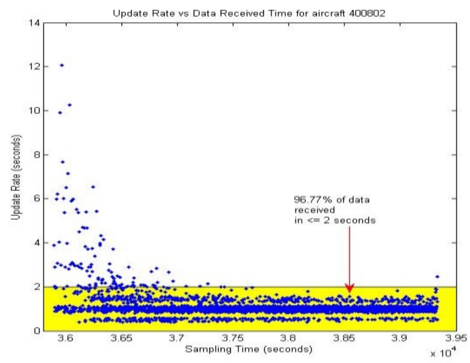


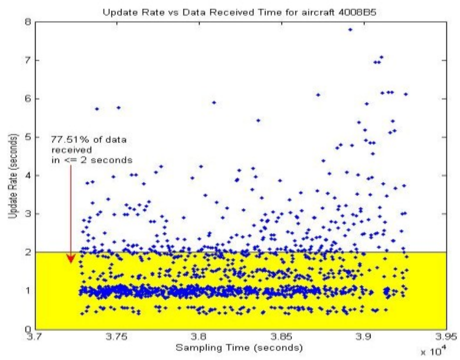


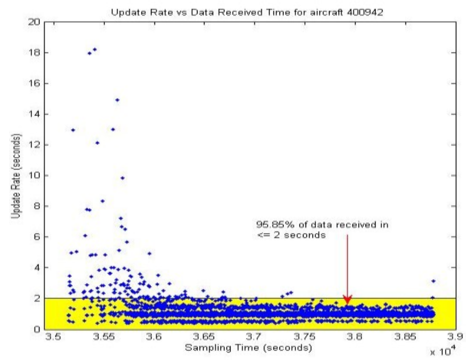




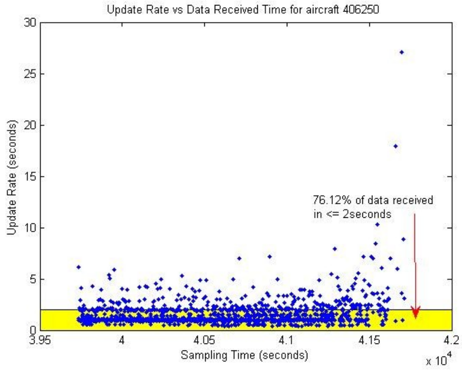


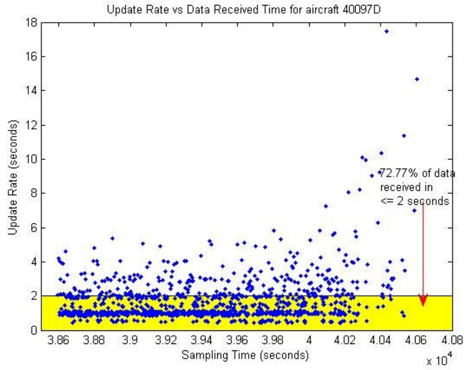


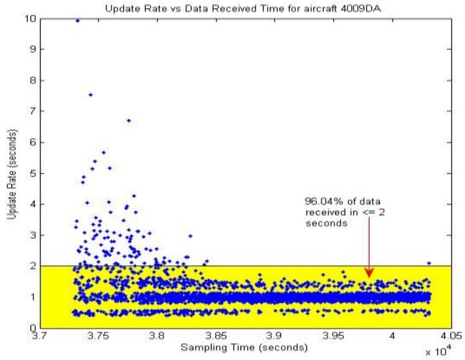


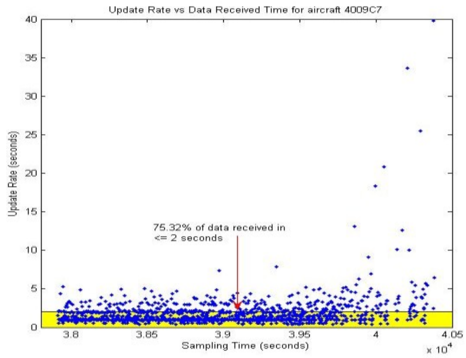


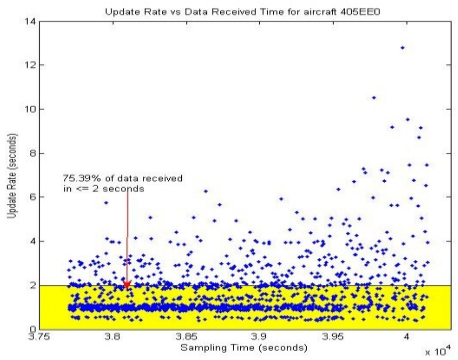
A320

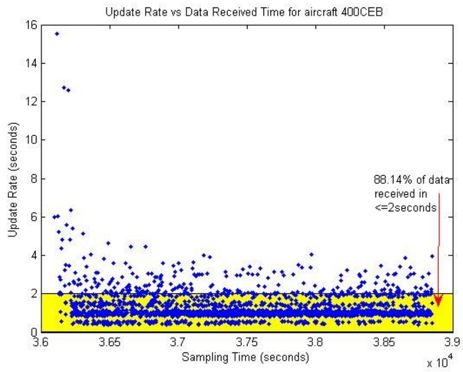

Update Rate vs Data Received Time for aircraft 406250
Update Rate (seconds)
Sampling Time (seconds)
x 10^4
76.12% of data received in <= 2seconds

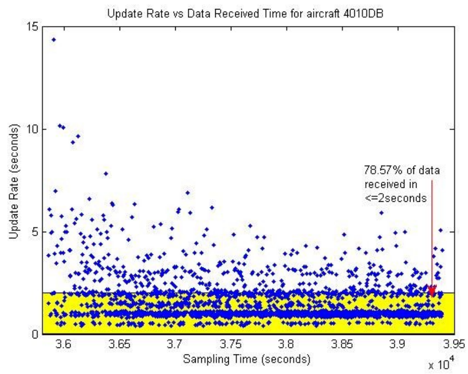

Update Rate vs Data Received Time for aircraft 40097D
Update Rate (seconds)
Sampling Time (seconds)
x 10^4
72.77% of data received in <= 2 seconds


Update Rate vs Data Received Time for aircraft 4009DA
Update Rate (seconds)
Sampling Time (seconds)
x 10^4
96.04% of data received in <= 2 seconds

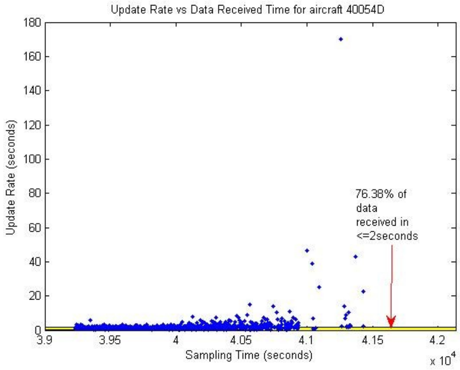

Update Rate vs Data Received Time for aircraft 4009C7
Update Rate (seconds)
Sampling Time (seconds)
x 10^4
75.32% of data received in <= 2 seconds

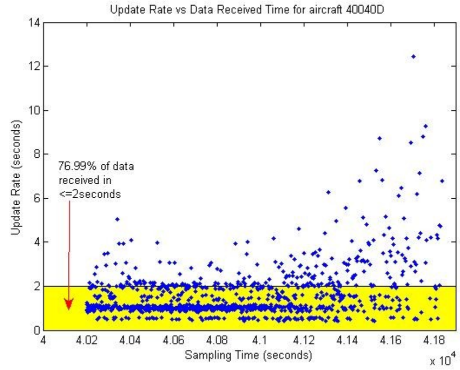

Update Rate vs Data Received Time for aircraft 405EE0
Update Rate (seconds)
Sampling Time (seconds)
x 10^4
75.39% of data received in <= 2 seconds

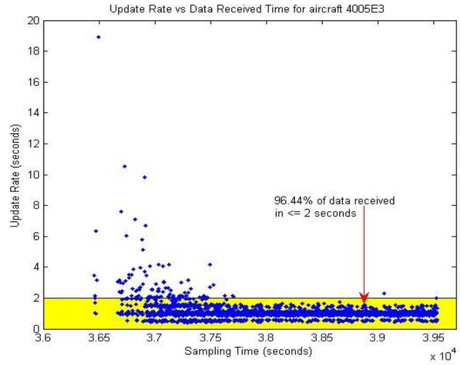

Update Rate vs Data Received Time for aircraft 400CEB
Update Rate (seconds)
Sampling Time (seconds)
x 10^4
88.14% of data received in <=2seconds

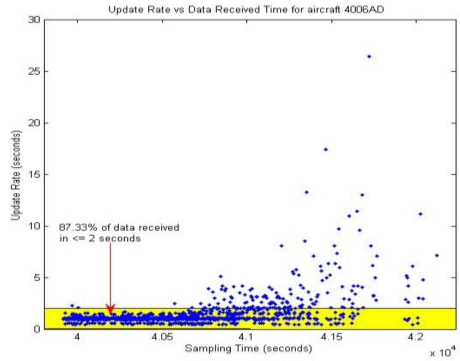

Update Rate vs Data Received Time for aircraft 4010DB
Update Rate (seconds)
Sampling Time (seconds)
x 10^4
78.57% of data received in <=2seconds

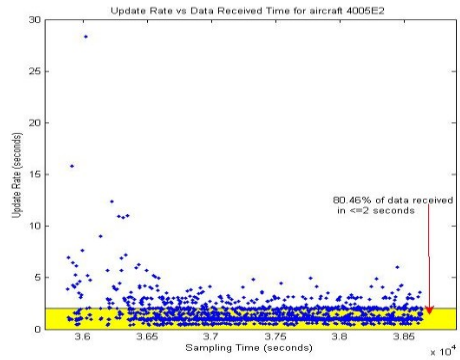
B744

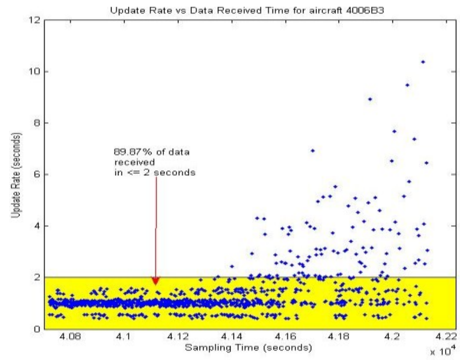

Update Rate vs Data Received Time for aircraft 40054D
76.38% of data received in <=2seconds
Update Rate (seconds)
Sampling Time (seconds)
x 10^4

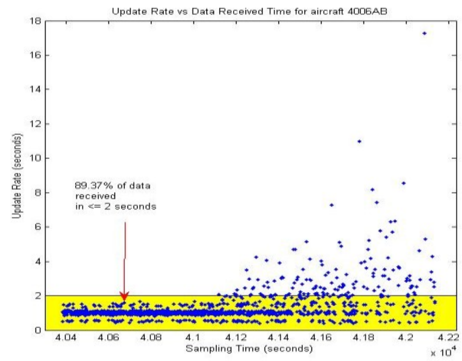

Update Rate vs Data Received Time for aircraft 40040D
76.99% of data received in <=2seconds
Update Rate (seconds)
Sampling Time (seconds)
x 10^4

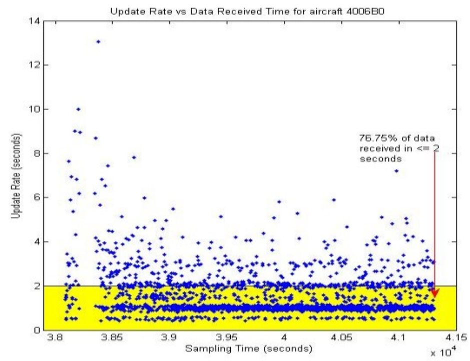

Update Rate vs Data Received Time for aircraft 4005E3
96.44% of data received in <= 2 seconds
Update Rate (seconds)
Sampling Time (seconds)
x 10^4

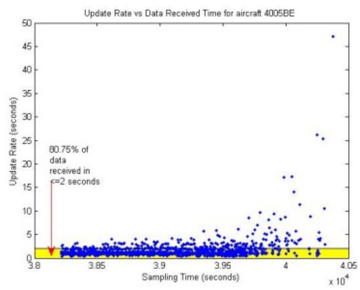

Update Rate vs Data Received Time for aircraft 4006AD
87.33% of data received in <= 2 seconds
Update Rate (seconds)
Sampling Time (seconds)
x 10^4


Update Rate vs Data Received Time for aircraft 4005E2
80.46% of data received in <=2 seconds
Update Rate (seconds)
Sampling Time (seconds)
x 10^4

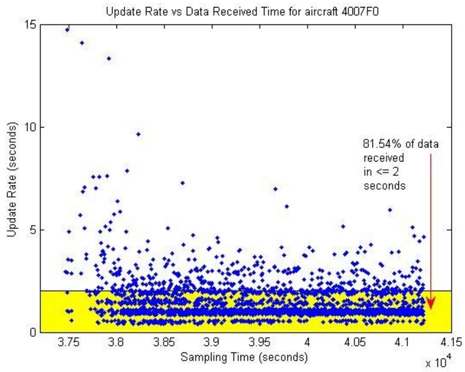

Update Rate vs Data Received Time for aircraft 4006B3
89.87% of data received in <= 2 seconds
Update Rate (seconds)
Sampling Time (seconds)
x 10^4


Update Rate vs Data Received Time for aircraft 4006AB
89.37% of data received in <= 2 seconds
Update Rate (seconds)
Sampling Time (seconds)
x 10^4

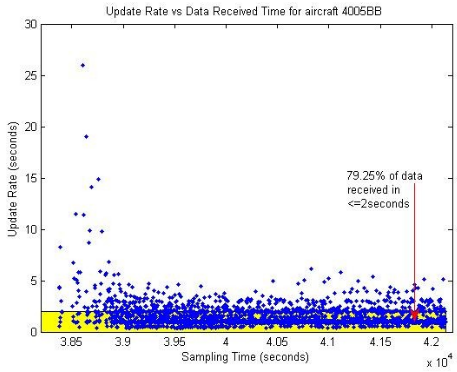

Update Rate vs Data Received Time for aircraft 4006B0
76.75% of data received in <= 2 seconds
Update Rate (seconds)
Sampling Time (seconds)
x 10^4


Update Rate vs Data Received Time for aircraft 4005BE
80.75% of data received in <=2 seconds
Update Rate (seconds)
Sampling Time (seconds)
x 10^4

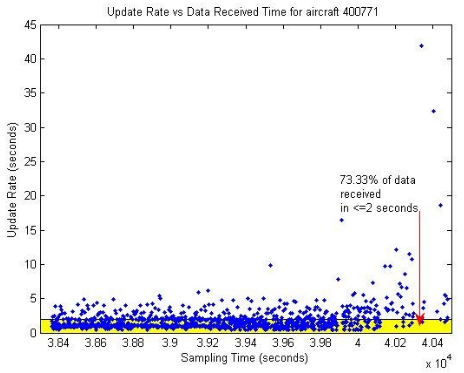
B777-200



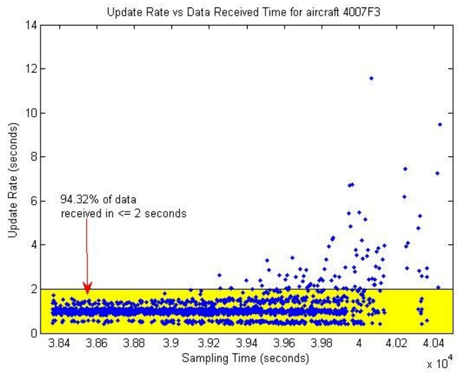
Update Rate vs Data Received Time for aircraft 4007F0
Update Rate (seconds)
Sampling Time (seconds)
x 10^4
81.54% of data received in <= 2 seconds



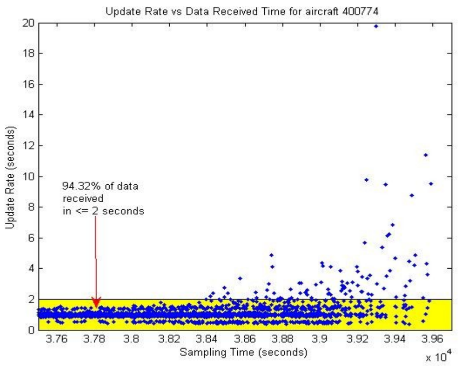
Update Rate vs Data Received Time for aircraft 4005BB
Update Rate (seconds)
Sampling Time (seconds)
x 10^4
79.25% of data received in <=2seconds



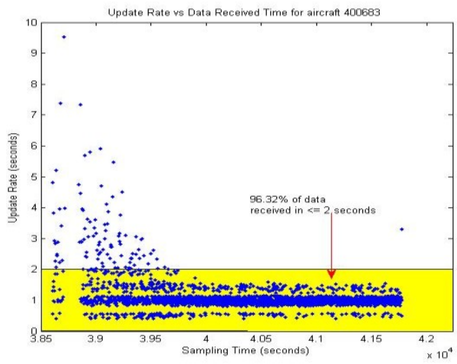
Update Rate vs Data Received Time for aircraft 400771
Update Rate (seconds)
Sampling Time (seconds)
x 10^4
73.33% of data received in <=2 seconds



Update Rate vs Data Received Time for aircraft 4007F3
Update Rate (seconds)
Sampling Time (seconds)
x 10^4
94.32% of data received in <= 2 seconds



Update Rate vs Data Received Time for aircraft 400774
Update Rate (seconds)
Sampling Time (seconds)
x 10^4
94.32% of data received in <= 2 seconds



Update Rate vs Data Received Time for aircraft 400683
Update Rate (seconds)
Sampling Time (seconds)
x 10^4
96.32% of data received in <= 2 seconds

Appendix E

Spearman's Rho test for Update rate (seconds) vs. Flight level (feet)

Aircraft	Sample size	Correlation test results		
		Correlation coefficient, r	Significance, p	Finding
40054D	1071	0.274	0.000	Correlation is significant at the 0.01 level
4005BE	1257	0.197	0.000	Correlation is significant at the 0.01 level
400CEB	2159	0.038	0.077	Correlation is not significant
406250	1210	0.151	0.000	Correlation is significant at the 0.01 level
40087C	1355	0.206	0.000	Correlation is significant at the 0.01 level
4010DB	2244	0.165	0.000	Correlation is significant at the 0.01 level
40040D	1017	0.202	0.000	Correlation is significant at the 0.01 level
4007F0	2421	0.115	0.000	Correlation is significant at the 0.01 level
4005BB	2371	0.070	0.001	Correlation is significant at the 0.01 level
400771	1140	0.193	0.000	Correlation is significant at the 0.01 level
40097D	1076	0.064	0.000	Correlation is significant at the 0.01 level
400936	3197	0.076	0.000	Correlation is significant at the 0.01 level
4008AD	3097	0.110	0.000	Correlation is significant at the 0.01 level
400940	2666	0.060	0.002	Correlation is significant at the 0.01 level
4007F3	1603	0.153	0.000	Correlation is significant at the 0.01 level
400774	1728	0.202	0.000	Correlation is significant at the 0.01 level
4008B4	1606	0.144	0.000	Correlation is significant at the 0.01 level
4005E3	2587	0.122	0.000	Correlation is significant at the 0.01 level
400683	2747	0.145	0.000	Correlation is significant at the 0.01 level
4009DA	2755	0.127	0.000	Correlation is significant at the 0.01 level
4006AD	1287	0.334	0.000	Correlation is significant at the 0.01 level
400802	3126	0.099	0.000	Correlation is significant at the 0.01 level
4008B5	1263	0.143	0.000	Correlation is significant at the 0.01 level
4009C7	1394	0.144	0.000	Correlation is significant at the 0.01 level
405EE0	1475	0.279	0.000	Correlation is significant at the 0.01 level
4005E2	1730	0.207	0.000	Correlation is significant at the 0.01 level
4007F9	2316	0.146	0.000	Correlation is significant at the 0.01 level
4006B3	1066	0.379	0.000	Correlation is significant at the 0.01 level
4006AB	1308	0.331	0.000	Correlation is significant at the 0.01 level
400942	3033	0.199	0.000	Correlation is significant at the 0.01 level
4006B0	2026	0.114	0.000	Correlation is significant at the 0.01 level

Appendix F

Spearman's Rho test for Update rate vs. Range

Aircraft	Sample size	Correlation test results		
		Correlation coefficient, r	Significance, p	Finding
40054D	1071	0.280	0.000	Correlation is significant at the 0.01 level
4005BE	1257	0.222	0.000	Correlation is significant at the 0.01 level
400CEB	2159	0.056	0.009	Correlation is significant at the 0.01 level
406250	1210	0.154	0.000	Correlation is significant at the 0.01 level
40087C	1355	0.191	0.000	Correlation is significant at the 0.01 level
4010DB	2244	0.146	0.000	Correlation is significant at the 0.01 level
40040D	1017	0.197	0.000	Correlation is significant at the 0.01 level
4007F0	2421	0.093	0.000	Correlation is significant at the 0.01 level
4005BB	2371	0.103	0.000	Correlation is significant at the 0.01 level
400771	1140	0.212	0.000	Correlation is significant at the 0.01 level
40097D	1076	0.157	0.000	Correlation is significant at the 0.01 level
400936	3197	0.082	0.000	Correlation is significant at the 0.01 level
4008AD	3097	0.116	0.000	Correlation is significant at the 0.01 level
400940	2666	0.076	0.000	Correlation is significant at the 0.01 level
4007F3	1603	0.159	0.000	Correlation is significant at the 0.01 level
400774	1728	0.204	0.000	Correlation is significant at the 0.01 level
4008B4	1606	0.143	0.000	Correlation is significant at the 0.01 level
4005E3	2587	0.131	0.000	Correlation is significant at the 0.01 level
400683	2747	0.150	0.000	Correlation is significant at the 0.01 level
4009DA	2755	0.136	0.000	Correlation is significant at the 0.01 level
4006AD	1287	0.337	0.000	Correlation is significant at the 0.01 level
400802	3126	0.116	0.000	Correlation is significant at the 0.01 level
4008B5	1263	0.155	0.000	Correlation is significant at the 0.01 level
4009C7	1394	0.295	0.000	Correlation is significant at the 0.01 level
405EE0	1475	0.279	0.000	Correlation is significant at the 0.01 level
4005E2	1730	0.281	0.000	Correlation is significant at the 0.01 level
4007F9	2316	0.257	0.000	Correlation is significant at the 0.01 level
4006B3	1066	0.444	0.000	Correlation is significant at the 0.01 level
4006AB	1308	0.403	0.000	Correlation is significant at the 0.01 level
400942	3033	0.388	0.000	Correlation is significant at the 0.01 level
4006B0	2026	0.156	0.000	Correlation is significant at the 0.01 level

Appendix G

Aircraft ID	Aircraft Make-model	GPS Receiver	ADS-B Emitter	Findings
40087C	A319	Thales TLS755 MMR	Honeywell TRA	GPS Clock error –after the 59th second, the minute does not increase by 1,e.g. after 10:48:59 the time was 10:48:00, it did not change to 10:49:00.
400936	A319	Thales TLS755 MMR	Honeywell TRA	
4008AD	A319	Thales TLS755 MMR	Honeywell TRA	
400940	A319	Thales TLS755 MMR	Honeywell TRA	
4008B4	A319	Thales TLS755 MMR	Honeywell TRA	
400802	A319	Thales TLS755 MMR	Honeywell TRA	
4008B5	A319	Thales TLS755 MMR	Honeywell TRA	
400942	A319	Thales TLS755 MMR	Honeywell TRA	
406250	A320	Thales TLS755 MMR	Honeywell TRA	
40097D	A320	Thales TLS755 MMR	Honeywell TRA	
4009DA	A320	Thales TLS755 MMR	Honeywell TRA	
4009C7	A320	Thales TLS755 MMR	Honeywell TRA	
405EE0	A320	Thales TLS755 MMR	Honeywell TRA	
400CEB	A321	Thales TLS755 MMR	Honeywell TRA	
4010DB	A321	Thales TLS755 MMR	Honeywell TRA	
40054D	B744	Rockwell Collins GLU920 MMR	ACSS XS	Aircraft latitude and longitude given every 4 seconds. Duplicate time and missing time without any pattern found in the clock information.
40040D	B744	Rockwell Collins GLU920 MMR	ACSS XS	
4005E3	B744	Rockwell Collins GLU920 MMR	ACSS XS	
4006AD	B744	Rockwell Collins GLU920 MMR	ACSS XS	
4005E2	B744	Rockwell Collins GLU920 MMR	ACSS XS	
4006B3	B744	Rockwell Collins GLU920 MMR	ACSS XS	
4006AB	B744	Rockwell Collins GLU920 MMR	ACSS XS	
4006B0	B744	Rockwell Collins GLU920 MMR	ACSS XS	
4007F0	B777-200	Rockwell Collins	Honeywell	Missing time 10:44:26 and 11:27:46 in the GPS data.

Aircraft ID	Aircraft Make-model	GPS Receiver	ADS-B Emitter	Findings
		GLU920 MMR	TRA	
400771	B777-200	Rockwell Collins GLU920 MMR	Honeywell TRA	No GPS data obtained for this aircraft from British Airways.
4005BE	B777-200	Honeywell GNSSU	Honeywell TRA	
4005BB	B777-200	Honeywell GNSSU	Honeywell TRA	Duplicate and missing time information without any deterministic pattern found in the GPS data.
4007F3	B777-200	Rockwell Collins GLU920 MMR	Honeywell TRA	
400774	B777-200	Rockwell Collins GLU920 MMR	Honeywell TRA	
400683	B777-200	Rockwell Collins GLU920 MMR	Honeywell TRA	
4007F9	B777-200	Rockwell Collins GLU920 MMR	Honeywell TRA	