DEVELOPMENT OF AN ALGORITHM FOR CORRELATION OF AIRCRAFT POSITIONING DATA FROM RADAR AND ADS-B SENSORS

KOH CHE HUN

FACULTY OF COMPUTER SCIENCE AND
INFORMATION TECHNOLOGY
UNIVERSITY OF MALAYA
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KOH CHE HUN

DISSERTATION SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SOFTWARE ENGINEERING

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INFORMATION TECHNOLOGY
UNIVERSITY OF MALAYA
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DEVELOPMENT OF AN ALGORITHM FOR CORRELATION OF AIRCRAFT POSITIONING DATA FROM RADAR AND ADS-B SENSORS

ABSTRACT

The Multi-radar Tracking System (MRTS) is implemented in aircraft surveillance with high confidence in terms of reliability and safety in Air Traffic Control (ATC) centers worldwide. The MRTS integrates two types of radar: Primary Surveillance Radar (PSR) and Secondary Surveillance Radar (SSR) to produce a Single Integrated Air Picture (SIAP). Its main function is to track aircraft in an airspace by using data from tracks collected from several radars. Advancement in aircraft surveillance sensor technology saw the emergence of new sensors, such as the Automatic Dependent Surveillance Broadcast (ADS-B) and Multilateration systems. Therefore, the radar is no longer the sole technology for air traffic surveillance. The ADS-B enables aircraft, ground vehicles and controllers to exchange positioning information via a dedicated communication link. This realizes unprecedented air-to-air and air-to-ground surveillance capabilities. It also provides surveillance coverage in remote and low altitude areas that are not covered by the radar. A Multi-sensor Tracking System (MSTS) makes use of different type of sensors to produce a SIAP rather than only radar. Hence, the integration of ADS-B into MSTS is gaining interest among researchers in its necessity to enhance the performance of ATC in terms of continuity, integrity, accuracy, and at the same time serves as a backup surveillance sensor. To fuse data from different sensors, the correlation algorithm is vital. Correlation is a process that associates the positioning data from different sensors to keep the SIAP up-to-date. The process needs to take account the differences in performance and characteristic of different sensors. Correlation algorithm aims to resolve ambiguities and conflicting information to provide an operationally useful synthesis of the surveillance data. However, at certain circumstances, ambiguities such as missed tracks, extra tracks or position and velocity errors may occur. Nonetheless, research on the use

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of MSTS for ATC is still in infancy. Several studies were carried out to apply and improve on existing correlation algorithms involving radars and the new surveillance sensors. Most of these studies are conducted by the Original Equipment Manufacturers (OEM) and hence the findings are not widely available in the public domain. However, findings indicate that there are still lack of effective correlation algorithms to resolve the ambiguities and differences in the multi-sensor data correlation environment. This research aims to develop an effective and high-performance multi-sensor correlation algorithm. To achieve the aim, the work reviews multi-sensor tracker architectures to identify the problems that arise when performing data correlation for multi-sensors; conducts study on existing correlation algorithms available in the public domain for MRTS and MSTS; analyzes the advantages and drawbacks of each algorithms; and derives the vital characteristics of a high-performance correlation algorithm. Based on the findings, a multi-sensor data correlation algorithm is developed. The algorithm is validated using real time radar and ADS-B data from Department of Civil Aviation Malaysia (CAAM).

Keywords: Radar, ADS-B, Correlation Algorithm, Multi-Sensor Tracking

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PEMBINAAN ALGORITMA UNTUK MENGORELASIKAN MATLUMAT KEDUDUKAN PESAWAT YANG DIKUMPUL DARIPADA PENGESAN - PENGESAN RADAR DAN ADS-B

ABSTRAK

Sistem Pengesan Multiradar (MRTS) digunakan di Pusat Kawalan Trafik (ATC) di seluruh dunia untuk pengawasan pesawat kerana kebolehpercayaan dan keselamatannya. Ia mengintegrasikan maklumat daripada dua jenis radar, iaitu Radar Pengawasan Primer (PSR) dan Radar Pengawasan Sekunder (SSR) untuk menghasilkan Gambar Udara Bersepadu Tunggal (SIAP). Fungsi utamanya adalah untuk mengesan pesawat di ruang udara dengan menggunakan data daripada trek-trek yang dikumpul daripada beberapa radar. Perkembangan terkini dalam teknologi pengesan pengawasan pesawat telah mewujudkan pengesan-pengesan baru seperti Automatik Bergantung Pengawasan - Disiarkan (ADS-B), sistem *Multilateration* and lain-lain. Oleh yang demikian, radar bukan lagi teknologi tunggal yang digunakan untuk pengawasan trafik udara. Sebaliknya, pengesan baru seperti ADS-B membolehkan pesawat-pesawat, kenderaan-kenderaan darat dan juga pengawal ruang udara untuk tukar-menukar maklumat kedudukan melalui pautan komunikasi khusus antara satu sama lain. Ini membolehkan pengawasan pesawat antara udara-ke-udara dan udara-ke-darat yang sebelum ini tidak dapat dilaksanakan. Ia juga berkeupayaan untuk mengesan pesawat-pesawat di kawasan beraltitud rendah dan jauh yang tidak dapat dikesan oleh radar. Sistem Pengesanan Multisensors (MSTS) menggunakan teknologi pengesan yang berlainan untuk menghasilkan SIAP dan bukan hanya menggunakan radar sahaja. Oleh yang demikian, integrasi ADS-B ke dalam MSTS semakin mendapat perhatian peyelidik-peyelidik untuk meningkatkan prestasi ATC dari segi kesinambungan, integriti dan ketepatan, selain berfungsi sebagai pengesan pengawasan sandaran. Algoritma korelasi memainkan peranan yang penting dalam penggabungan maklumat dari pengesan-pengesan yang berbeza. Korelasi adalah satu

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proses yang mengaitkan maklumat kedudukan pesawat dari pengesan-pengesan yang berbeza untuk memastikan SIAP yang dikemaskini pada setiap masa. Proses ini mengambil kira perbezaan dari segi prestasi dan ciri-ciri pengesan. Algoritma korelasi bertujuan untuk menyelesaikan kesamaran dan konflik dalam maklumat-maklumat untuk menghasilkan suatu sintesis data pengawasan pesawat yang berguna. Kesamaran yang berkemungkinan termasuklah trek yang terlepas secara tidak sengaja, trek tambahan atau kesilapan kedudukan dan halaju. Kajian bagi MSTS untuk kegunaan ATC masih di peringkat awal. Walau bagaimanapun, beberapa kajian yang melibatkan radar dan pengesan-pengesan pengawasan yang baru telah dijalankan untuk meningkatkan prestasi algoritma korelasi yang sedia ada. Kebanyakan kajian ini dilaksanakan oleh pihak *Original Equipment Manufacturers* (OEM) dalam sektor swasta dan penemuan kajian tersebut tidak dikongsi di sektor awam. Walau bagaimanapun, terdapat kekurangan algoritma korelasi yang efektif untuk menyelesaikan kesamaran dan perbezaan dalam persekitaran korelasi maklumat pelbagai pengesan (*Multisensor*). Kajian ini bertujuan untuk menghasilkan sebuah algoritma korelasi pelbagai pengesan yang berprestasi tinggi dan efektif. Untuk mencapai matlamat tersebut, tugas-tugas yang disenaraikan di bawah telah dilaksanakan, iaitu kajian di atas pengesan-pengesan dari segi ciri-ciri dan perkembangan dijalankan untuk mengenalpasti masalah yang timbul untuk menghasilkan korelasi maklumat pelbagai pengesan; kajian di atas algoritma-algoritma korelasi yang sedia ada dalam sektor awam untuk MRTS dan MSTS dijalankan; menganalisa kebaikan dan kelemahan dalam rekabentuk algoritma-algoritma yang sedia ada; dan ciri-ciri penting untuk sebuah algoritma korelasi yang berprestasi tinggi juga ditentukan. Algoritma korelasi pelbagai pengesan akan dibina berdasarkan keputusan dari kajian-kajian yang disenaraikan di atas. Algoritma tersebut akan disahkan dengan menggunakan maklumat dari radar dan ADS-B yang dikumpul dari Pihak Berkuasa Penerbangan Awam Malaysia (CAAM).

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Kata-kata kunci: Radar, ADS-B, Algoritma Korelasi, Sistem Pengesan Multisensor

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LIST OF SYMBOLS AND ABBREVIATIONS

ACAS	:	Airborne Collision Avoidance System
ADS	:	Automatic Dependent Surveillance
ADS-B	:	Automatic Dependent Surveillance - Broadcast
ADS-R	:	Automatic Dependent Surveillance Broadcast Rebroadcast Service
ANN	:	Artificial Neural Networks
ANP	:	Actual Navigation Performance
ANSP	:	Air Navigation Service Provider
APV	:	Precision Approach
ARTAS	:	Air Traffic Management Surveillance Tracker and Server
ASTERIX	:	All Purpose Structured EUROCONTROL Surveillance Information Exchange
ATC	:	Air Traffic Control
ATM	:	Air Traffic Management
ATN	:	Aeronautical Telecommunication Network
ATS	:	Air Traffic Service
CAAM	:	Civil Aviation Authority of Malaysia
CDTI	:	Cockpit Display of Traffic Information
CFAR	:	Constant False Alarm Rate
CFC	:	Central Fusion Center
CNS/ATM	:	Communication, Navigation and Surveillance/Air Traffic Management
DME	:	Distance Measuring Equipment
EPE	:	Estimated Position Error
EPU	:	Estimated Position Uncertainty

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ES	:	Extended Squitter
FANS	:	Future Aviation Organization
FC	:	Fusion Center
FFT	:	Fast Fourier Transform
FIM-S	:	Flight deck Interval Management – Spacing
FIS-B	:	Flight Information Service – Broadcast
GBAS	:	Ground-based Augmentation System
GBT	:	Ground Based Transceiver
GIM-S	:	Ground-based Interval Management – Spacing
GNSS	:	Global Navigation Satellite Systems
GPS	:	Global Positioning System
GUI	:	Graphical User Interface
GVA	:	Geometric Vertical Accuracy
HF	:	High Frequency
HFDL	:	High Frequency Data Link
HFOM	:	Horizontal Figure of Merit
HTML 5	:	Hypertext Markup Language
ICAO	:	International Civil Aviation Organization
IIF	:	Identification Friendly or Foe
ILS	:	Instrument Landing System
IM-S	:	Interval Management – Spacing
INS	:	Inertial Navigation System
JEM	:	Jet Engine Modulation
JPDA	:	Joint Probabilistic Data Association
KLIA	:	Kuala Lumpur International Airport
LFC	:	Local Fusion Center

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LRT : Likelihood Ratio Test

MHT : Multiple Hypothesis Testing

MRTS : Multi Radar Tracking System

MSTS : Multi Sensor Tracking System

NAC : Navigation Accuracy Category

NACp : Navigation Accuracy Category for Position

NACv : Navigation Accuracy Category for Velocity

NDB : Non-Directional Beacon

NIC : Navigation Integrity Category

NN : Nearest Neighbor

NPA Non-Precision Approach

NUC : Navigation Uncertainty Category

OC : Object Correlator

OEM : Original Equipment Manufacturers

PC : Personal Computer

PDA : Probabilistic Data Association

POP : Period of Operation

PSR : Primary Surveillance Radar

RAIM : Receiver Autonomous Integrity Monitoring

RAIM : Receiver Autonomous Integrity Monitoring

RCP : Required Communication Performance

RNAV : Area Navigation

RNP : Required Navigation Performance

RSP : Required Surveillance Performance

SASS-C : Surveillance Analysis Support System for Centre

SBAS : Space-based Augmentation System

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SIAP	:	Single Integrated Air Picture
SMNDNN	:	Sequential Minimum Normalized Distance Nearest Neighbor
SNR	:	Signal-to-Noise Ratio
SSR	:	Secondary Surveillance Radar
TCAD	:	Traffic and Collision Alert Device
TCAS	:	Traffic Alert and Collision Avoidance System
TIS-B	:	Traffic Information Service – Broadcast
TXT	:	Text
UAT	:	Universal Access Transceiver
VDL		Very High Frequency Data Link
VHF	:	Very High Frequency
VOR	:	Very High Frequency Omnidirectional Range
WAM	:	Wide Area Multilateration

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CHAPTER 1: INTRODUCTION

1.1 Background

Nowadays, air traffic surveillance no longer solely relies on radar. The extensive deployment of satellite systems and air-to-ground data links lead to the emergence of complementary means and techniques. Great deals of research and experiments have been carried out over the past ten years. A key element in Air Traffic Control (ATC) which is the sensor data processing, has been relentlessly enhanced in such an environment to adhere to the sensor technology evolution and performance quality in terms of continuity, integrity and accuracy.

The sensor technology evolution has led to emergence of techniques to fuse multi-sensor outputs to produce a single output of higher accuracy. Although multi-radar data fusion techniques are well established and are being used by many ATC centers worldwide, research on multi-sensor data fusion for ATC is still lacking. In fact, considering differences in sensor performance, the first step in data fusion that is correlation of data from different sensors is not an easy task indeed.

1.2 Research Scope

One of the ultimate goals of multi-sensor air traffic surveillance is the formation of Single Integrated Air Picture (SIAP) – a common operational view of the airspace of interest of which all measurements are incorporated to form one air picture, and at the same time, the different estimates of positions and velocities of aircraft provided by sensors such as radar within the airspace of interest must be deconflicted. This research has reviewed the architectures of multi-sensor trackers to identify the problems involved in multi-sensor data correlation. This has been followed by a review of the advantages and drawbacks of existing multi-sensor track correlation algorithms in the public domain. Based on the findings, an effective algorithm for multi-sensor data correlation has been proposed. Finally, the proposed correlation algorithm has been implemented in a

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correlation tool for radar and ADS-B sensors. It is important to highlight that the scope of this work is only up to multi-sensor data correlation and does not cover multi-sensor data fusion. However, the research outcome serves as a way forward to improve on multi-sensor data fusion.

1.3 Aims and Objectives

This research aims to develop an effective algorithm for multi-sensor data correlation for aircraft surveillance. This has been achieved by studying and analyzing the characteristics of real-time data from two different surveillance sensors: radar and ADS-B. The output of this research has significantly contributed to the efficiency of ATCs by enabling the controllers to obtain a more accurate aircraft positioning information and complementary aircraft positioning information in the case of any sensor failures. The aim of the study has been achieved by the objectives formulated below to:

- Review the state of art of the aircraft surveillance sensors;
- Identify, review and analyze existing multi-sensor data correlation algorithms available in the public domain;
- Analyze and differentiate the characteristics of aircraft positioning data from each surveillance sensor;
- Develop an algorithm to correlate the aircraft positioning data from the two sensors; and
- Develop a tool called – Multi-sensor Data Correlator.

1.4 Research Methodology

The methodology of this research is shown in the flow chart in Figure 1.1. In the first part of the research, a comprehensive literature review has been conducted to identify the differences between the surveillance technologies: Radar and ADS-B. This has been done by reviewing technical documents from International Civil Aviation Organization

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(ICAO), original equipment manufacturers (OEM) and aviation journals. In the second part, an exhaustive search for existing multi-sensor data correlation algorithms has been performed by engaging industrial experts in Malaysia. Industrial experts include air traffic controllers, radar technician in airport, authorities in CAAM as well as researchers from local universities. It is worth noting that availability of data were scarce in the public domain as the work done in this field are for commercial purpose.

Next, the Air Navigation Service Provider (ANSP) data of the same time interval from the two types of sensors has been collected from Civil Aviation Authority of Malaysia (CAAM) based on the availability of the operational infrastructures at Kuala Lumpur International Airport (KLIA) and Sultan Mahmud Airport in Kuala Terengganu. The amount of data collected was based on opportunity traffic on a specific duration in the airspace. The collected data was in an encoded format and was subsequently decoded into a readable format. A program to decode the data has been to be developed to achieve this goal.

After that, analyses were conducted on the sample aircraft track data throughout the flight duration obtained from both surveillance sensors. The purpose of the analysis is to identify temporal/spatial pattern/characteristic in each surveillance sensor data. Based on the identified patterns, an algorithm was developed to correlate aircraft tracks from the two surveillance sensors. Finally, the algorithm was transformed into Multi-sensor Surveillance Data Correlation Tool.

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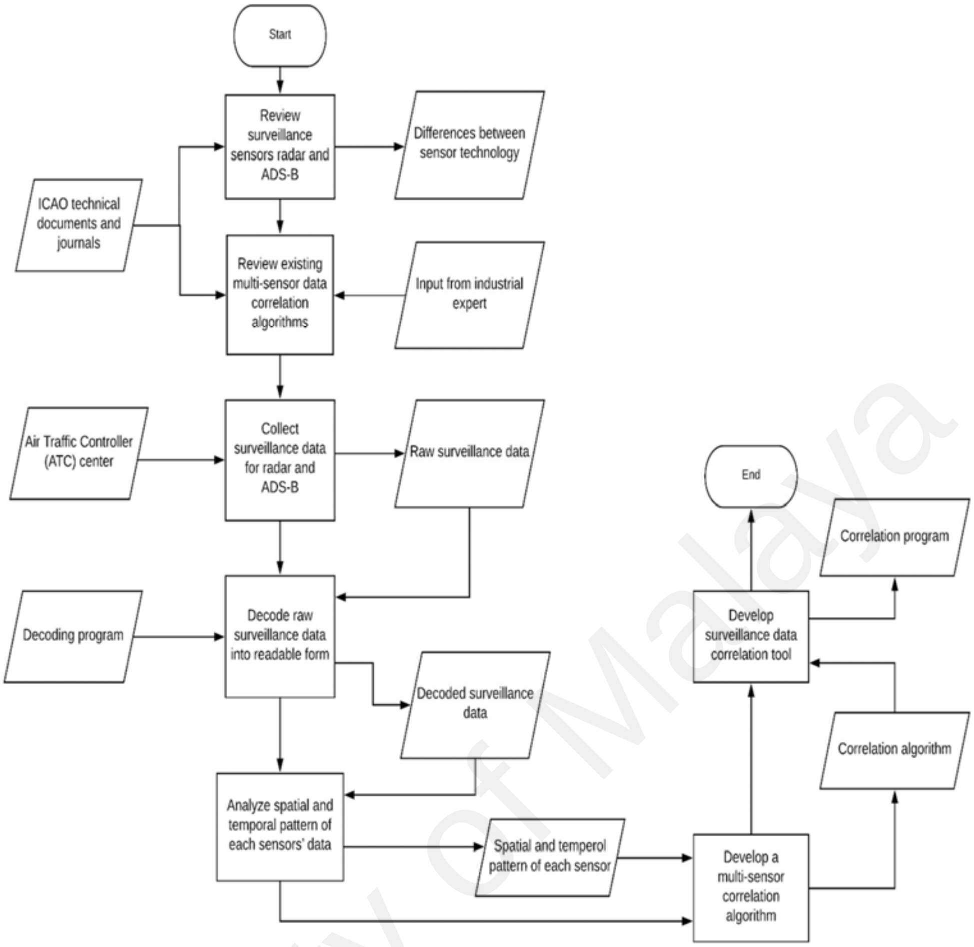

Figure 1.1: Research Methodology

1.5 Thesis Structure

The thesis is organized into seven chapters corresponding to the objectives of the research. Following is the short chapter-wise description provided in the thesis:

Chapter Two: Radar and Automatic Dependent Surveillance Broadcast (ADS-B)

This chapter reviews radar and ADS-B sensor technologies in terms of their characteristics and performance. The differences between the two sensors are identified.

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Chapter Three: Existing Correlation Algorithms

This chapter identifies and analyzes existing multi-sensor correlation algorithms that are available in the public domain. The advantages and drawbacks of each algorithm is weighed to determine the needs of an effective correlation algorithm.

Chapter Four: Radar and ADS-B Data Pattern Analysis

In this chapter, radar and ADS-B measurements obtained from the CAAM had been inspected statistically, as well as for the identification of systemic and random errors. Additionally, measurement patterns of both sensors have also identified to derive an effective correlation algorithm.

Chapter Five: Proposed Correlation Algorithm and Tool

This chapter explains the proposed correlation algorithm and tool development in detail. The correlation algorithm is derived based on the analysis result from Chapter Four with the consideration of advantages and drawbacks identified in Chapter Three.

Chapter Six: Testing and Validation

In this chapter, results from the testing of the proposed correlation algorithm has been elaborated. Sample measurement data have been fed into the algorithm for testing, outputs are evaluated and discussed.

Chapter Seven: Conclusions, Recommendations, and Future Work

This chapter concludes the findings, limitations, recommendations and suggestions of the research for future work.

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CHAPTER 2: RADIO DETECTION RANGING (RADAR) AND AUTOMATIC DEPENDENT SURVEILLANCE – BROADCAST (ADS-B)

In summary, this chapter introduces the sensor technologies used in Air Traffic Management (ATM) as stated in the first objective of this research and reviews the state of art of the aircraft surveillance sensors. This research focuses on two type of sensors that are commonly used in the industry, namely radar and ADS-B. Firstly, this chapter gives an introduction on radars, including the types of radar, interrogation mode, and the ICAO standard that is currently implemented in the industry. Next, the same aspects are discussed on ADS-B. This chapter ends with discussion on the differences between the two sensors and their roles in ATM respectively.

2.1 Introduction

Advancement of technologies in air travel have placed high demand on safety, efficiency, and regularity of air traffic due to the limited airspace with growing number of aircraft. Therefore, the Communication, Navigation and Surveillance and Air Traffic Management (CNS/ATM) concept (ICAO, 2000; Whelan, 2001) is introduced. The CNS/ATM is applied in support of a seamless global ATM system by employing digital technologies, including automated satellite systems. The CNS/ATM aims to establish an extensive and unified system to support the groundwork of Air Traffic Service (ATS). It standardizes the use of equipment in different regions by offering high level automation that reduces human dependency to optimize the airspace. The CNS/ATM consists of communication, navigation, and surveillance subsystems.

Communications in current ATM relies heavily on voice commands, which does not allow high rates of data transmissions (Ali, 2013). Therefore, to overcome this challenge, digital data links, such as High Frequency Data Link (HFDL), Very High Frequency Data Link (VDL) Mode 4, Mode-S Extended Squitter, and Universal Access Transceiver

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(UAT) with high rates of data transfer, reliability, and integrity are introduced (Vismari & Camargo, 2005). It improves the utilization of frequency spectrum and capable of interfacing with any automated system.

Navigation is the ability to determine the state of an aircraft precisely, followed by the path to pilot and arrive at the next destination (Whelan, 2001). With the help of Global Navigation Satellite Systems (GNSS), aircraft can obtain and broadcast their own position information, thus enabling worldwide coverage of CNS/ATM.

On the other hand, surveillance is the capability to precisely determine the position of an aircraft at a specific time with high reliability (Whelan, 2001). It is crucial for the separation of aircraft in a clustered airspace, and improved efficiency of airspace utilization, peculiarly with the growth of air travel.

Table 2.1 shows the paradigm shift of satellite-based technologies (Ali, 2013). Given the importance of surveillance, this research focuses on the two commonly used technologies in surveillance, namely Secondary Surveillance Radar (SSR) and ADS-B, especially in terms of their characteristics, behaviors, and limitations.

Table 2.1: Comparison of Technologies in Current and New CNS

CNS	Current Technologies	New Technologies
Communication	- Very High Frequency (VHF) (voice) - High Frequency (HF) (voice)	- VHF (Voice/Data) - Satellite Communication (Voice/Data) - Mode S data link - Aeronautical Telecommunication Network (ATN) - Required Communication Performance (RCP)

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Table 2.1 continued.

CNS	Current Technologies	New Technologies
Navigation	- Loran-C Non-Directional Beacon (NDB) - VHF Omnidirectional Range/Distance Measuring Equipment (VOR/DME) - Barometric Altimeter - Inertial Navigation System (INS) - Instrument Landing System (ILS)	- Area Navigation (RNAV) - Required Navigation Performance (RNP) - GNSS - Barometric Altimeter - INS - GNSS Landing System
Surveillance	- Primary Surveillance Radar (PSR) - Secondary Surveillance Radar (SSR) Mode A/C or Mode S - Procedural Control	- Automatic Dependent Surveillance (ADS) - SSR Mode A/C or Mode S - Required Surveillance Performance (RSP)

2.2 Radar

The Radio Detection and Ranging (RADAR) is a technology used to determine an aircraft's range and azimuth by using the time difference between transmission and receipt of energy pulses to and from the aircraft. Radar requires a large rotating antenna and associated machinery. It feeds the ATC with precise and reliable real time position of an aircraft and reduces to a great extent the dependency of an aircraft on procedural separation. There are two types of radar that are commonly used in ATC, namely Primary Surveillance Radar (PSR) and Secondary Surveillance Radar (SSR).

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2.2.1 Primary Surveillance Radar (PSR)

The PSR is a conventional radar system that irradiates the airspace with energy signal, and subsequently collects the signal reflected by any objects within the airspace. It has a ground station with transmitter and receiver. A pulse of energy signal is transmitted outwards and a small proportion of the signals is reflected from the target aircraft back to the receiver as depicted in Figure 2.1. The bearing of the aircraft is determined by the azimuth orientation of the radar antenna, whereas the distance of the target aircraft from the ground station is determined by the time taken for the signals to travel to the target aircraft and return (Wasson, 1994). This information is processed by the surveillance data processor and displayed on the ATC's display screen.

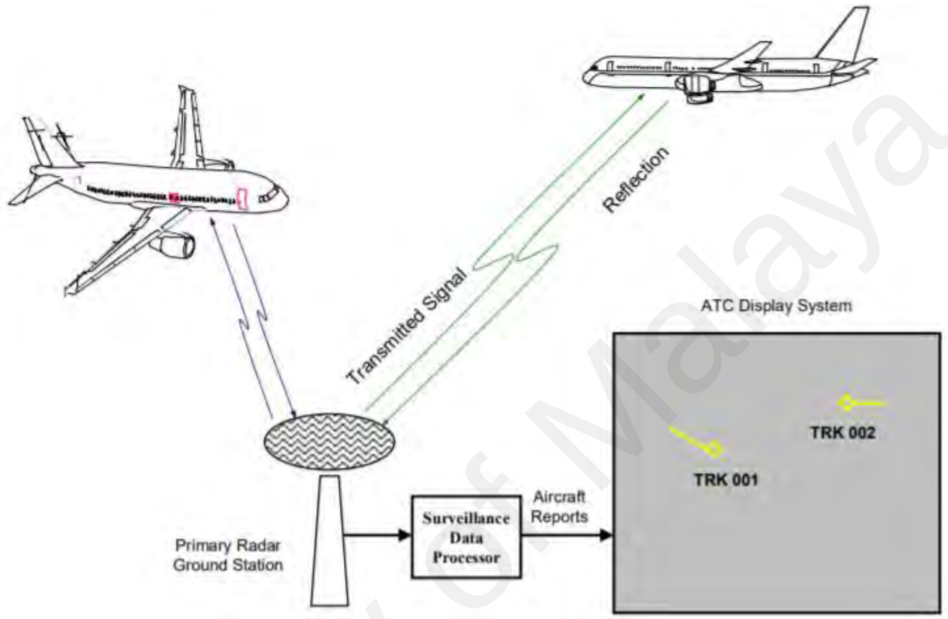

Figure 2.1: Operation of Primary Surveillance Radar (ICAO, 2007)

2.2.2 Secondary Surveillance Radar (SSR)

The Secondary Surveillance Radar (SSR) system is almost similar to the conventional PSR system that functions by having a ground station with transmitter and receiver; the only difference is having an additional transponder equipped on the aircraft. The transponder was first developed in 1939 using the Identification Friendly or Foe (IFF) system, which transmits a signal encoded with identity upon receiving of radio signal radiated by ground station. The SSR relies on the interrogation of the transponder to obtain the encoded data, which can be seen in Figure 2.2. That is the main feature that differentiates the SSR from PSR. The advantages of SSR over PSR include implementation of data link using the transponder, minimum influences of weather or other unwanted signals reflected from other objects on the desired signals, and long

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ranges achieved with comparatively low power. However, the drawback is that SSR required the aircraft to be equipped with functioning transponder as it is a cooperative system (Trim, 1990).

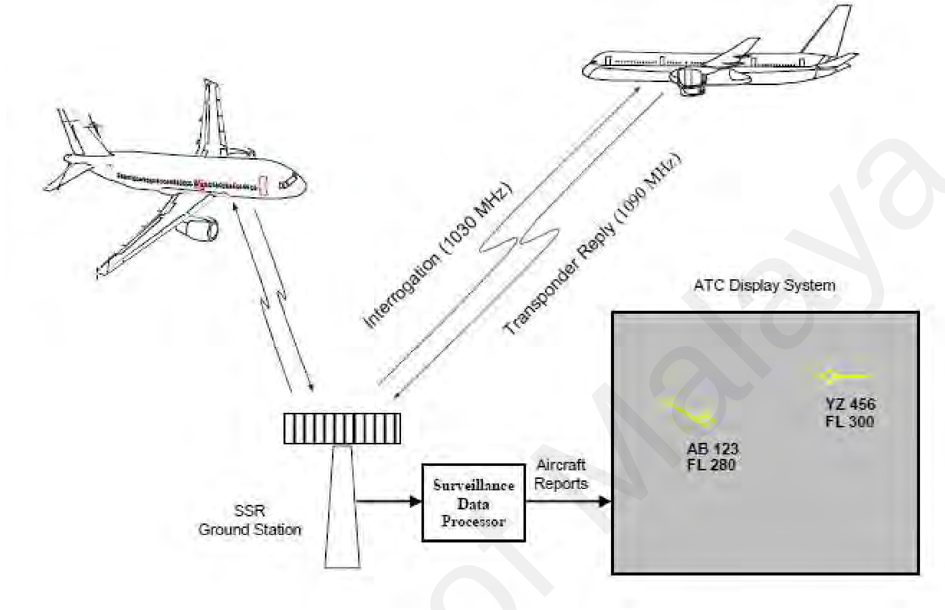

Figure 2.2: Operation of Secondary Surveillance Radar (ICAO, 2007)

2.2.2.1 Interrogation Modes

The SSR aims to enhance the ability to detect and identify aircraft, as well as to provide a reading of the Flight Level (pressure altitude) of an aircraft. The ground station emits interrogation pulses at 1030 MHz while rotating its antenna. An aircraft within the surveillance range that is equipped with a transponder receives the interrogation signal and replies at 1090 MHz. The reply provided by the specific aircraft contains encoded aircraft information and other information depending on the interrogation mode. An aircraft without transponder may still be detected by PSR and displayed on the ATC screen but without the rich information provided by SSR. In controlled air space, only one working transponder is required, but many aircraft have an additional back-up transponder to as a replacement if the main transponder malfunctions. (EUROCONTROL, 2003).

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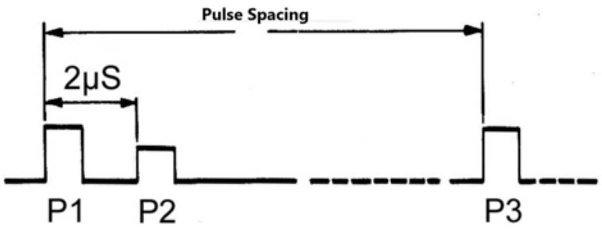

Figure 2.3: SSR Interrogation Pulse Signal

The interrogation mode is determined by the spacing between two transmitted pulses emitted by the SSR ground station illustrated in Figure 2.3. The variety of pulse spacing is shown in Table 2.2. Basically, there are four interrogation modes: Mode A, Mode C, Mode S and intermode. Mode A/C ground station can only perform Mode A/C interrogation, whereas Mode S ground station is able to perform all modes of interrogation. Similarly, Mode A/C transponder can only respond to Mode A/C and intermode interrogation, while Mode S transponder respond to all modes.

Table 2.2: Pulse Spacing and Purpose of Interrogation Modes

Mode	Pulse Spacing (µs)	Purpose
A	8	Identity
C	21	Altitude
S	3.5	Multipurpose

The ground station transmits the interrogation signal that consists of three pulses (P1, P2, and P3) as illustrated in Figure 2.3. When interrogation signals are transmitted, there is often signal leakages through the side of antenna, known as sidelobe signals. A transponder on the aircraft may respond to the sidelobe signal causing interference. Therefore, Pulse P2 acts as sidelobe suppression, whereby the transponder only replies to interrogation with amplitude of P1 that is significantly stronger than P2. This is to prevent the transponder from replying to sidelobe interrogations.

The "Purpose" column in Table 2.2 clarifies the information encoded in the reply from the transponder. In general, Mode A transponder provides individual aircraft

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identification (also known as call sign), Mode C transponder replies with the encoded pressure-altitude for vertical separation purpose, whereas the Mode S reply consists of 24-bit aircraft address, altitude, and other data depending on the ground station's request.

On the other hand, the combination of intermode and Mode S all-call and lockout protocols are used to ensure operational compatibility between Mode S and Mode A/C equipped aircraft and ground station. Mode S ground station transmits all-call interrogation regularly and all Mode A/C/S transponders will respond to it respectively (ICAO, 2004). In fact, Mode S transponder replies with 24 bits aircraft's address whilst Mode A/C transponders reply with conventional message. Once Mode S transponder is known to the ground station by its address, it can be locked out and only reply to certain selective interrogations, and it is known as locked out protocol. Intermode interrogations also serve as filter to allow ground stations to receive replies from either Mode A/C or Mode S aircraft exclusively. The compatibility of Mode A/C and Mode S are illustrated in Figure 2.4.

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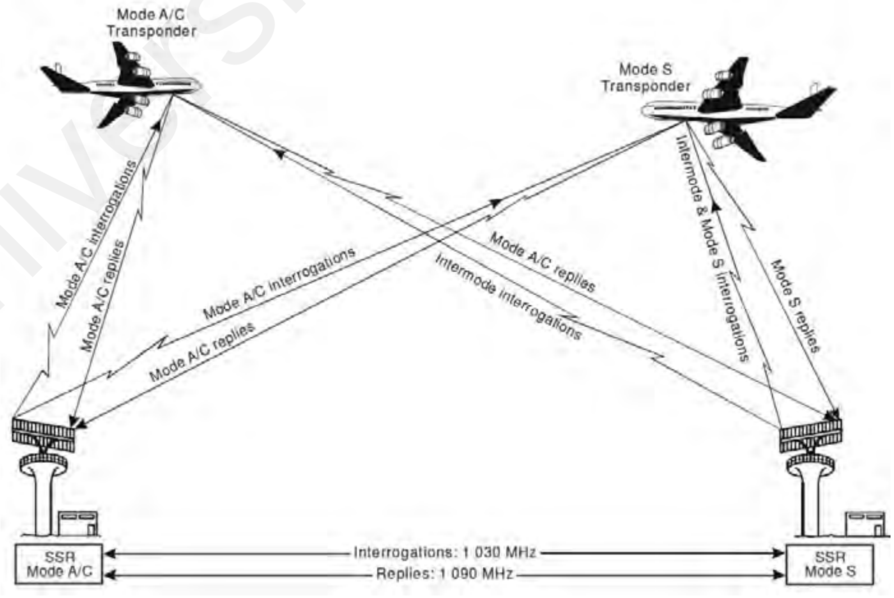

Figure 2.4: Compatibility of SSR Mode A/C and Mode S

It has been found that in Mode-S system, the sharing of common uplink and downlink frequencies for all aircraft has contributed to co-channel interference, which can be categorized as capture, fruit, and garble. Firstly, capture refers to the situation where the aircraft is only able to reply to one ground station at one time, thus causing a delay in replying to the interrogation of another ground station. Next, fruit or false replies unsynchronized in time occurs when the ground station receives replies that meant for other interrogations. Finally, garble is the overlapping replies of two or more aircraft at the ground station that causes decoding and detecting problem. All these may downgrade the reliability of the reply data, especially when calculating the bearing of the aircraft (Stevens, 1985).

The usage of SSR system has been growing rapidly due to its capability of identifying the aircraft and reporting height, range, and bearing information. However, it is worth noting that these mentioned aspects may cause critical problems to the SSR as well. As a result, the monopulse azimuth measurement has been developed to mitigate these problems (Blair, Richards, & Long, 2010). It is a diffraction technique used to measure the azimuth position of the target aircraft that allows for the measurement of target azimuth to be made on a single pulse within any transponder reply. The monopulse processing does not require any modification on the interrogation or equipment in aircraft. Besides that, it is also more accurate, especially in an interference environment (ICAO, 2004; Jacovitti, 1983).

2.2.3 Strengths and Weaknesses

The radar has its strengths and weaknesses over other sensors. There is no one radar technology that fulfills all requirements. In fact, the choice of radar technology depends on the required application under various circumstances. The strengths and weaknesses of each radar technology identified by ICAO (2007) are listed in the Table 2.3.

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Table 2.3: Strengths and Weaknesses of Radar

Type	Strengths	Weaknesses
PSR	- Able to provide weather channel output - Transponder is not needed on aircraft, thus allowing for the detection of non-equipped/faulty aircraft or non-cooperative aircraft - Well suited for aerodrome surface surveillance	- False targets reported frequently from ground vehicles, weather, birds etc. - No identity information provided - Poor detection performance for flight tangential in the presence of ground and weather clutters - No altitude information provided - Position is based on slant range measurement rather than true range - Long range performance requires high transmitter power - Expensive compared to SSR - Low update rate between four and 12 seconds - High maintenance fees - Optimum site with unobstructed view to aircraft, and with the minimum of ground clutter visible to the radar - Unable to resolve two aircraft at a similar location at the same range due to poor azimuth resolution performance
SSR	- Direct communication of identity when matched with flight plan data - Allows for communication of altitude and emergency states to ground system - Reliable performance independent of clutter and weather	- Classical SSR has low azimuth accuracy and resolution - Reflections and multipath cause reporting of false targets or positions - Confusion between Mode A and Mode C replies - Report false altitude

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Table 2.3 continued.

Type	**Strengths**	**Weaknesses**
	- Moderately high update rate - Provision of altitude allows correction for slant range error	- No error detection provided in downlinked 4-digit code and altitude from Mode C transponders - High installation and maintenance fees - Optimum site with unobstructed view to aircraft required - Unable to resolve data provided by two aircraft situated at the same location due to garbling or resolution performance - Dependent on aircraft avionics - Not accurate enough for aerodrome surface applications due to transponder delay uncertainty
Mode S SSR	- Altitude and identity are protected, and the downlink is error free - Able to resolve data of two aircrafts that are situated at the same location - Provides 25-foot altitude quantization - Operates with Mode A/C aircraft, albeit with no advantages compared to a Mode A/C radar	- Only applicable to Mode S equipped aircraft More complex to set up than SSR Mode A/C transponders are non-compliant with the standards and fail to respond to Mode S interrogations properly whilst these transponders are tolerated by Mode A/C radars - Dependent on aircraft avionics - Optimum site with unobstructed view to aircraft required

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2.2.4 The ICAO Standard

The ICAO defines a standard named All Purpose Structured Eurocontrol Surveillance Information Exchange (ASTERIX) for data exchange purposes. It is globally accepted by the ATM system manufacturing industry. ASTERIX Category 48 (EUROCONTROL, 2012) is the format defined by ICAO for radar data transmission. It lists all the standardized data items that are used for the transmission of mono-radar target reports from a Mode S station. Appendix A provides a complete list of the data item.

The ICAO has provided four levels of Mode S transponder capacities (Trim, 1990). The transponder is categorized by its capability to interact with ground station and other air traffic services. High level transponders are preferable for ADS-B implementation.

Transponders with Mode A/C operations, basic data protocols, as well as intermode and Mode S all-call and lock-out protocols are classified under Level 1. In general, Level 1 transponders may be utilized in an individual state or within the term of a regional air navigation agreement. This is the minimum requirement that supports the operation with Mode S interrogation, introduced with the purpose of discouraging the propagation of non-Mode S compatible transponders. However, it is worth noting that air-air service transaction and reporting are not supported in Level 1 transponders.

In addition, Level 2 transponders are equipped with aircraft identity and data link reporting, as well as standard-length communications capabilities. These extra capabilities enable aircraft equipped with level 2 transponders to support communications from ground-to-air and air-to-ground with data link. This is the minimum requirement for an aircraft to fly international routes. Level 2 transponders are the reason for widespread use of ICAO standard equipment worldwide, together with the planning to facilitate Mode S ground facilities and services. It also discourages the adoption of level 1 transponders in the industry.

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On top of that, Level 3 transponders support ground-air extended length communications. Level 3 transponders can retrieve data from ground base data bank and receive data from other air traffic services. Lastly, level 4 transponders support air-ground extended length communications on top of the capabilities of level 3 transponders.

2.3 Automatic Dependent Surveillance – Broadcast (ADS-B)

The ADS-B is a new technology introduced to furnish the capabilities of existing surveillance sensors for pilots and ATCs. The major goal of ADS-B is to upgrade the capacity, safety, and efficiency of air traffic system (Duan, 2010). It plays a huge part in the Next Generation Air Transportation System (NextGen) (FAA).

2.3.1 ADS-B Technology

The ADS-B technology brings cutting-edge changes to the conventional ground-based surveillance services which relies on the radar system as the former enables ATM to make use of satellite-based cooperative surveillance system. Transceivers equipped on ground stations, ground vehicles, and aircraft allow all users to exchange position, velocity, intent, and aircraft identification information straightly through an ADS-B data link. Apart from that, it also improves the surveillance by deriving the precise state vector from Global Positioning System (GPS) and automatically broadcasting it to all aviation users.

2.3.1.1 Operation of ADS-B

The operation of an ADS-B system is illustrated in Figure 2.5. The GNSS technology and simple broadcast communication links are the main components of the ADS-B. An aircraft derives its precise position from the GNSS constellation, and subsequently associates it with information such as speed, altitude, and flight number. This information is then broadcasted to the ground station and other ADS-B equipped aircraft (RTCA, 2002).

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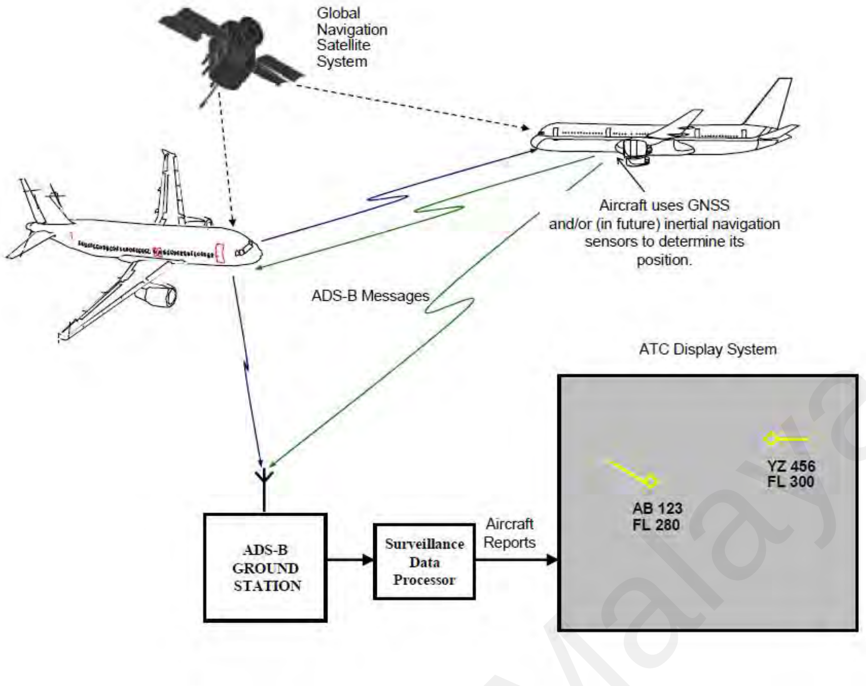

Figure 2.5: Operation of ADS-B

The ADS-B has two functionalities, referred to as ADS-B Out and ADSB In (ICAO, 2003). The ADS-B Out instructs the ADS-B equipped aircraft to broadcast its position, velocity, and identification information to ground station and other ADS-B equipped aircraft. The ATC makes use of this information to enhance situational awareness and manage air traffic flows. Additionally, in comparison to the radar, the ADS-B Out also provides advantageous surveillance service in terms of accuracy and high update rates during departure, en-route, and arrival. This greatly improves the efficiency of the ATM system. On the other hand, the ADS-B In is the ability of receiving ADS-B state vectors from other aircraft as well as ground stations. In fact, the received information is not available to the pilots in radar-based surveillance system. It is used to update the cockpit display of traffic information (CDTI) apart from improving situational awareness and conflict detection in a timely, accurate, and efficient way. The ADS-B Out has a higher priority than ADS-B In, therefore the former should be implemented first.

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Generally, the two data links provided by ADS-B are: 1090 Extended Squitter (ES) and Universal Access Transceiver (UAT) that operate at 1090 MHz and 978 MHz, respectively. An aircraft needs to be equipped with at least one data link for the operation of ADS-B. Information can only be exchanged when both aircraft have the same data link; otherwise, an ADS-B ground station transceiver is required to receive and broadcast the information through the other data link. This operation is referred as ADS-B Rebroadcast Service (ADS-R).

The 1090 ES is implemented by air carriers and high-performance aircraft that enhances the existing Mode-S transponder with a globally agreed extended squitter ADS-B message. Apart from responding to SSR interrogations, both 1090 ES and Mode-S transponders are used in Traffic Alert and Collision Avoidance System (TCAS) (FAA, 2011), therefore its bandwidth is limited. On the other hand, the UAT is introduced to prevent the potential frequency congestion on 1090 MHz. This wideband link is designed for general aviation users. Two types of message, namely the ADS-B and ground uplink messages are transmitted through the UAT, that is usually installed on aircraft operating below Flight Level 180. The ADS-B message consists of the state vector of an aircraft, along with the integrity information of the measurement whereas the ground uplink message includes Traffic Information Services-Broadcast (TIS-B) and Flight Information Services-Broadcast (FIS-B) service. The TIS-B and FIS-B transmit meteorological and aeronautical information from ground to air. ADS-B has high capacity application with the use of dual frequency link along with ground-based ADS-R (Duan, 2010).

At the beginning when not all aircraft have ADS-B equipment, the radar is used to track the non-ADS-B equipped aircraft. This information would be broadcasted by the ADS-B ground-based transceivers (GBTs) to ADS-B equipped aircraft via TIS-B. However, once the ADS-B was fully implemented, the TIS-B is then no longer needed.

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2.3.2 Strengths and Weaknesses

There is a critical issue when promoting usage of ADS-B in CNS/ATM. It requires all participating aircraft equipped with ADS-B to include the use of GPS or similar technology. However, the use of GPS differs according to region. In some parts of the world where air travels are rapidly growing, new aircraft are fitted with ADS-B and GPS technologies; however at some regions, aircraft are still unequipped with these technologies. The benefits of ADS-B are significant and may allow for air-to-air surveillance applications to be delivered more effectively. The strengths and weaknesses of ADS-B have been identified by ICAO (2007) are listed in Table 2.4 below.

Table 2.4: Strengths and Weaknesses of ADS-B

Sensor	Strengths	Weaknesses
ADS-B	- Simple ground station design without transmitter - Can be installed at sites shared with other users - Very low ground station cost - Very high update rate - Almost perfect resolution - High accuracy and integrity (airborne measurements) - Higher performance velocity vector measured by avionics and then broadcast - Accuracy not dependent on range from ground station - Facilitates exchange of surveillance data - Can be easily deployed for temporary use like emergency, special events etc. - Support the display of callsigns on simple display systems without interfaces to flight planning systems - Facilitates future provision of innovative ATM services based on air-to-air ADS-B.	- Dependent on aircraft avionics. - Equipage rates are relatively low at this stage (2007) - Optimum site with unobstructed view to aircraft required - Some outages expected due to poor GPS geometry when satellites out of service

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2.3.3 ICAO Standards and Requirements

The ADS-B data are processed and shared in a common format designed by ICAO, i.e. the ASTERIX Category 21 (ICAO, 2011b) format standard. In general, the ADS-B data in ASTERIX Cat 21 are categorized into four main groups:

i. Group 1 contains the mandatory data;
ii. Group 2 contains the desirable data;
iii. Group 3 contains the optional data; and
iv. Group 4 is for future data items.

The data items for Groups 1, 2 and 3 are defined in Appendix A, B, and C, respectively. When the ADS-B ground station receives a reply from a specific aircraft, the data is transmitted to the ATC system for operational use, as well as technical recording and analysis. An ASTERIX Cat 21 message should only be transmitted when all the data items in Group 1 is present. On the other hand, data items in Group 2 are operationally desirable and may be transmitted whenever they are received by the ground station. As for the data items in Group 3, they may or may not need to be transmitted depending on the availability of such data as they are optional. Finally, Group 4 contains data for system designers to plan on future adaptability whenever possible. This ASTERIX standard is continuing to evolve from time to time.

2.4 Summary of Radar and ADS-B

Based on the comprehensive review on radar and ADS-B sensors, a thorough comparison is done between SSR and ADS-B in terms of applications and performance characteristics as summarized in Table 2.5 with reference to ICAO (2007) and Ali (2013).

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Table 2.5: Applications and Performance Characteristics of Radar and ADS-B

Field	SSR	ADS-B
En-route surveillance application	En-route is supported by Mode S SSR sensors around the world.	ADS-B may be used in en-route airspace, it will bring safety improvements and automated safety nets in remote area where there is no surveillance today.
Terminal area surveillance application	SSR radars are currently critical to the effective provision of terminal area surveillance due to their moderate update rate of position, identity and altitude.	ADS-B may be used in terminal area airspace to provide high quality surveillance data but currently hindered by lack of equipage of ADS-B avionics. It has advantages of positional data accuracy and high integrity as well as the better velocity vector performance.
Air-Air applications	None	ADS-B shows promise for use a large number of air to air applications include In Trail Procedure, Airborne situational awareness, Merging & Spacing etc.
Surface movement application	None	ADS-B has potential for surveillance on airport surfaces and has been commissioned to provide identity and emergency flag data to surface movement displays.
Precision Runway Monitor (PRM) application	SSR ground stations are used by to support precision runway approach monitoring to parallel runways.	ADS-B shows promise for use in PRM applications when enough aircraft are equipped because ADS-B meets the accuracy, velocity vector performance and update requirements of PRM.
Airborne	Airborne Collision Avoidance Systems (ACAS) including TCAS 1, TCAS 2 and other products such as Traffic and Collision Alert Device (TCAD) rely on SSR transmissions.	A significant number of airborne applications of ADS-B are envisaged by the international community including Air Traffic Situational awareness, In trail procedures, Merging & spacing etc.

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Table 2.5 continued.

Field	SSR	ADS-B
Accuracy	For a monopulse radar: In range: 0.03 NM rms In azimuth: 0.07 degrees rms or 0.14 degrees 2 σ for random errors. At 50 NM range the 0.14-degree error results in a position error of 0.12 NM. At 100 NM range: 0.24NM, At 200 NM: 0. 48 NM At 250 NM: 0.60 NM	Determined by the aircraft avionics and independent of range from sensor. For GPS, typically: 95% less than 0.1NM
Resolution	0.5 to 1 degree in azimuth	Perfect due to Mode S avionics unique 24bit code and random transmission requirements
Integrity	No message by message integrity. Subject to mode A/C code garbling. Subject to confusion between mode A and Mode C data. Mode S downlinked data is subject to stringent transmission error detection algorithms virtually eliminating the risk of undetected false data.	Position integrity guaranteed to $1*10^{-7}$ due to Receiver Autonomous Integrity Monitoring algorithm in avionics. Integrity value is downlinked in the ADS-B message. ADS-B downlinked data is subject to stringent transmission error detection algorithms virtually eliminating the risk of errors in the transmission medium
Update period	Between 4 & 15 seconds	0.5 seconds from aircraft. Normally 1 second from ground station. In high density environments with significant 1090 MHz FRUIT, the update rate may be reduced
Anomalies	Affected by multipath, reflections, second time around replies, plot splits, garbling, resolution loss & data corruption	Some avionics “bugs” identified.

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Table 2.5 continued.

Field	SSR	ADS-B
Implementation	Widely implemented all around the world	Implementing in USA (NextGen), Australia, Europe (SESAR, CASCADE), Canada, China and Japan.
Range	200 NM-250 NM	200 NM-250 NM
Availability	> 99 %	> 99 %
Typical Reliability	For duplicated system > 20,000 hours Reliance on single antenna. Relies on mechanical machinery for antenna rotation Duplicated transmitter/ receiver	Duplicated system >20,000 hours Receiver only Dependence on GPS Duplicated receiver

2.5 Summary

This chapter has introduced CNS/ATM system along with radar and ADS-B technologies used in current ATM. Strengths and weaknesses of each sensor are also identified. The ICAO standard is reviewed for radar and ADS-B because it is important to be communicated to users who make use of these technologies. Lastly, this chapter is summarized by comparing the application and performance characteristic of the two technologies.

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CHAPTER 3: EXISTING CORRELATION ALGORITHMS

This chapter begins by reviewing existing correlation algorithms used for surveillance data, explores the concepts in track correlation, and investigates the problems to perform correlation in a multi-sensor environment. First, the architecture of the multi-sensor tracking system is studied; then the state of art of multi-radar track correlation algorithms are intensively reviewed. Based on the review, the advantages and drawbacks of the algorithms are identified and examined. Lastly, multi-sensor tracker systems that are available in the public domain are identified and elaborated.

3.1 The Architectures of Multi-sensor Tracker

The multi-sensor tracker is a widely used technique in ATC as well as air, ground, and maritime surveillances. It processes and correlates data from different data sources including the radar, ADS, and other surveillance sensors into a unique real-time air picture composed of multiple tracks. Three main types of architecture are commonly used within multi-sensor multi-target tracking applications (Chen, Tharmarasa, & Kirubarajan, 2013). Figure 3.1 illustrates the structures where (a) is centralized, (b) is distributed, and (c) is decentralized. Each of the architecture has its own features and applications in different environment.

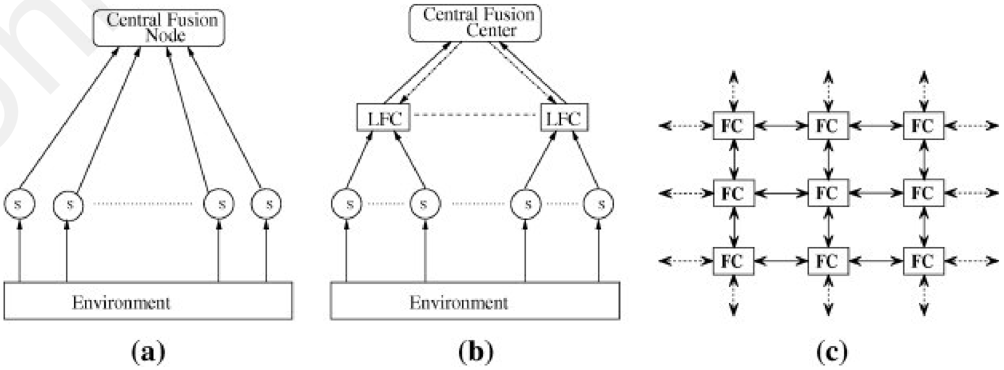

Figure 3.1: Multi-sensor tracking architecture (Chen et al., 2013)

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The centralized architecture is also known as the true multi-sensor tracking architecture. In the centralized architecture, the region of interest is monitored by several sensors and reported to only one fusion center. Measurements from all sensors are processed in the center and used to update the tracks. One of the problems of this tracking architecture, also considered as a special case, is that only one sensor is deployed to observe the region of interest. Nonetheless, the centralized architecture provides few advantages over other architecture, including:

- Providing good tracking continuity by combining measurements from several sensors, where false plots and false track initialization can be minimized;
- Preventing multiple initiations due to different responds in terms of speed and correctness from single radar trackers, and provide easier and safer manual interaction; and
- Better performance due to efficient update frequency that also improves the accuracy in maneuvers too.

In distributed architecture, fusion centers are categorized into two levels with independent functionalities. There is only one high level Central Fusion Center (CFC) and the remaining are low level Local Fusion Centers (LFC). The LFCs will first process the measurements generated by the sensors and update the local tracks which are then reported to CFC, where track-to-track fusion is performed to form the global track set (Zhang, Leung, Blanchette, Lo, & Litva, 1997).

In the decentralized architecture, each fusion center (FC) is a combination of LFC and CFC. Several sensors are connected to one FC, and measurements reported are used to update the track state inside the FC. Furthermore, each FC also performs track-to-track fusion whenever it receives additional information from its neighboring FCs. Generally, decentralized architecture is characterized by:

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- Absence of single central fusion center;
- No common communication facility, i.e. FC cannot broadcast result; and
- FC does not have global knowledge of sensor network topology.

As a result, decentralized architecture is scalable as not limited by communication bandwidth; survivable to loss or addition of FC and dynamic changes in network structure; and FC can be programmed in modular fashion (Durrant-Whyte, 2000).

3.2 Existing Correlation Algorithms

The main purpose of correlation is to resolve significant ambiguities between the tracks to provide operationally useful synthesis of surveillance data. Common errors may lead to dangerous situations, such as the failure to engage with enemy targets or misinterpret friendly targets. Examples of common errors are missed tracks, extra tracks due to false or multiple detections, missed-associations of targets, and problems due to time latency. When several sensors with its own data processing system carry out surveillance over a certain area of interest, track-to-track correlation problem arises as each such system has a few tracks. Therefore it is crucial to determine whether two tracks from different systems are reporting on the same target (Chen et al., 2013).

Targets are observed in a regular or irregular time interval depending on sensor types. The observations are translated to measurements for track correlation. In order to include a measurement into existing track and initiate new track, the gating method is used (Blackman, 2004). A simple concept of correlation based on the concept of “gating” is described as follow:

i. Tracks are propagating forward in the track registry to the current time.

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ii. For every new measurement entered into the system, a gate (uncertainty region) is formed around each track. The gate is based upon the maximum acceptable measurement plus tracking prediction error.

iii. All current measurements that fall inside the gate of a track fulfills the criteria for correlation.

iv. A combination of covariance matrix of the current track and possible associated measurements are used to determine the gate.

v. A measurement may be included in one or more gates; single track gate may have more than one measurement, whereas some tracks may contain gates with no measurement inside.

vi. A correlator is needed to perform ambiguities resolution, new tracks initialization, and existing tracks deletion based on measurements that fall inside the gates.

Kanyuck and Singer (1969) had identified redundant tracks in the surveillance area as a track correlation problem and explained further by Bar-Shalom (1981). The following algorithms have resolved this problem.

- Probabilistic Data Association (PDA) and Joint Probabilistic Data Association (JPDA) algorithm;
- Multiple Hypothesis Testing (MHT) algorithm;
- Nearest Neighbor (NN) algorithm;
- Likelihood Ratio Test (LRT) algorithm;
- Artificial Neural Networks (ANN) algorithm;
- Position and velocity test algorithm; and
- Grey Correlation Analysis.

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3.2.1 Probabilistic Data Association Algorithm

The Probabilistic Data Association (PDA) algorithm (Kanyuck & Singer, 1969, 1970; Kenari & Arvan, 2014) adopts a Bayesian approach that associates all the measurements from the sensors to the target by calculating the probability. It is possible to utilize all measurements around the gated region to update the track. The probability of the associations is calculated and used as weights to produce the weighted average measurement. The details of the correlation equation are explained by (Kanyuck and Singer (1969), 1970); Kenari and Arvan (2014)). However, one of the biggest challenges in a multitarget tracking environment is for the closely spaced targets to be correlated, hence the Joint Probabilistic Data Association (JPDA) (Mušicki & Evans, 2004) is proposed to handle this scenario. The JPDA calculates the measurement-to-target association events probabilities to correlate the measurements to the target. However, there are two rules to follow: (i) one measurement either originates from a target or a false alarm; and (ii) one target can only generate one measurement. Nonetheless, several improvements have been proposed on the PDA algorithm. One of it is by Mušicki et al., who have introduced track existence probability to measure the quality of the track as described by (Bar-Shalom (1981); Bar-Shalom and Li (1995)). Apart from that, He and Zhang (2006) proposed the use of the attenuation factor to build the sequential track correlation algorithm, as well as to restrict and attenuate the memory of it.

3.2.2 Multiple Hypothesis Testing Algorithm

The Multiple Hypothesis Testing (MHT) algorithm (Bar-Shalom, Kirubarajan, & Gokberk, 2005; Blackman, 2004) is a multi-frame assignment algorithm, which allows difficult decision to be deferred until more information in the next frame is received. It is effective in tracking multitargets in a cluttered environment, and in initiating tracks and accounting for false or missing tracks. Hypotheses containing current tracks are defined before receiving the next frame of measurements. Once measurements are available,

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probabilities are calculated for the hypotheses that the measurements came from existing target, new target or false alarm. A filter is used to sort the target states based on the hypotheses. Hence, the decision to correlate the current measurement into the track is based on previous and subsequent measurements received (Chen et al., 2013). Next, unlikely hypotheses need to be eliminated and similar hypotheses are combined to keep the number of hypotheses reasonable. One of the techniques used is clustering, as explained by Blackman (2004). The MHT can be implemented by using the hypothesis-oriented or track-oriented approach. Once the measurements are received and processed, hypothesis-oriented approach maintains and expands the hypotheses from scan to scan, whereas the track-oriented approach discards the hypotheses formed from previous scan. In closely-spaced targets, such as formation of aircraft flying in, a measurement can be produced by two or more targets. Under this circumstance, the MHT assumes one measurement that can only be produced by one target is invalid. Enhancement has been done in MHT to include the classification data as proposed by Bar-Shalom et al. (2005). In this approach, target classification and kinematic information are used simultaneously in tracking. As a result, track purity improved for missed detection, false alarms, and target maneuvers. This is because kinematic information alone is not enough to resolve the ambiguities.

3.2.3 Nearest Neighbor Algorithm

The Nearest Neighbor (NN) algorithm (Li & Bar-Shalom, 1996; Rogers, 1991) is the simplest form of association. This algorithm updates an existing track with the nearest measurement. The alternative approach, the All Neighbors or Global Nearest Neighbor by Blackman (2004) incorporates all measurements within a gated region and updates the existing track based on the probability of weighted sum of all measurements. This approach is effective in tracking target with single or multiple sensors in cluttered environment. Additionally, Zhang et al. (1997) have also presented a multi-sensor track-

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to-track correlation method called the Sequential Minimum Normalized Distance Nearest Neighbor (SMNDNN) correlation. In this method, AND/OR logic is used to solve multi-sensor assignment problems. This algorithm is sequential in both time and space, without referencing to previous or future scan.

3.2.4 Likelihood Ratio Test Algorithm

The Likelihood Ratio Test (LRT) algorithm (Chang & Youens, 1981; Sittler, 1964) compute the enough statistic, which is interpreted as the weighted distance between two measurements. In case they originate from the same target, the enough statistic follows a chi-square distribution. This assumption may be used to reject the unlikely measurements with appropriate threshold applied. When tracking with more than two sensors, the computational load increases with this straight forward concept.

3.2.5 Artificial Neural Network Algorithm

The Artificial Neural Network (ANN) algorithm (Winter & Favier, 1999) solves the association problem by using the Hopfield Neural Network as an alternative method for multi-sensor tracking. The constraints of this algorithm are that a measurement cannot be used twice each measurement must be used only once. This algorithm results a near optimal solution for 17.4 percent of the time, and for the rest, it approximates the true solution (Smith & Singh, 2006).

3.2.6 Position and Velocity Test Algorithm

A multi-frame track correlation algorithm (Gertz, 1989) puts the tracks through position and velocity matching test. Traditionally, the position testing in radar system uses a rectangular box. However, in a multi-sensor tracking system, ellipses with a totally different shape and orientation are used. The Kalman position test is developed to overcome this. The measurement is scored by its distance from the track, and a threshold is applied to eliminate unmatched measurements. Velocity matching test compares the

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predicted position using the track's velocity vector. A matched measurement is declared once it passes both the position and velocity tests. In the case where only one position test is passed, the measurement would be retested in the next scan.

3.2.7 Grey Correlation Analysis Algorithm

The grey correlation analysis of grey system theory is used by (Huang, Zhang, Li, and Zhou (2009)) in their research to solve the correlation problem. The bearing information of each track is translated into discrete time function and analyzed by grey correlation analysis using the B-mode correlation degree. Matrix of grey correlation degree is calculated to determine the correlation pairs.

3.3 Existing Multi-sensor Trackers

Several multi-sensor trackers are available in public or private domain. This research only reviews three such systems developed by manufacturers that are accessible in public domain.

3.3.1 Thales Multi-sensor Tracking System

The Multi Radar Tracking System (MRTS) has been enhanced by the Thales Group (Baud, Honore, & Taupin, 2006) to enable processing of multi-sensor surveillance data as a result of the evolution in aviation surveillance technologies. The Multi-sensor Tracking System (MSTS) fuses data from various sensors to create a unified and accurate surveillance picture. The data sources include Secondary Surveillance Radar (SSR), Primary Surveillance Radar (PSR), Wide Area Multilateration (WAM), and Automatic Dependent Surveillance-Broadcast (ADS-B). Figure 3.2 shows the flow of surveillance data correlation and fusion in MRTS and MSTS.

In the pre-correlation step, the possible measurements are filtered based on the gating technique by estimating the possible area volume, or gate, around the latest track. The

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pre-correlated plot-track pairs are then correlated based on a likelihood value, where track prediction is performed for each plot time and plot-track pair based on the Kalman Filter. Plot-track pairs are categorized into groups by their likelihood rankings. Next, the Global Nearest Neighbor approach is applied to associate the correlated measurements that best suit aircraft detection, as well as resolve correlation conflicts.

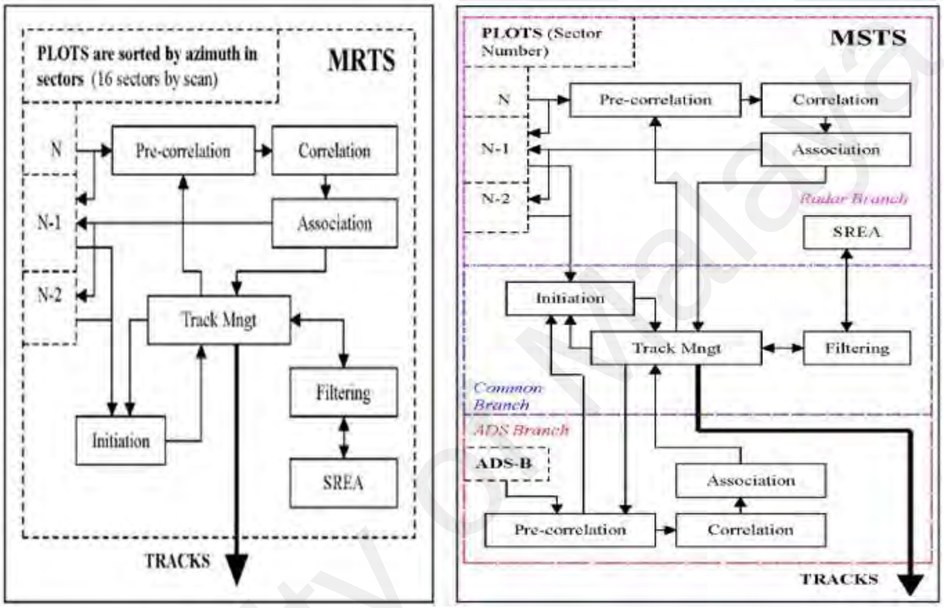

Figure 3.2: Functionalities of MRTS and MSTS (Baud et al., 2006)

As shown in Figure 3.2, the MSTS has most of the functionalities of MRTS. The Automatic Dependent Surveillance branch takes ADS-B reports as input. Pre-correlation and correlation filter the measurements that are correlated to the MSTS track, thereafter the association process would determine the best pairs report-track and supply them to the track management process. Track management is responsible in updating the track according to the auto adaptive extended Kalman filter, managing possible maneuvers, track identification, track drop, and information update.

3.3.2 Air Traffic Management Surveillance Tracker and Server (ARTAS)

The ATM Surveillance Tracker and Server (ARTAS) (EUROCONTROL, 2018a) was designed by EUROCONTROL to help ATCs to establish an accurate air traffic situation

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over the area of interest. The ARTAS consists of five units, namely the Tracker, Server, Router Bridge, System Manager, as well as the Recording and Offline Application. Each of the unit processes the surveillance data to generate a best estimate report. The process flow of the ARTAS is summarized as following:

i. Tracker receives radar input data and maintains the latest air traffic situation in a database;
ii. Server handles all the communication requests from users, and transmits the relevant data to users;
iii. Router Bridge carries out the external interfaces to the Normal Users, Broadcast Users, Adjacent ARTAS units, and surveillance sensors;
iv. System Manager plays a supervisory role over the ARTAS units; and
v. Recording and Offline Application records all internal and external interface, and performs data analysis for offline analysis.

The ARTAS uses the MHT algorithm for track initialization, JPDA algorithm for plot-to-track association, and finally estimates and extrapolates the track with Interacting Multiple Models. Plots that are not associated with existing tracks are used to consider possible branching of tracks. The branches are consolidated or pruned after receiving the next scan of data.

3.3.3 Surveillance Analysis Support System for Centre (SASS-C)

The Surveillance Analysis Support System for Centre (SASS-C) (EUROCONTROL, 2018b) is a surveillance sensor data analysis software provided by EUROCONTROL. It takes surveillance sensor data as input and reconstructs the data to output as the most perfect measurement as possible. SASS-C aims to provide top-level verification and prediction functionality to civil and military Air Navigation Service Providers (ANSP), research and Air Traffic Management (ATM) industry. Three objectives of SASS-C

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verification are: (i) to verify the compliance of the surveillance infrastructure with EUROCONTROL’s standards and specification; (ii) to support air incident investigation and (iii) to support the development and implementation of ATM. On the other hands, prediction functionality provides the theoretical calculation for the surveillance infrastructure performance, environment interference, accuracy of position measurement and probability of receipt of message. Each customized module provides different features, such as like evaluation, calculation of theoretical visibility, visualization of multi-radar coverage, and multi-radar data simulator.

All the data collected into SASS-C would be processed by an Object Correlator (OC) in the system. The OC performs data projection and verification, whereby data are rejected if they are of an unknown record type, miss plots, negative time, negative azimuth, jumps in time, or range greater the maximum range. Next, the OC would perform chaining, including chain extension, initialization, and termination. All the data are compared with the existing chains. The highest confidence plot would be taken to extend the chains. Rejected plots would be tested by using chain initialization to create a new chain. Lastly chains that fail to extend would be terminated. With a list of chains collected, tracks from the tracker are associated to the chains. Quality of the association state vector that consists of speed, position, heading, and code are computed; and tracks with the highest quality state vector are associated to the chain. There are two conditions to fulfill the association, namely: (i) Association value is higher than the association threshold; and (ii) Highest association value of all possible pairs.

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3.4 Conclusions

The advantages and drawbacks of examined correlation algorithms are listed in Table 3.1.

Table 3.1: Advantages and Drawbacks of Existing Correlation Algorithms

Algorithm	**Advantages**	**Drawbacks**
PDA	- Less normalized error estimation	- Can only be used under well-separated targets in clutter - Closely spaced targets will lead to track combination - Computation time rises exponentially with the increase in targets - Only for single target tracking
JPDA	- Effective in cluttered environment	- No explicit method for track creation - All measurements update all targets, tracks initiated by noise will be kept alive - Computation time rises exponentially with the increase in targets
MHT	- Effective in track initiation and accounting false alarm - Effective in cluttered environment	- High computational resource, intricate logic needed to delete hypotheses - Invalid assumption under closely-spaced target scenarios
LRT	- Higher accuracy	- Difficult to construct
ANN	- Require less formal statistical training - Able to detect complex nonlinear relationships	- High computational burden - Black box nature
NN	- Simple and easy to implement - Little computational cost - Sequential in time and space, track established in each scan and pairing up sensors in space is possible (SMNDNN)	- High error rate in dense environment - Weak performance in multitarget tracking
Position and Velocity Testing	- Biased insensitive - Unaffected by registration errors - Better prediction in maneuvers	- Complex computation for secondary-sensor position using flat-earth model. - Time smoothing procedure needed.

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Based on the data in Table 3.1, a set of criteria that an effective multi-sensor data correlation algorithm should have is derived as following:

- Least normalized error;
- Least computational time;
- Effective in cluttered environment;
- Able to account for false alarm, such as multipath, biases and noise;
- Good maneuvering prediction;
- Accurate in dense environment (closely spaced targets);
- Effective in track initiation;
- Able to account for the different characteristics of the tracks from multi-sensors;
- Produce high performance positioning information (in terms of accuracy, update interval, and integrity);
- Able to perform multitarget tracking;
- Sequential in time and space; and
- Track established in each scan and pairing up sensors in space is possible.

3.5 Summary

A total of seven correlation algorithms that track multiple targets in a clustered environment with data source from multiple sensors have been introduced. This chapter first presented the architectures of commonly used multi-sensor tracking systems. It also gave a state-of-the-art overview of existing correlation algorithms, along with the strengths and weaknesses of each algorithm. A collection of three multi-sensor trackers available in public domain for a wide variety of tracking applications are presented. Finally, the criteria of an effective multi-sensor data correlation algorithm is derived from the comprehensive review.

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CHAPTER 4: RADAR AND ADS-B DATA ANALYSIS

This chapter analyzes in detail ADS-B and radar data provided by the Civil Aviation Authority of Malaysia (CAAM). The data was collected based on opportunity traffic in the Kuala Lumpur Flight Information Region. The set of data were recorded on 22 April 2016 between 00:00:00 to 09:00:00. The first section of this chapter analyzes the information reported by the radar and ADS-B sensors, including the attributes and meaning for each sensor. The next section discusses the identified errors in the data collected, which are divided into system errors found in all aircraft or random errors in an individual aircraft. The conclusions are presented in the last section.

This chapter aims to analyze the measurement pattern of ADS-B and radar sensors, which leads to the development of correlation algorithm that correlates positioning data from multiple surveillance sensors elaborated in Chapter 5. Statistical analysis is performed using the proposed correlation algorithm to analyze the data and identify the pattern between ADS-B and radar data.

4.1 Introduction

All data collected are encrypted in the ASTERIX format, defined as low-level implementation of data format used for communication between surveillance-related devices and ATM applications as described in Chapter 2. The ASTERIX is developed and maintained by the European Air Traffic Services organization, EUROCONTROL. Radar data are encrypted in ASTERIX Cat 48 format, and ADS-B data are encrypted in ASTERIX Cat 21 format. The ASTERIX is widely used by the surveillance and ATM community and considered the universal gold standard in the industry.

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4.2 Observations and Data Processing

Observations refer to the observed measurements reported by a sensor. Generally, a modern surveillance system consists of two important components, namely the signal and data processors. The signal processor is used for target detection. A common form of adaptive algorithm, the Constant False Alarm Rate (CFAR), is used in the signal processor to determine the validity of a reflected signal and avoid background noise, cluster, and interference. It determines the power threshold above which any reflected signal is originated from a target rather than false alarm. In other words, only the reflected signal that exceeds the detection threshold in CFAR can be determined as a target. After a target is detected, the target signal is transmitted to the data recording device for recording purposes. Next, the outputs of the data recording device are processed in the data processor. During this stage, association, tracking, filtering, smoothing, and prediction are done on the measurement data. In this sense, radar signal processing is viewed as the primary processing of the information detected by the radar unit. A signal processor collects information obtained from the same radar at the same scanning period and distance unit to extract useful target information from clutter, noise, as well as various active and passive jamming backgrounds.

On the other hand, radar data processing is viewed as secondary processing of the radar information. Data processor processes information from the same radar but at different scanning periods and distance units. It can be done both at the independent radar station, as well as at the information processing center or system command center of the radar network. The function of the secondary processing of radar information is to filter and track several targets and estimate the targets' motion parameters and characteristic parameters. Tertiary processing of the radar information refers to multiple radar data fusion. This is done at the information processing center, where the information is received from the primary processing or the local track from the secondary processing of

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multiple radar. Secondary processing is done strictly after primary processing, although there is no strict time limit between secondary and tertiary processing (He, Xiu, & Guan, 2016).

Results from the detection algorithm in signal processing subsystem are known as measurements or observations (Ristic, Arulampalam, & Gordon, 2003). In other words, measurements are the output from data recording device after signal processing, and not raw data points. On the other hand, measurements can be divided according to whether they are associated with a known target track, free measurements or correlated measurements. Free measurements are spots that are not correlated with the known target track, while correlated measurements are spots that are correlated with the known target track.

4.2.1 Measurements and Its Properties

An observation consists of kinematic parameters and measured attributes. Kinematic parameters refer to the position or range rate and bearing of the aircraft. On the other hand, measured attributes are the identification number, target type, integrity, and so on. Estimation of time when the measurements are received is essential in an observation. Time interval between observations, which is known as the update rate, can be regular or irregular depending on the type of surveillance sensors.

Measured attribute quantities, such as signal-to-noise ratio (SNR) and intensity, target shape, and other target ID-related quantities are useful in data association. These attributes are used in few researches to enhance the accuracy of tracking system and aircraft performance (Mohleji & Wang, 2010; Ochieng & Sauer, 2003; Speidel, Tossaint, Wallner, & Ávila-Rodriguez, 2013). The use of measured intensity has been shown to significantly enhance track confirmation performance for dim targets in a dense clutter background. Target ID information can either be cooperative, as in the case of transponder

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data in ATC, or non-cooperative, as in the case of radar measured Jet Engine Modulation (JEM) (RTO/NATO, 1998). In either case, this information can be very useful in the maintenance of solid tracks on closely spaced targets.

4.2.2 Radar and ADS-B Measurements

The ADS-B reports a total of 19 fields in the measurement, which contains more details on the aircraft and positioning measurement, including the integrity, accuracy or uncertainties from GPS unit. On the other hand, the radar only reports 14 fields in the measurement, including the positioning data together with the identity, date, and radar related indicator listed below. Table 4.1 shows a comparison of the fields reported in ADS-B and radar sensors.

Table 4.1: Comparison of data fields reported by ADS-B and radar

No.	Field	ADS-B	Radar
1	Identity	Yes	Yes
2	Date	Yes	Yes
3	Call Sign	Yes	Yes
4	Latitude	Yes	Yes
5	Longitude	Yes	Yes
6	Heading	Yes	Yes
7	Level	Yes	Yes
8	Speed	Yes	Yes
9	Port	No	Yes
10	SSR or PSR Indicator	No	Yes
11	Radar Type	No	Yes
12	Radar Simulator Indicator	No	Yes
13	Radar Operations Center	No	Yes
14	Radar Vital Signs Monitor	No	Yes
15	ICAO 24 bit	Yes	No
16	Mode A Indicator	Yes	No
17	Version	Yes	No
18	Navigation Uncertainty Category (NUC)	Yes	No
19	Navigation Accuracy Category (NAC)	Yes	No

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Table 4.1 continued.

No.	Field	ADS-B	Radar
20	Navigation Integrity Category (NIC)	Yes	No
21	Surveillance/Source Integrity Level	Yes	No
22	GPS Level	Yes	No
23	GPS Reliability	Yes	No
24	Vertical Rate	Yes	No
25	GPS Direction	Yes	No

The Special Committee on Future Air Navigation Service (FANS) is established by the ICAO to cope with growing demands in airspace capability due to ineffectiveness of the traditional ATC systems. It aims to provide suggestion for future development in civil aviation navigation systems and conduct research on new technologies. As a result of this initiative, the satellite-based system concept is proposed to meet the civil aviation requirement for Communication, Navigation and Surveillance/Air Traffic Management (CNS/ATM). The Global Satellite Navigation Systems (GNSS) is used to support the navigation function of CNS/ATM. In fact, the disadvantages that arise from conventional ground-based systems can be addressed by GNSS-based air navigation. For example, frequent maintenance and calibration are not needed by GNSS. Furthermore, the cost of ground-based system is reduced greatly due to fewer navigation beacons that are required in GNSS.

The GPS is the main component in GNSS for navigation applications and employed in ADS-B sensor. It is worth noting that the Required Navigation Performance (RNP) is a requirement in the GPS report for civil aviation. The four parameters specified in RNP are accuracy, integrity, continuity of service, and availability (Ochieng & Sauer, 2003). For this reason, the ADS-B has more measurement attributes than the radar, where the extra attributes are associated to the RNP, for example the NAC, NUC, NIC, and so on.

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4.2.2.1 Measurement Integrity

Integrity is the critical element and has the highest concern because it is most related directly to safety in safety critical applications such as civil aviation. It indicates the level of reliability of the information supplied by the navigation system. There are three existing methods to provide integrity (Speidel et al., 2013), namely Spaces-based Augmentation System (SBAS), Ground-based Augmentation System (GBAS) and Receiver Autonomous Integrity Monitoring (RAIM).

The SBAS is a well-established method which makes use of a group of monitoring stations and a master control station. Positioning accuracies are determined by comparing the computed position with the actual position reported by GNSS. The stations then generate the integrity message which is transmitted to users along with the correction information by a set of uplink stations through geostationary satellites.

The GBAS, on the other hand, compares the true position of the ground station with the calculated position from the GNSS to determine the integrity. The correction information is transmitted to aircraft by ground monitoring stations located close to airports. Another approach is to perform calculations within the user equipment itself, which is referred as RAIM. The level of integrity is derived from multiple redundant position calculation by enough visible satellites.

Service providers and users need to understand thoroughly safety issues in terms of requirements and performance limitations linked to the use of GPS in civil aviation. This ensures the integration of GPS into traditional and safety critical applications is done without compromising safety. In fact, Ochieng and Sauer (2003) had assessed the level of integrity offered by GPS and its impact on civil aviation safety. They have assembled the performance requirements of GNSS expressed in RNP as shown in Table 4.2. Each performance parameters is defined by Ochieng and Sauer (2003) as below.

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Table 4.2: GNSS Aviation Operational Performance Requirements

Operation	Accuracy (95%)	Integrity (1 – Risk)	Continuity (1 – Risk)	Availability
Oceanic	12.4 nm	1x10^{-7} / hr	1x10^{-5} / hr	0.99 - 0.99999
En-route	2.0 nm	1x10^{-7} / hr	1x10^{-5} / hr	0.99 - 0.99999
Terminal	0.4 nm	1x10^{-7} / hr	1x10^{-5} / hr	0.99 - 0.99999
Non Precision Approach	220m	1x10^{-7} / hr	1x10^{-5} / hr	0.99 - 0.99999
Precision Approach APVI	220m (H)	1 – 2 x10^{-7} / approach	1 – 8 x10^{-6} / 15 sec	0.99 - 0.99999
	20 m (V)			
Precision Approach APVII	16 m (H)	1 – 2 x10^{-7} / approach	1 – 8 x10^{-6} / 15 sec	0.99 - 0.99999
	8 m (V)			
Cat. I	16 m (H)	1 – 2 x10^{-7} / approach	1 – 8 x10^{-6} / 15 sec	0.99 - 0.99999
	4.0 – 6.0 m (V)			
Cat. II	6.9 m (H)	1 –10^{-9} / 15 sec	1 – 4 x10^{-6} / 15 sec	0.99 - 0.99999
	2.0 m (V)			
Cat. III	6.2 m (H)	1 –10^{-9} / 15 sec	1 – 2 x10^{-6} / 30 sec (H)	0.99 - 0.99999
	2.0 m (V)		1 – 2 x10^{-6} / 15 sec (V)	

* (H) denotes the horizontal requirement and (V) denotes the vertical requirement, which is the more stringent.

i. Accuracy is defined as the level of uniformity of the measured position data relative to the reference value. The reference value should ideally be the true value, otherwise a defined standard value agreed upon. Accuracy is different from precision, which describes how close the measurements agree among themselves instead of with the reference value. Accuracy requirement of 95% in GNSS navigation system means the position error probability for any estimated position at a specific location should be at least 95%.

ii. Continuity is the efficiency of a navigation system to operate as intended without unexpected interruptions during the period of operation (POP). The level of accuracy and integrity produced should be maintained at a specified

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level during the intended POP. Continuity risk which represents the system unreliability, is the probability that the system will be disrupted and unable to produce position information for the intended POP.

iii. Availability measures the duration of time when the service is available, with the condition that accuracy, integrity, and continuity requirements are satisfied. However, movement of satellites, coverage area, and long restoring time during failure complicates the calculation of GNSS availability, which can take many years. Therefore, instead of measurement, the availability of GNSS is determined through design, analysis, and modelling. The actual availability of a system can only be determined by measurement after the end of its life.

iv. Integrity is the confidence level of information provided by the navigation system. Contrarily, integrity risk the probability of the misleading information where the positioning error exceeds the alert limit but not detected. Integrity measures the ability of the system to provide legitimate warnings to users during the POP where the system must not be used, for instance a system should prompt warning of any malfunction to users as soon as possible when the event occurs.

The Merging and Spacing concept (Mohleji & Wang, 2010) makes use of ADS-B sensor with satellite-based surveillance information for advanced airborne merging and spacing. Aircraft depart from airport often share a common departure route in close proximity or different runways of the airport. Therefore, merge operation with other aircraft is required under this circumstance. Merging aircraft demands enough spacing and synchronized timing while maintaining the minimum separation between aircraft. Loads of information needed by ATC in order to successfully perform a merging with the

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separation restrictions applied. ATC has a heavy workload in this situation, where ADS-B is useful in better supporting ATC, as well as the flight deck.

The Interval Management-Spacing (IM-S) consists of ground (or GIM-S) and flight deck (or FIM-S) components (Penhallegon, Mendolia, Bone, Orrell, & Stassen, 2011). Flight crews can be involved in the merging operation with the help of FIM-S. In the FIM-S concept, the ATC first assigns the aircraft a spacing goal behind the target, and then this information is entered into FIM-S system by the flight crew. The FIM-S provides the flight crew with the flying speed to achieve the spacing goal when the requirements are met. Under this circumstance, accuracy of the position measurement is needed and crucial for decision making. Additionally, the Navigation Accuracy Category for position (NACp) and Navigation Accuracy Category for velocity (NACv) are introduced to determine what level of support it may provide to Aircraft Surveillance Applications (ASA). The IM-S concept is one of the applications achieved by ADS-B. As a result, FIM-S equipped aircraft may achieve and maintain the assigned spacing interval from target aircraft with minimum guidance from ATC. Important attributes like integrity, as well as NACp and NACv values that are collected from CAAM are examined in the following sections.

4.2.2.2 Analysis of Measurement Integrity

The transponder on the aircraft which enables airborne surveillance function must convert the position vector into ASTERIX Cat 21 data format for transmission between surveillance systems. The standard data format includes parameters that specify navigation data quality requirement to determine the accuracy for position and velocity recorded by transponder. Estimated Position Uncertainty (EPU), NACp, and Geometric Vertical Accuracy (GVA) are the position accuracy parameters.

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The EPU signifies the estimated performance of the aircraft's current position according to a defined scale, measured in nautical miles. It is also known as Actual Navigation Performance (ANP), Estimated Position Error (EPE) in some aircraft, or Horizontal Figure of Merit (HFOM) by GPS and other GNSS systems (ICAO, 2013; Mohleji & Wang, 2010).

The NACp represents EPU in 4-bit format, ranging from 0 to 11, whereas GVA is a 2-bit representation of geometric altitude accuracy in the ADS-B state vector. The NACp does not specify if the measurement errors in successive measurements over time are correlated (Parkinson & Spilker, 1996). Similarly, the NACv parameter outlines the accuracy of the reported aircraft's velocity. Mohleji and Wang (2010) explained the values and corresponding accuracies of NACv and NACp as demonstrated in Table 4.3 and Table 4.4, respectively. This information is used as the guideline in analyzing the collected ADS-B measurements.

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Table 4.3: Navigation Accuracy Category for Velocity (NACv)

NACv	Horizontal Velocity Error
0	Unknown or ≥ 10 m/s
1	< 10 m/s
2	< 3 m/s
3	< 1 m/s
4	< 0.3 m/s

Table 4.4: Navigation Accuracy Category for Position (NACp)

NACp	95% Horizontal Accuracy Bound (EPU)	Comment
0	EPU ≥ 10NM	Unknown accuracy
1	EPU < 10NM	RNP-10 accuracy
2	EPU < 4NM	RNP-4 accuracy
3	EPU < 2NM	RNP-2 accuracy
4	EPU < 1NM	RNP-1 accuracy
5	EPU < 0.5NM	RNP-0.5 accuracy
6	EPU < 0.3NM	RNP-0.3 accuracy

Table 4.4 continued.

NACp	95% Horizontal Accuracy Bound (EPU)	Comment
7	EPU < 0.1NM	RNP-0.1 accuracy
8	EPU < 0.05NM	GPS (with SA)
9	EPU < 30m	GPS (SA off)
10	EPU < 10m	Wide Area Augmentation System
11	EPU < 3m	Local Area Augmentation System

The NACp and NACv from the collected ADS-B measurements are plotted against sampling time in Figure 4.1 to Figure 4.6.

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Figure 4.1: NACv values reported by MAS 72

Figure 4.2: NACv values reported by MAS 388

Figure 4.3: NACv values reported by MAS 786

Figure 4.4: NACv values reported by MAS 750

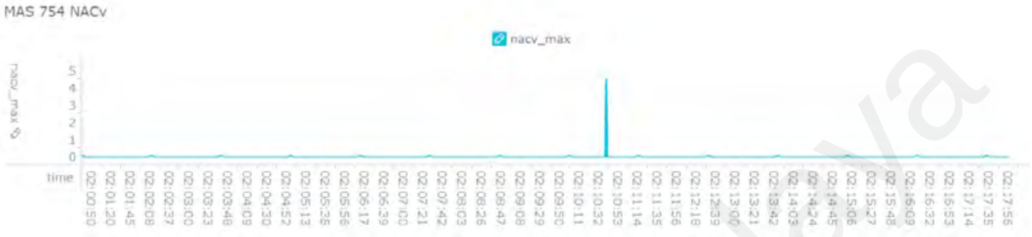

Figure 4.5: NACv values reported by MAS 754

Figure 4.6: NACv values reported by MAS 784

Figure 4.1 to Figure 4.6 show the NACv values reported by the ADS-B of each aircraft throughout the surveillance time. The NACv ranges from 0 to 4 as stated in Table 4.3. However, it was found that GPS reported NACv = 0 (unknown or ⩾ 10 m/s) in most of the surveillance time. On the other hand, MAS 754 and MAS 784 reported NACv values of more than 4. NACv can be updated dynamically from the GNSS or set statistically based on the quality of the GNSS (FAA, 2010). Therefore, it may be caused by system error or random error in the GNSS. Meanwhile, ADS-B does not report any significant value of NACp for all the observed aircraft.

The Navigational Integrity Category (NIC) indicates the containment radius integrity of the horizontal position data. Conversely, the integrity of the horizontal position data is referred as Navigation Uncertainty Category (NUC) (ICAO, 2011a). They characterize

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the accuracy and integrity of horizontal position data broadcasted by ADS-B. In general, an NUC that is less than five or an NIC that less than 6 indicates low quality data compared to the data reported by single monopulse SSR. The ADS-B data can only be used for merging and spacing along with a satisfactory means of determining data integrity.

The NUC data gathered for the six observed aircraft, namely MAS 72, MAS 754, MAS 784, MAS 388, MAS 786, and MAS 750 has a value of more than six 95% of the recording interval.; on the other hand, the lowest value of one was reported by MAS 786, and highest value nine was reported by three observed aircraft, namely MAS 72, MAS 754 and MAS 750. The NIC ranges between 1 and 10, with value more than five 95% of the recording interval. Hence, the measurements collected in this research are valid for separation in ATC. The graphs of NUC and NIC against sampling time are plotted for all observed aircraft in Figure 4.7 to Figure 4.12 below.

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Figure 4.7: NUC and NIC values reported by MAS 72

Figure 4.8: NUC and NIC values reported by MAS 754

Figure 4.9: NUC and NIC values reported by MAS 784

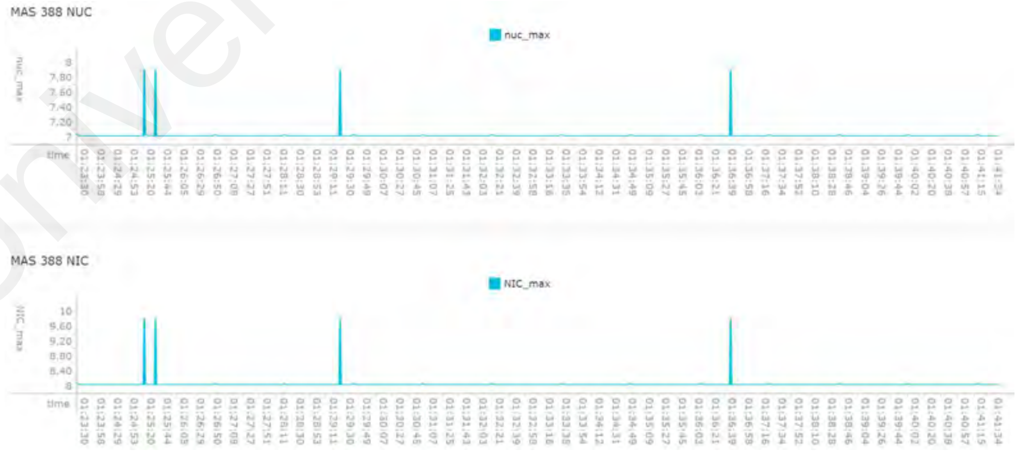

Figure 4.10: NUC and NIC values reported by MAS 388

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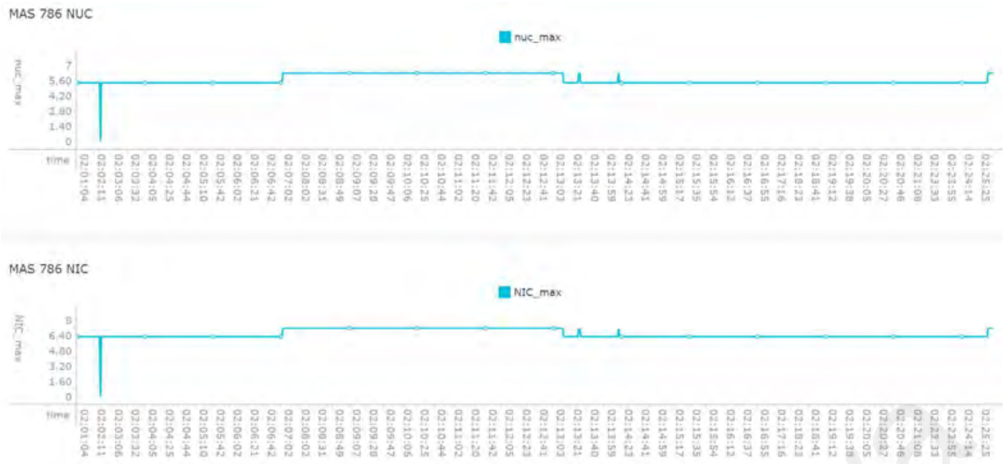

Figure 4.11: NUC and NIC values reported by MAS 786

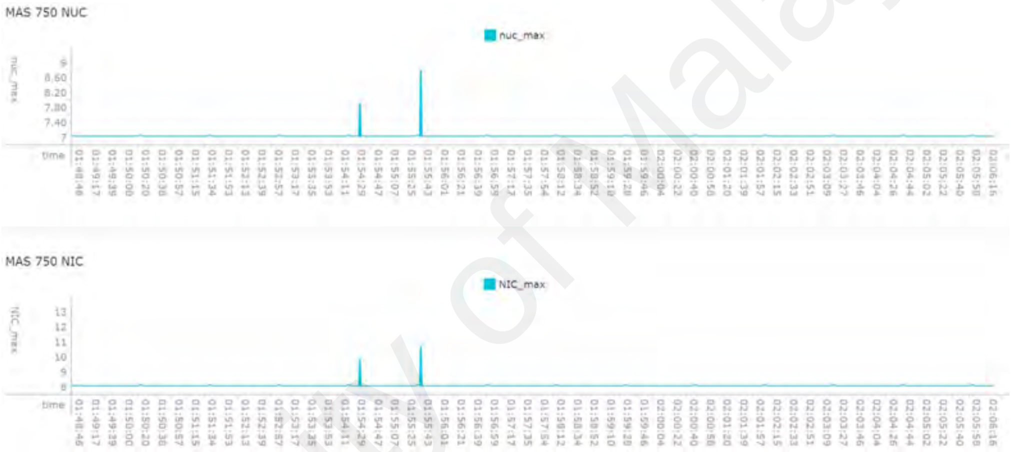

Figure 4.12: NUC and NIC values reported by MAS 750

4.3 Identification of Errors

The measurement data from a surveillance system may contain two types of error, namely system or random errors. It was found that random errors were found in MAS 72, MAS 788, MAS 750 aircraft whereas system errors occurred in all aircraft. In summary, the errors include missing speed value in radar measurements, duplicate messages in both radar and ADS-B measurements, outliers in the update interval, position jumps, and aircraft reappearing in ADS-B measurements, that are elaborated below.

4.3.1 System Errors

System errors are resulted from measurement environment, antenna, servo system, and such non-calibration factors in the data correction process as the position error of radar stations and zero deviation of altimeter. System error is complex, and has a non-random, slowly varying function that can be viewed as an unknown variable in a relatively long-time interval.

4.3.1.1 Inconsistent Update Rate

Radar and ADS-B should provide measurement data over a consistent interval for the tracker to plot a continuous path of the targeted aircraft. Inconsistent update rates are detected in all aircraft in both radar and ADS-B data sets, ranging from three to 58 seconds. However, we can observe from Figure 4.13 to Figure 4.18 that the radar sensor has a more consistent update rate compared with the ADS-B sensor for all the aircraft studied.

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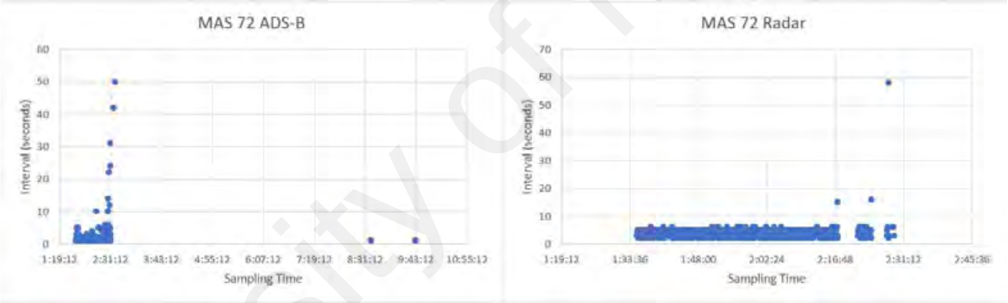

Figure 4.13: Update Rate of aircraft MAS 72 for Radar and ADS-B measurement

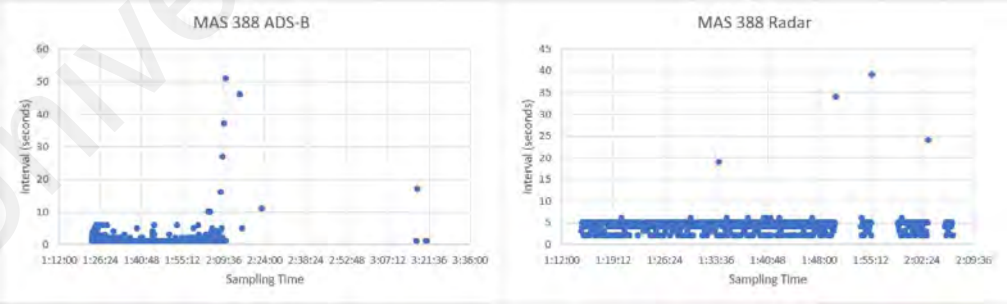

Figure 4.14: Update Rate of aircraft MAS 388 for Radar and ADS-B measurement

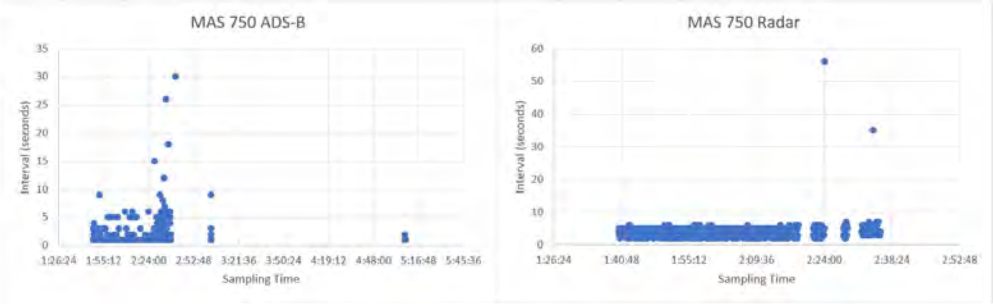

Figure 4.15: Update Rate of aircraft MAS 750 for Radar and ADS-B measurement

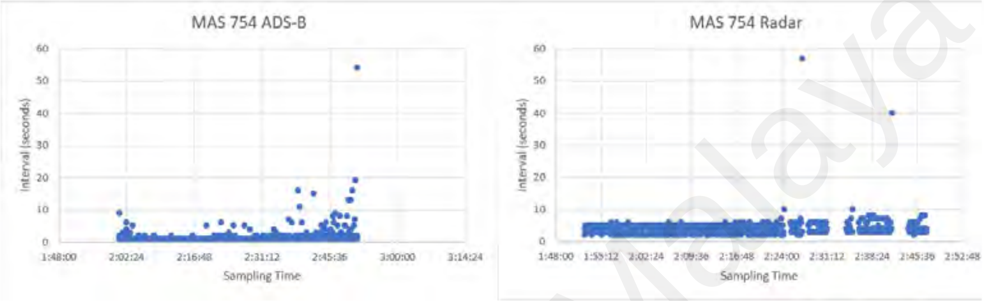

Figure 4.16: Update Rate of aircraft MAS 754 for Radar and ADS-B measurement

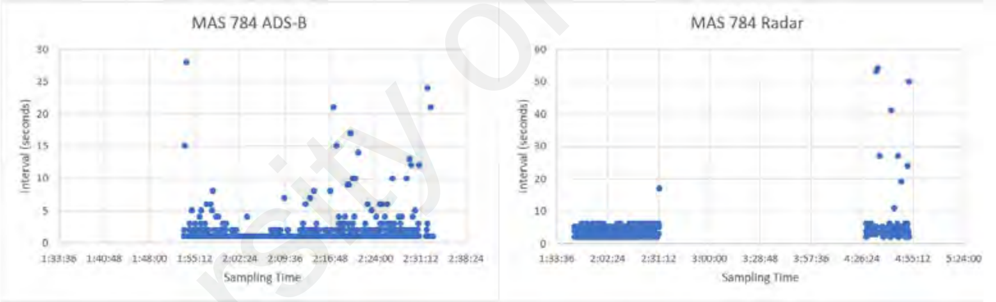

Figure 4.17: Update Rate of aircraft MAS 784 for Radar and ADS-B measurement

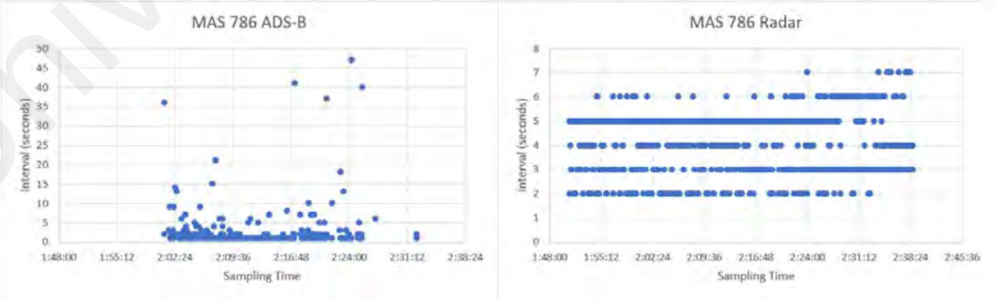

Figure 4.18: Update Rate of aircraft MAS 786 for Radar and ADS-B measurement

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4.3.1.2 Position Jumping

Latitude and longitude position jumping were identified in ADS-B data for all the aircraft observed in this work. The jumping degree varies between 0.1 to 2.0 degree for longitude, and 0.1 to 6.0 degree for latitude measurements. The position jumping is independent of the stamping time and happened randomly throughout the recording period. Contrarily, the corresponding radar data, which were filtered by the processing centre at ground station, did not record such position jumping. Figure 4.19 to Figure 4.24 show the position jumping in latitude and longitude over the recording time for four aircraft.

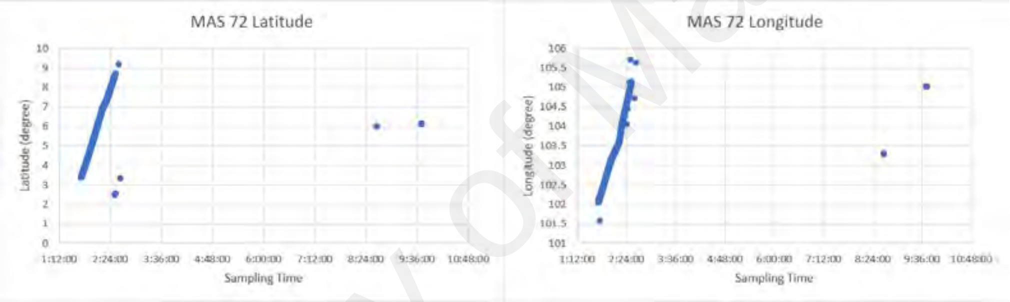

Figure 4.19: Longitude and latitude position jumps for MAS 72

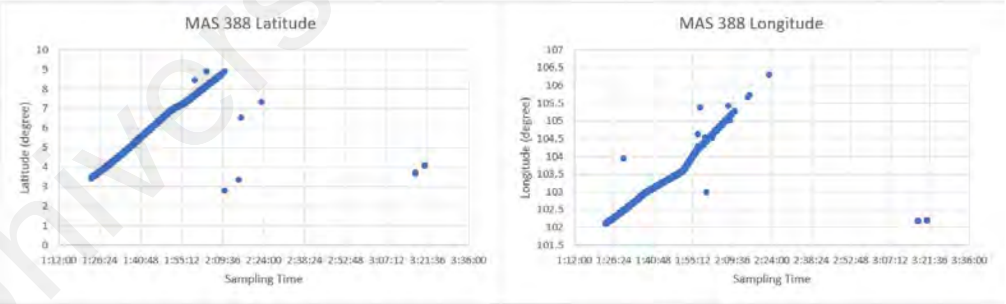

Figure 4.20: Longitude and latitude position jumps for MAS 366

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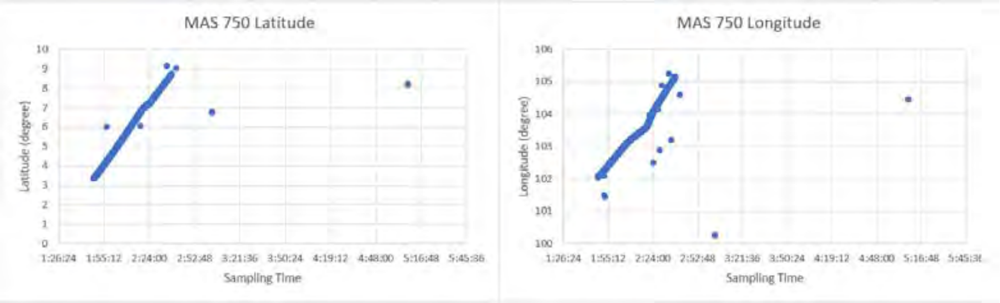

Figure 4.21: Longitude and latitude position jumps for MAS 750

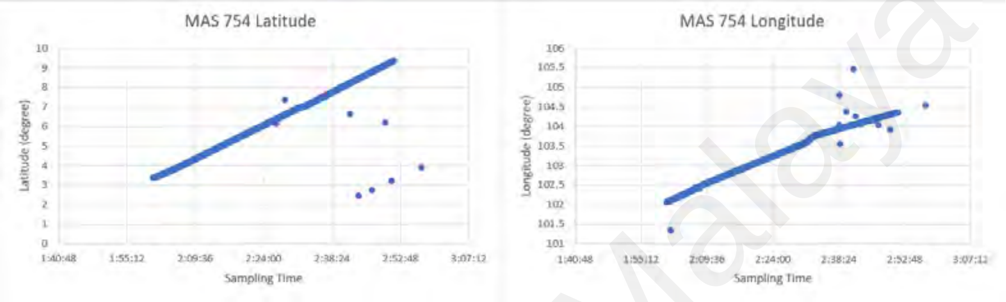

Figure 4.22: Longitude and latitude position jumps for MAS 754

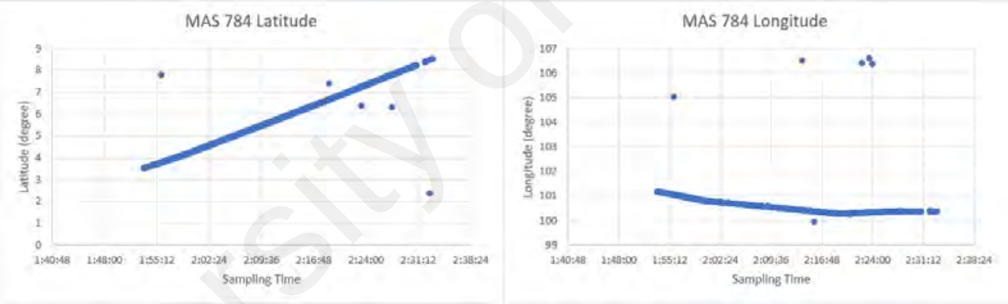

Figure 4.23: Longitude and latitude position jumps for MAS 784

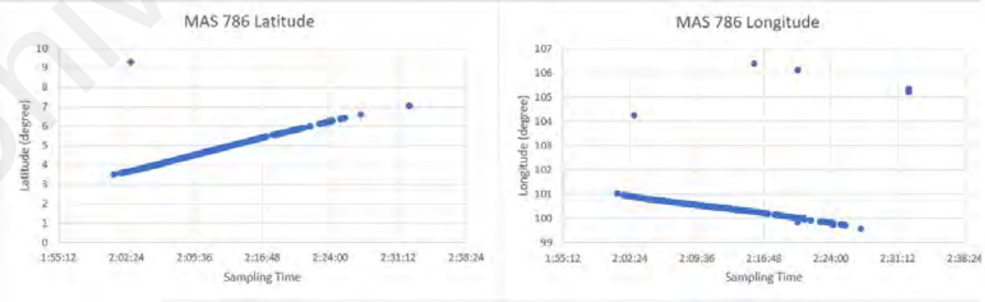

Figure 4.24: Longitude and latitude position jumps for MAS 786

Position jumping were observed in ADS-B measurements but not found in radar measurements. As position information of ADS-B is obtained from GNSS, there is a possibility that the measured position data from the GPS is incorrect. On the other hand,

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position information of the radar is obtained from the reflection of signal emitted and processed in the ground station to eliminate the outline position before sending to users; therefore, there is no position jumping found in radar measurements.

4.3.1.3 Duplicate Radar and ADS-B Data

Duplicate messages were identified in both the radar and ADS-B data sets of all aircraft. In fact, the sensors recorded the same longitude and latitude measurements at the same sampling time. There is a possibility that the central processing unit has failed to remove duplicate messages at the overlapping airspace when an aircraft was detected by multiple radar and ADS-B ground stations at the same time.

4.3.2 Random Errors

Random errors are resulted from the interior noise of the measurement system. Random errors may vary with each measurement and may be eliminated to some extent by increasing the frequency of measurement, as well as minimizing its variance statistically, by means of method like filtering.

4.3.2.1 Missing Speed Value in Radar Data

Speed is one of the attributes reported by both radar and ADS-B sensors. In summary, missing speed values were observed in radar measurements but not those of ADS-B. In fact, this circumstance is found in most of the aircraft under observation. For instance, aircraft MAS 784 reported zero speed value at time 02:31:36, 04:36:35, 04:38:38, 04:44:57, and 04:52:21, even though its longitude and latitude measurements are recorded. On the other hand, MAS 366 reported full speed values in all the measurements. The missing rate for each aircraft throughout the sampling time is calculated in this work. The results are summarized in Table 4.5.

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Table 4.5: Missing Speed Value in Radar

Aircraft Call Sign	Total Measurement Count	Missing Speed Measurement Count	Percentage (%)
MAS 72	721	28	3.88
MAS 388	672	44	6.54
MAS 750	724	53	7.32
MAS 754	752	71	9.44
MAS 786	713	14	1.96
MAS 784	1028	58	5.64

4.3.2.2 Discontinuous Tracking

Discontinuous tracking was observed in three out of the six aircraft, whereby the involved aircraft were reported reentering the surveillance space after a few hours of leaving. For instance, MAS 72 was tracked by ADS-B at 02:38:06 AM and the next tracking time was 08:39:56 AM. The aircraft seemed to be missing during that period and reappeared in the surveillance space. The latter measurement may be a random error and not an actual reporting data from aircraft. The same was observed for MAS 388 and MAS 750. Figure 4.25 to Figure 4.27 below show the sampling time throughout the surveillance. There is a large gap of one to few hours in the measurements reported.

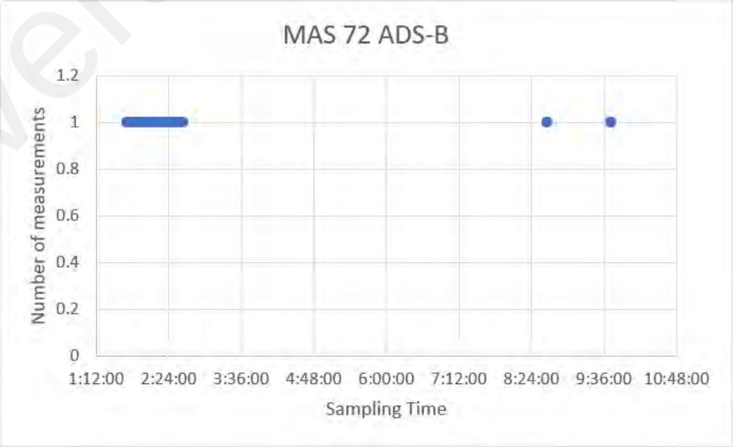

Figure 4.25: Discontinuous Tracking of MAS 72

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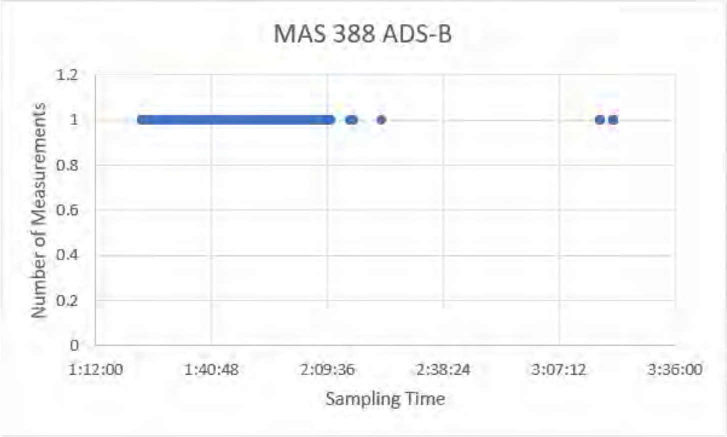

Figure 4.26: Discontinuous Tracking of MAS 388

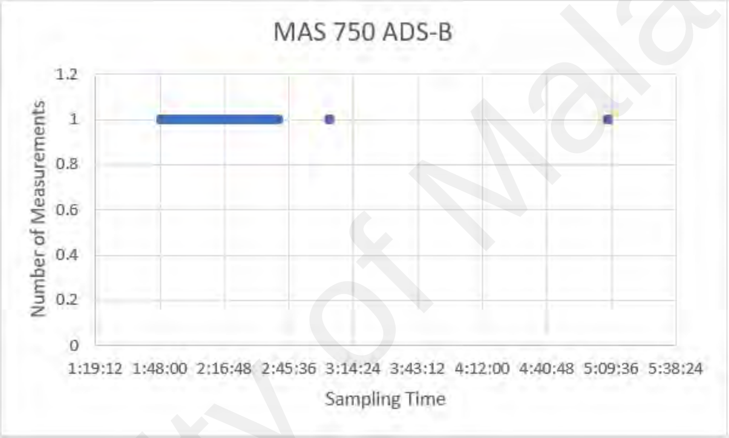

Figure 4.27: Discontinuous Tracking of MAS 750

4.4 Conclusion

From the analysis of data above, it is concluded that the radar produces stable measurements, but ADS-B provides informative parameters.

The ADS-B makes use of the GNSS service to get its position information when reporting to ground station. Its measurements specify the accuracy, integrity, availability, and continuity of service. These RNP parameters increase the accuracy and integrity levels, provide safety advantages, and reduce the operational cost due to inefficiencies.

However, by comparison the radar is unable to provide such information in its scanning. Nonetheless, it has higher consistencies for its measurement. Apart from the random errors which were caused by the interior noise of the measurement system, the

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radar has a better performance over ADS-B in terms of update rate and position accuracy. Besides that, the radar shows no position jumping in its measurements, and a relatively consistent update rate over ADS-B.

Next, it was found that the ADS-B and radar both show system errors in their measurements, such as duplicated measurement and inconsistent update rate. Measurements from both surveillance systems cannot completely fulfill the requirement of the ATC due to the significant errors that appear in the measurements. Therefore, a correlation algorithm is vital to produce a set of measurements with high integrity, availability, and accuracy. The proposed correlation algorithm is discussed in next chapter.

4.5 Summary

This chapter analyzed the measurements collected using the radar and ADS-B in terms of their attributes, system, and random errors. Lastly conclusion is drawn based on the observations.

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CHAPTER 5: PROPOSED CORRELATION ALGORITHM AND TOOL

In this chapter, an algorithm is proposed to correlate the measurements collected from the radar and ADS-B sensors, each with its own properties and characteristics as discussed in Chapter 4. Conventional correlation cannot be applied to the measurements directly due to differences of both sensors, particularly in the sampling rate (time). Hence firstly, pre-correlation steps are introduced to pre-process the collected measurements. Existing data pre-processing techniques have been reviewed before the suitable steps are applied in this research. These steps are explained in detail together with the existing available techniques. Next, cross correlation is applied to radar and ADS-B measurements to identify their relationship and pattern. Additionally, post data process normalization is then applied to the output of the correlation to obtain results and values of precision. Subsequently, a tool is developed based on the proposed algorithm using C# programming language. The tool accepts a text file as the measurements input from both sensors. Finally, testing and validation of the tool is presented in Chapter 6.

5.1 Data Pre-processing Methods

The main challenge in correlating radar and ADS-B measurements is the uneven sampling rate (time). The output of these sensors is a sequence of observation time and position pairs with uneven and inconstant spacing of observation times. The reasons and behaviors of this uneven sampling time for the radar and ADS-B are explained in Chapter 4. Uneven time sampling is not only a problem in aircraft tracking but also observed in astronomy, biomedical rhythms, and turbulence research (Rehfeld, Marwan, Heitzig, & Kurths, 2011). Most of the traditional correlation estimation techniques rely on regular sampling time, therefore they cannot be applied to measurements with irregular sampling time. Hence, data reconstruction (interpolation) or other advanced methods are needed to handle uneven sampling. However, even though data of uneven sampling time occurs

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naturally in many industrial and scientific fields, few methods exists in handling it. The most common approach is to transform the irregular spaced data into regular spaced observations using interpolation, and then apply existing methods used in regular spaced time series. However, this may introduce several biases (Eckner, 2017; Rehfeld et al., 2011; Scholes & Williams, 1977).

5.1.1 Existing Methods to Handle Data with Uneven Sampling Time

Few approaches have been proposed to handle data with uneven sampling time. They can be categorized into four classes: (a) least square methods; (b) slotting methods; (c) model-based estimators; and (d) time series reconstruction methods (Rehfeld et al., 2011).

The least square methods estimate a frequency spectrum based on a least square fit of sinusoids to data samples. Lomb-Scargle periodogram (Lomb, 1976; Scargle, 1989) is one of the least square methods acknowledged for its capability to observe and identify reiteration in an unevenly sampled time series, however the obtained least squares spectrum turned out to be severely biased for turbulence spectra. It loses its strength in higher noise level with smaller peaks environment (Broersen, Waele, & Bos, 2000; VanderPlas, 2018).

Next, the slotting methods apply binning on all data with predefined interval, where single measurement only attribute to bin which it resides (Edelson & Krolik, 1988; Mayo, 1978). The main advantage of this technique is that it can have a small bias and produces accurate spectral estimate. However, this method does not guarantee a positive spectrum. A variety of the slotting methods have been proposed by (Babu and Stoica (2009); Mudelsee (2010); Stoica, Li, and He (2008)) to overcome the problem.

Thirdly, model-based methods fit parametric spectral models to raw data (Maanen & Oldenziel, 1998; Müller, Nobach, & Tropea, 1998). The imposed spectral shape is

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independent of the data and requires prior knowledge of the shapes. Moreover, this method gives no attention to spectrum area with low power (Broersen et al., 2000).

Lastly, time series reconstruction resamples the data through interpolation. The time series is reconstructed on a regularly spaced grid for standard Fast Fourier Transform (FFT) analysis. Linear interpolation is applied most often, but it causes a significant reduction in variance, especially in high-frequency range of the estimated spectrum when analyzing the irregularly sampled data.

5.1.2 Slotting Technique

Based on the review of conventional techniques in the previous section, the slotting technique with binned correlation is chosen in this research to regulate the radar and ADS-B measurements. The slotting technique is robust and has a comparably low bias than the traditional techniques using interpolation to handle regular and irregular sampling time (Rehfeld et al., 2011). Besides, slotting smoothens the data by consulting the values around it. In smoothing by slot, it means the slot is represented by the mean value. However, all reported measurements are not fully utilized individually in the slotting technique, which may cause loss of information. In addition, when there are gaps where the measurements are missing due to random or system errors within reporting period, the slots would have a null value. Details on handling this situation are explained in the following section.

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5.2 Proposed Correlation Algorithm

The flow chart in Figure 5.1 illustrates the proposed correlation algorithm. It consists of four major blocks and each block is divided into several steps. The four major blocks are: (i) Data Pre-processing; (ii) Slotting Technique; (iii) Cross Correlation; and (iv) Normalization. The measurements from radar and ADS-B sensors are streamed into the blocks respectively following the order listed above. Each block has its own functionalities and purposes that is achieved according to the individual step inside the block. The steps in each block are explained in detail in the next sub-sections.

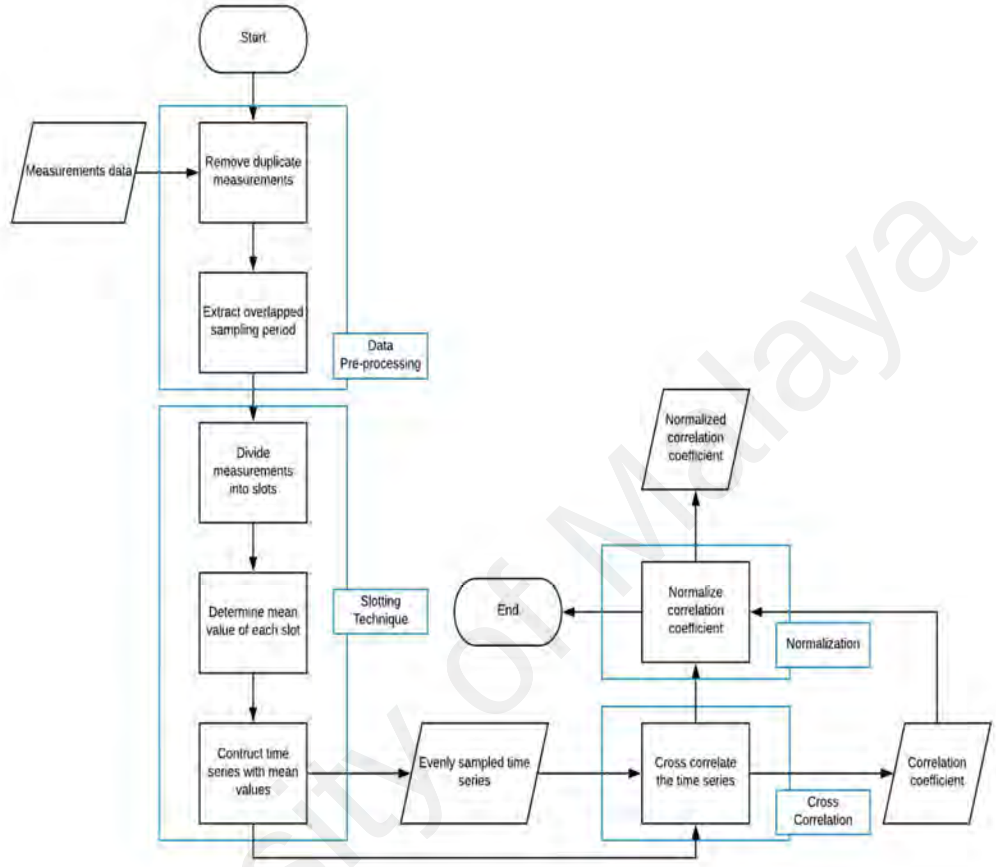

Figure 5.1: Flow Chart of Proposed Correlation Algorithm

5.2.1 Data Pre-processing

Firstly, all duplicated data are removed from the radar and ADS-B measurements. The latter measurement is compared to the previous measurement in terms of all the attributes discussed in Chapter 4. The main attributes that determine the position of an aircraft are date/time, longitude, latitude, speed, and heading. If all these attributes have the same value as the previous measurement, the latter measurement would be discarded. Duplication happens frequently in ADS-B measurements, where no data processing is done to the measurement prior data collection. Unlike ADS-B, the radar measurements go through data processing routines where duplicate measurements are eliminated before

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data collection is done at the radar ground station. Removing the duplicate measurements helps to save limited resources at the ATC and reduces the processing time to correlate radar and ADS-B data.

Next, overlapped periods between radar and ADS-B sensors are identified. Correlation requires at least two time series for comparison to be made. Missing either one of the radar or ADS-B data makes the calculation impossible. Radar and ADS-B measurements are obtained and compared to determine the point of time in which both measurements occurred to find the overlapped periods. Correlation would only start at this point of time until either radar or ADS-B does not report any measurement for more than three minutes. The discontinuity in the data broadcast is assumed as loss of target if there is no report any measurements within three minutes. In case the sensor resumes reporting measurements of the tracked target after three minutes, then, it is taken as a new path with no continuity from the previous correlation. New correlation would be started without taking into consideration the previous measurements. This is to make sure that the position data of the tracking aircraft is always up-to-date during correlation process. The measurements that do not overlap are truncated since they are useless in the correlation calculation.

5.2.2 Slotting Technique

The overlapped measurements are then subdivided into slots of designated time duration, t_s. The slot duration should be chosen carefully. A slot duration that is smaller than the update rate of either radar or ADS-B should be avoided because there would be empty slots without any measurements, as no data would be reported yet due to the short duration. Conversely, the slot duration should also not be too large that it may contain a turning point of the tracked aircraft. As there are possibilities that the tracked aircraft may turn back in any point of its path, therefore the choice of slot duration should account for

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the least time for turning path too. Ideally, the measurements in a slot should be in a straight line in accordance to the path of the aircraft. In other words, the combination of slots would perfectly reflect the path of the aircraft, including its turning point. In this research, the slot duration is set to 10 seconds, whereby it is larger than the update rate for both radar and ADS-B sensors, as well as small enough to include the important turning measurement of the aircraft. From the radar and ADS-B measurement $r(i) = r(t_1, i), i = 0, 1, 2 \ldots N_1 - 1$ and $a(i) = a(t_2, i), i = 0, 1, 2 \ldots N_2 - 1$, with the slot duration d and slot sequence $j = i + d$, the slot mean values for radar and ADS-B are calculated using Equation 5.1 and Equation 5.2:

Equation 5.1: Mean Calculation for Radar

$$\overline{r_j} = \frac{\sum_j^{i+d} r_i}{d}$$

Equation 5.2: Mean Calculation for ADS-B

$$\overline{a_j} = \frac{\sum_j^{i+d} a_i}{d}$$

The mean value is taken as the slot value. This would reduce the discrepancies among measurements within the slot. However, if there is an outlier within the slot, the variance of the slot would be huge. Despite this, it is not acceptable to drop a measurement just because it is an outlier. In fact, it can be a legitimate observation and sometimes, the most interesting one. An outlier can only be dropped when it is confirmed that it is due to incorrect measurement. Anyhow there is no way to find out the cause of the outlier from the measurement. Nonetheless, outliers from one sensor can be identified by comparing them with the data pattern of the other sensor from the same time frame. A drawback of this algorithm is its incapability to confirm the incorrect measurement; hence, the outliers are not removed from this algorithm.

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There are occasions when the radar or ADS-B sensors do not report any position from a few seconds to minutes. There would a large gap when the missing measurements have a period that is longer than the slotted time duration, t_s. Therefore, Nobach (2016) suggested that when there is a large gap, the slot value should be set to zero to suppress the affecting influence on the derived statistical functions. In this research, it is assumed that the tracked aircraft is moving with constant speed towards a constant direction that would not change dramatically. Therefore, the missing slot value is set as the previous slot value to maintain the position of the aircraft. Two assumptions are made in this research to come to this decision: (a) the aircraft is moving at a constant speed in a constant direction from the last reported position; (b) the missing measurements are caused by inability of the onboard or ground system to transmit or receive the signal.

The radar and ADS-B measurements with irregular sampling time are transformed into time series with regular sampling time via the pre-processing stage. The pattern between radar and ADS-B sensors can now be correlated and identified with the use of these measurements.

5.2.3 Correlation

Correlation describes the relationship between two data sets. Correlation is useful because it shows a predictive relationship that can be exploited in practice. However, correlation is insufficient to infer the presence of a causal relationship between the data sets. It only indicates how close two data sets are to a linear relationship with each other. Correlation can positive, negative, or zero. Positive correlation indicates simultaneous increment in both data set. Conversely, negative correlation indicates the opposite, as one data set increases, the other decreases. In case the data sets show no change with the other, it means there is no correlation between the two data sets.

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Correlation can also be described by its strength, which include perfect, strong or weak correlation. The Correlation Coefficient is used to describe the strength of the correlation between two data sets, with values between -1.0 to 1.0. Existing state-of-the-art correlation algorithms used in multi-radar tracking system have been studied and explained in Chapter 3.

5.2.3.1 Cross Correlation

Cross correlation estimates the level of association between two time series. To calculate the level of correlation between two signals, simply multiply and sum two time series together. Consider two time series *x(i)* and *y(i)*, where *i = 0, 1, 2… N-1*, the cross-correlation *r* is defined as Equation 5.3:

Equation 5.3: Cross Correlation

$$\boldsymbol{r} = \sum_{\boldsymbol{i}=\boldsymbol{0}}^{\boldsymbol{N}-\boldsymbol{1}} \boldsymbol{x}[\boldsymbol{i}] * \boldsymbol{y}[\boldsymbol{i}]$$

Cross correlation can be modified by applying a time shift to detect if a signal is lagging or leading another. A lagging signal is the signal that moves steps behind another, whereas a leading signal moves steps ahead of another. Cross correlation is done by moving one of the time series *d* elements to the right or left. The cross correlation with delay is defined as Equation 5.4:

Equation 5.4: Cross Correlation with Delay

$$r_d = \sum_{i=0}^{N-1} x[i] * y[i-d]$$

If Equation 5.4 is computed for all delays *d = 0, 1, 2 … N-1*, a cross correlation with twice the length of original series is produced. All possible time shifts need to be calculated to detect if two time series are correlated with a time shift.

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When the delay applied is more than or equal to the length of the time series, it causes the index into time series ($i - d$) out of range: $i - d < 0$ or $i - d >= N$ which the index less than zero or greater than or equal to the number of points. For circular cross correlation, the out-of-range indexes are wrapped back within the range like *x(-1) = x(N-1), x(N+5) = x(5)* etc. Since we know that the path of a tracked aircraft cannot be circular, a condition where the previous measurement would not be the same as the current or future measurement, circular cross correlation is not applied in this research.

5.2.4 Normalization of Cross Correlation

It is difficult to understand the scoring value in cross correlation. The scoring value varies from a single digit to a few thousand. Hence, it is hard to determine the relationship between the tested signals. Besides that, the amplitude of the tested signals has significant effect on the correlation too. If both signals have the same shape but huge difference in amplitude, the correlation would not be detected because the low amplitude signal reduces the output significantly. The output of cross correlation is normalized using Equation 5.5 to overcome these difficulties:

Equation 5.5: Normalize Cross Correlation

$$norm_{corr(x,y)} = \frac{\sum_{i=0}^{N-1} x(n) * y(n)}{\sqrt{\sum_{i=0}^{N-1} x(n)^2 * \sum_{i=0}^{N-1} y(n)^2}}$$

Normalization limits the scoring value of cross correlation to -1 to 1, whereby 1 means a high positive correlation, -1 means a high negative correlation, and 0 means no correlation between the tested signals. Normalized cross correlation can also be used to detect the correlation of two signals with different amplitudes.

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5.3 Design of Proposed Correlation Tool

This section illustrates the thorough design process of the proposed correlation tool, including the requirements, use case model, class diagram, and the system flow of the tool.

5.3.1 Requirements

The requirements of the correlation tool are derived from the proposed correlation algorithm, in line with the review of existing correlation algorithms in Chapter 3. They are categorized as functional and non-functional requirements. Functional requirements explain the essential tasks of the tool, input and output of the system, as well as the interaction with external user. Non-functional requirements describe the performance and limitations that restrict the selections of developing the tool.

5.3.1.1 Functional Requirements

Functional requirements are derived and listed in Table 5.1.

Table 5.1: Functional Requirement for correlation tool

No.	Requirement
RQ1	The tool should accept text file with specific format as input, together with the call sign of desired aircraft.
RQ2	The tool should be able to extract the overlapped sampling period of radar and ADS-B.
RQ3	The tool should be able to transform the radar and ADS-B measurements to time series with even sampling time by means of the slotting technique.
RQ4	The tool should be able to cross-correlate the time series output from slotting.
RQ5	The tool should be able to product a correlation output to an excel file.
RQ6	The tool should be able to draw the slotted path of the aircraft on map panel.

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5.3.1.2 Non-functional Requirements

The Non-functional Requirements are identified and listed as follow.

- Security – Aircraft's position is classified as sensitive data that should not be exposed freely. The tool can only accept file with specific format.
- Capacity and Performance – The tool should be capable of processing files with huge input containing tens of thousands of measurements. Performance of the tool depends on the file size and measurements to be processed.
- Reliability – The tool processes the file and measurements, and produces correct output.
- Maintainability – The design of the tool shall be easily maintained and improved with minimum modification of the structure and components.
- Usability – The tool is intended for air traffic controllers, ATM engineers, and researchers in related field.

5.3.2 Class Diagram

All classes involved in the correlation tool are illustrated in Figure 5.2. The RadarTrack and ADS-BTrack are built as collection of class Measurement, which consists of position data of an aircraft. Next, the class Correlator contains all the logics and calculations by using RadarTrack and ADS-BTrack classes to generate output.

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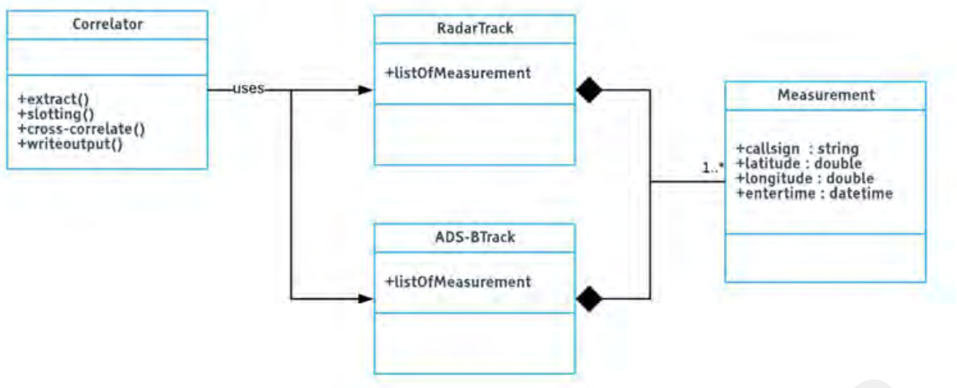

Figure 5.2: Class Diagram for Correlation Tool

5.3.3 Use Case Models

The correlation tool is divided into three modules, of which each holds specified functional requirements. The design of the tool is illustrated in Table 5.2.

Table 5.2: Modules, Functional Requirements and Sub-requirements

Modules	Functional Requirements	Sub-requirements
Input and Measurement Module	**RQ1** The tool should accept text file with specific format as input, together with the call sign of desired aircraft.	RQ1.1 Read file
		RQ1.2 Check file format
		RQ1.3 Read call sign
	RQ2 The tool should be able to extract the overlapped sampling period of radar and ADS-B.	RQ2.1 Extract the measurements according to call sign
		RQ2.2 Identify the overlap sampling period
Proposed Correlation Algorithm Module	**RQ3** The tool should be able to transform the measurements of radar and ADS-B to time series with even sampling time with slotting technique.	RQ3.1 Slot the measurement
		RQ3.2 Calculate the mean value of each slot
		RQ3.3 Restructure the measurements
	RQ4 The tool should be able to cross-correlate the time series output from slotting technique.	RQ4.1 Cross-correlate the time series

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Table 5.2 continued.

Modules	Functional Requirements	Sub-requirements
Output and Result Module	**RQ5** The tool should be able to write the correlation output to an excel file.	RQ5.1 Write output of cross-correlation into excel file
	RQ6 The tool should be able to draw the slotted path of the aircraft on map panel.	RQ6.1 Draw the slotted path on map panel

5.3.3.1 Use Case and Description

There is only one actor involved in this tool, i.e. the Air Traffic Controller, whose task is to analyze radar and ADS-B measurements, as well as observe the slotted path of both sensors on screen. Use case for the modules identified in previous section are shown in Figure 5.3 to Figure 5.5, followed by the description in Table 5.3 to Table 5.7.

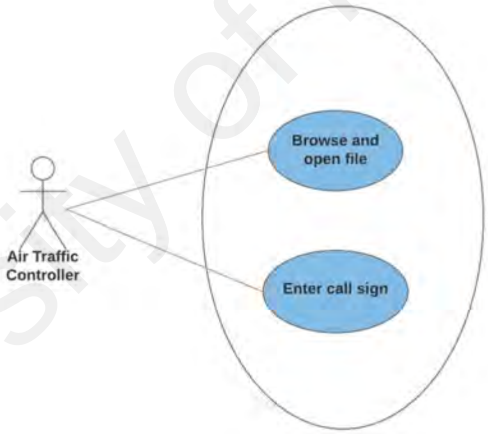

Figure 5.3: Input and Measurement Module

Table 5.3: Browse and Open File Description

Use Case Name	Browse and open file
Actor	Air Traffic Controller
Precondition	User clicks "Search File" to choose desired file, file must be a text file.
Description	User inputs any file that contains measurements with specific format defined in this research.

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Table 5.4: Enter Call Sign Description

Use Case Name	Enter Call Sign
Actor	Air Traffic Controller
Precondition	Input files have been selected by user.
Description	User enters desired aircraft’s call sign in the text box. The tool filters the measurements in input files according to call sign.

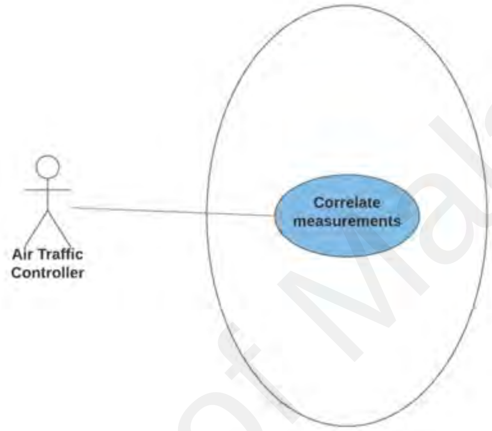

Figure 5.4: Proposed Correlation Algorithm Module

Table 5.5: Correlate Measurements Description

Use Case Name	Correlate Measurements
Actor	Air Traffic Controller
Precondition	Input files and call sign have been inputted by user.
Description	User clicks on “Correlate” button, the tool extracts measurements from input files, applies slotting and cross correlation on the measurements.

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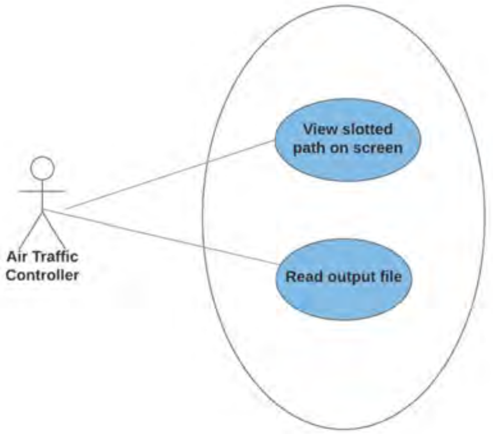

Figure 5.5: Output and Result Module

Table 5.6: View Slotted Path on Screen Description

Use Case Name	View Slotted Path on Screen
Actor	Air Traffic Controller
Precondition	Input files and call sign have been inputted by user, user clicked on “Correlate” button.
Description	Results from the Correlate Measurement use case are plotted on map panel on screen.

Table 5.7: Read Output File Description

Use Case Name	Read Output File
Actor	Air Traffic Controller
Precondition	Input files and call sign have been inputted by user, user clicked on “Correlate” button.
Description	Correlation coefficients are written in a local excel file for user’s perusal.

5.3.4 Flow Chart

Figure 5.6 illustrates the sequence of process, flow of data, and decision making in the tool.

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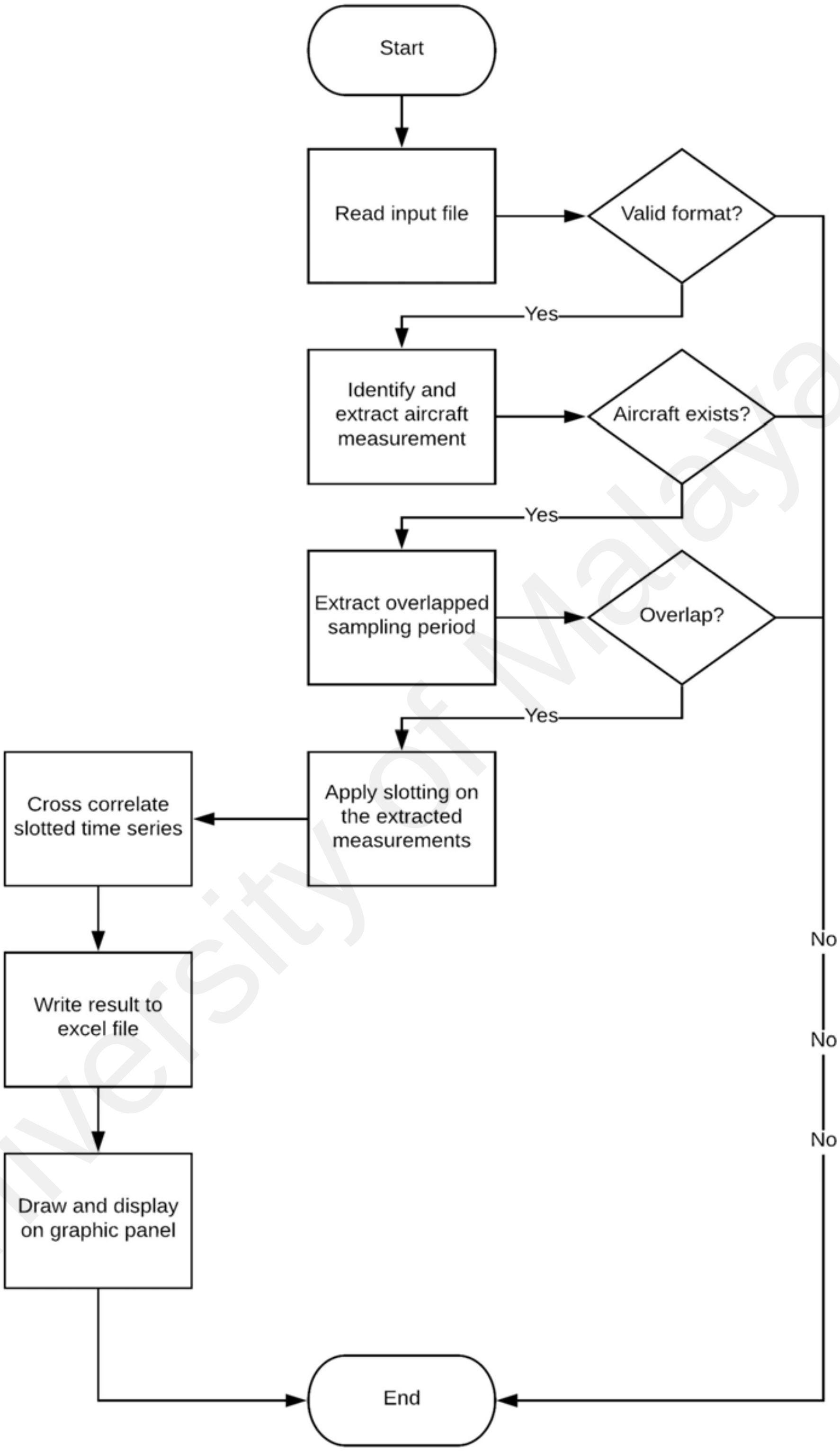

Figure 5.6: Flow Chart of Correlation Tool

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Brief comments on each process in flow chart are elaborated below.

- First, the correlation tool reads the input text file to collect radar and ADS-B measurements based on the call sign provided.
- Overlapped sampling period of radar and ADS-B is then identified and extracted from the measurements.
- Next, the slotting technique is applied on the overlapped measurements to transform them into evenly sampled time series.
- Then, time series produced by the slotting technique are channeled into the cross correlation algorithm.
- The output of the cross correlation is written into an excel file.
- Lastly, the slotted time series are shown on the tool.

5.4 Development of Proposed Correlation Tool

The correlation tool is developed according to the requirements and design deliberated in the previous sections. It is a standalone Windows compatible application that interacts with users. The correlation tool accesses the local file system to read and write files.

5.4.1 Programming Language and Platforms

Windows Forms (WinForms), .Net C# from Microsoft .Net Framework, and Bing Maps V8 Web Control are chosen to develop the correlation tool. WinForms is a graphical (GUI) class library that provides a rich application development platform for desktop, laptop, and tablet PCs. It simplifies the application tasks, such as reading and writing to local file system. Abundant of controls are provided in this platform to interact with the user. A control is a discrete user interface element that displays data or accepts data input. Every action that a user performs on the application's form, for instance a mouse clicks or key presses, generates an event that can be handled by using code aimed to process the

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event when they occur. In addition, the WinForms provides library that contains a large selection of classes for calculation and data processing.

Bing Maps V8 Web Control is a web mapping platform introduced by Microsoft. It runs with JavaScript control that contains objects, methods, and events; hence, it can be easily integrated into the WinForms application and website. It provides a wide range of features to make data visualization richer and interactive. HTML 5 canvas used in this control provides a significant rendering performance boost, allowing for smooth zooming in and out interaction. As a result of these benefits, WinForms and Bing Maps V8 Web Control are chosen as development platforms in this research.

5.4.2 User Interface

The user interface used in the correlation tool are listed in this section. The target users of this tool are air traffic controllers, ATM engineers, and researchers who may have minimum or no software development experience; hence, it is important to design a simple and user-friendly interface.

5.4.2.1 Main Screen

The main screen of the correlation tool is shown in Figure 5.7. Each component of the main screen is described below Figure 5.8. Status label shows the current process that is running, which are “Processing data files”, “Pre-processing data”, “Slotting data” or “Correlating data”.

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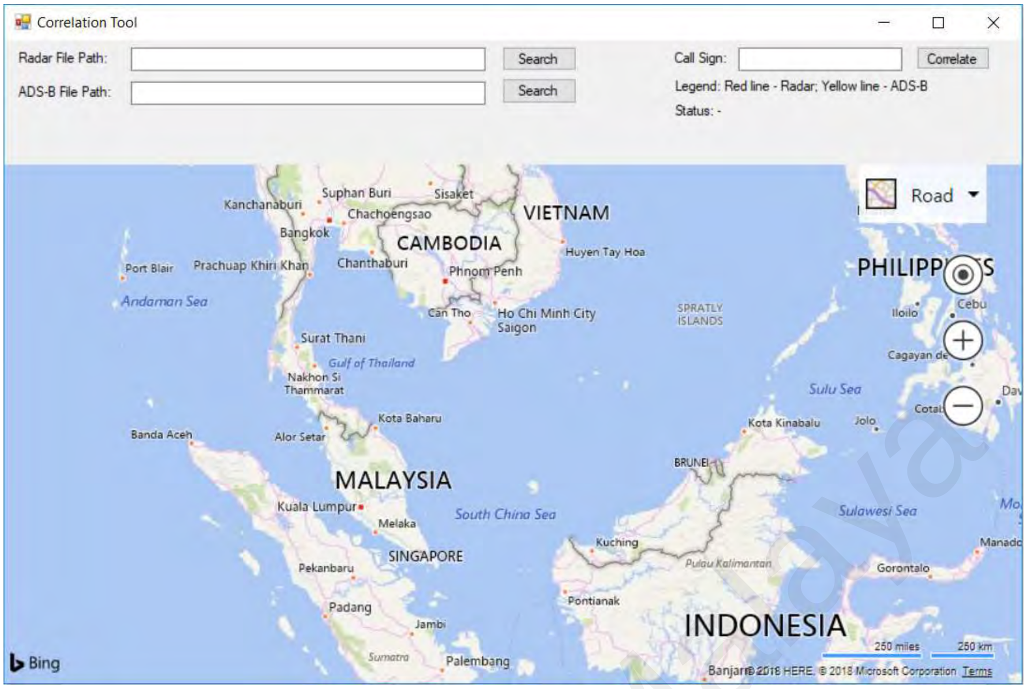

Figure 5.7: Main Screen of Correlation Tool

Table 5.8: Components in Main Screen

No	Components	Type	Constrains
1	Map Panel	Bing Maps V8 Web Control	None
2	Radar File Input	Text Box	None
3	Radar File Search	Button	None
4	ADS-B File Input	Text Box	None
5	ADS-B File Search	Button	None
6	Call Sign Input	Text Box	Cannot be empty
7	Correlate	Button	Only allow when all inputs are filled in.
8	Legend	Label	None
9	Status	Label	None

5.4.2.2 File Browsing Screen

When the user clicks on the "Search File" button for either radar or ADS-B, file browsing screen shown in Figure 5.8 is prompted. It is a built-in dialog box by WinForms that allows user to navigate through file system to select the desired file.

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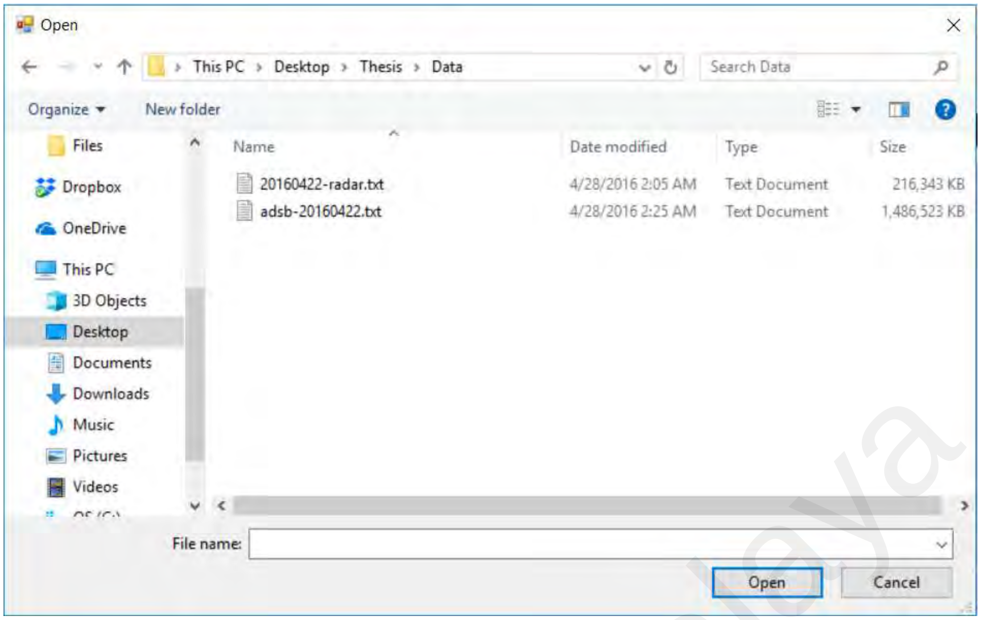

Name	Date modified	Type	Size
20160422-radar.txt	4/28/2016 2:05 AM	Text Document	216,343 KB
adsb-20160422.txt	4/28/2016 2:25 AM	Text Document	1,486,523 KB

Figure 5.8: File Browsing Screen of Correlation Tool

5.5 Summary

This chapter proposes a correlation algorithm using the slotting technique and cross correlation. Radar and ADS-B measurements are divided into slots of width t_s, the mean of the slot is calculated to represent the measurements fall within the slot. Two evenly sampled time series can then be constructed using the mean values. It also specifies the user interface design and development of the correlation tool that implements the proposed correlation algorithm.

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CHAPTER 6: TESTING AND VALIDATION

This chapter discusses the testing and validation of the proposed correlation algorithm and tool explained in Chapter 5. The algorithm is tested and validated using radar and ADS-B data provided by the Civil Aviation Authority of Malaysia (CAAM). There are two parts to the testing process: a) the slotting technique, and b) correlation with the results from slotting. In the following section, measurements of radar and ADS-B before and after slotting are compared, followed by the correlation output between the two sensors.

6.1 Testing and Validation

The proposed algorithm is tested to identify whether it addresses the research objectives. Following are the objectives of the validation process:

a) The slotting technique effectively transforms measurements from radar and ADS-B into time series that are evenly sampled; and
b) Results from (a) are perfectly cross correlated.

The developed tool that is elaborated in Chapter 5 takes the collected measurements as input and produces time series according to the technique explained in the same chapter. The time series are evaluated to ensure that they are evenly sampled for radar and ADS-B data. The time series are cross correlated between radar and ADS-B in order to achieve the second objective of the research.

6.2 Correlation Tool

The correlation tool is used to correlate measurements from radar and ADS-B. The tool takes text files with TXT format as input for radar and ADS-B measurements. Besides that, the call sign information of the particular aircraft is needed to accurately identify the aircraft from a clustered data environment.

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The radar and ADS-B input files contain the information elaborated in Chapter 4, with fields that are separated by a whitespace character, and lines that are split by line break. The first line in the input file must be the header line that lists all field names. In the first step, the tool extracts all the measurements with the matching call sign from both radar and ADS-B sensors. Next, the measurements would be slotted, with 10-second interval in this research, to produce two evenly sampled time series with the same length. The time series are validated against each other in cross correlation testing. Finally, the time series in longitude and latitude are mapped into the grid coordinate and presented on the map panel as shown in Figure 6.1 above. Results of the cross correlation are written into an excel file for further analysis.

6.3 Slotting Technique

The slotting technique is used in this research as justified in Chapter 5. In summary, the correlation process requires two time series with the same sampling time and length. To achieve this, radar and ADS-B measurements are divided into slots with the same width. This resulted in two time series with even sampling time, where the slot value is derived from the mean of measurements that fall within the respective slots. To validate the measurements, they are compared before and after implementing the slotting technique. Only valid measurements are inputted into the correlation module. To present the validation process, measurements of six aircraft are injected into the correlation tool. Each process described earlier is run using the tool. The output and results are analyzed and discussed in the following section.

6.3.1 Measurement Count and Sampling Interval

Only overlapping radar and ADS-B measurements can only be used in correlation. The correlation tool identifies and extracts the overlapping periods of both sensors. Table 6.1 shows the measurement count within the sampling period of radar and ADS-B before and

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after the slotting technique applied. The comparison shows that slotting technique has effectively transformed the measurements into time series with equal count for both sensors.

Table 6.1: Measurement Count for Radar and ADS-B Before and After Slotting

Call Sign	Radar before slotting	Radar after slotting	ADS-B before slotting	ADS-B after slotting
MAS 72	669	276	2659	276
MAS 388	617	260	2540	260
MAS 750	661	284	2652	284
MAS 754	673	279	2655	279
MAS 784	882	239	1782	239
MAS 786	700	189	970	189

A fixed sampling interval is applied in the transformation which contributes to the same amount of measurement count for both sensors within the same time interval. From the results in Table 6.1, it is observed that the measurement count for ADS-B dropped dramatically. This is caused by the high update rate in ADS-B compared to the radar. The ADS-B reports one or more measurements every second whereas the radar only reports one measurement every four to five seconds, and all these measurements are grouped together as one measurement under the same slot for every ten seconds.

Another vital characteristic to consider for cross correlation is the sampling interval of the time series. Correlation requires having two time series with the same sampling period and interval to identify their relationships. Analysis in Chapter 4 showed that both sensors have irregular sampling interval and inconsistent update rate. One of the functions of the correlation tool is to tune the sampling interval of the measurements to a standard interval, which is set at ten seconds in this research. The time series produced by the slotting technique are analyzed to ensure that the sampling period and interval are consistent for both sensors.

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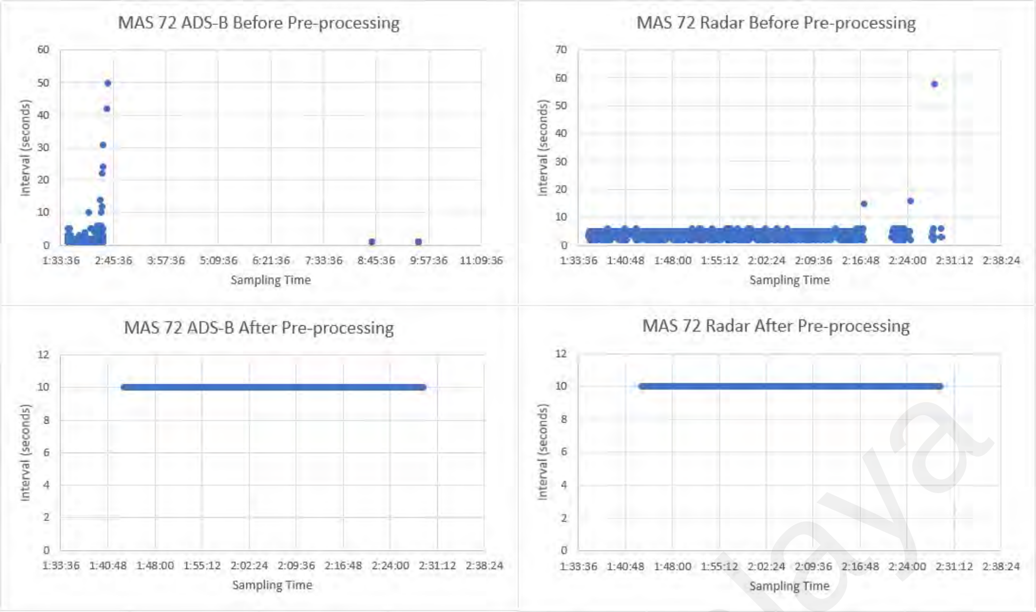

Figure 6.1: Comparison of Sampling Interval of Radar and ADS-B for MAS 72

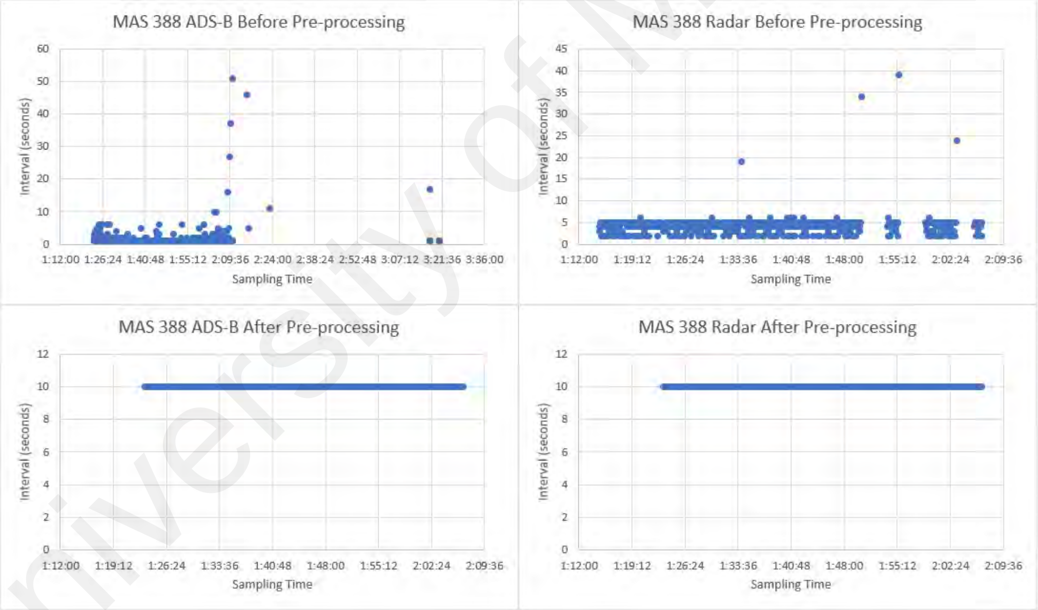

Figure 6.2: Comparison of Sampling Interval of Radar and ADS-B for MAS 388

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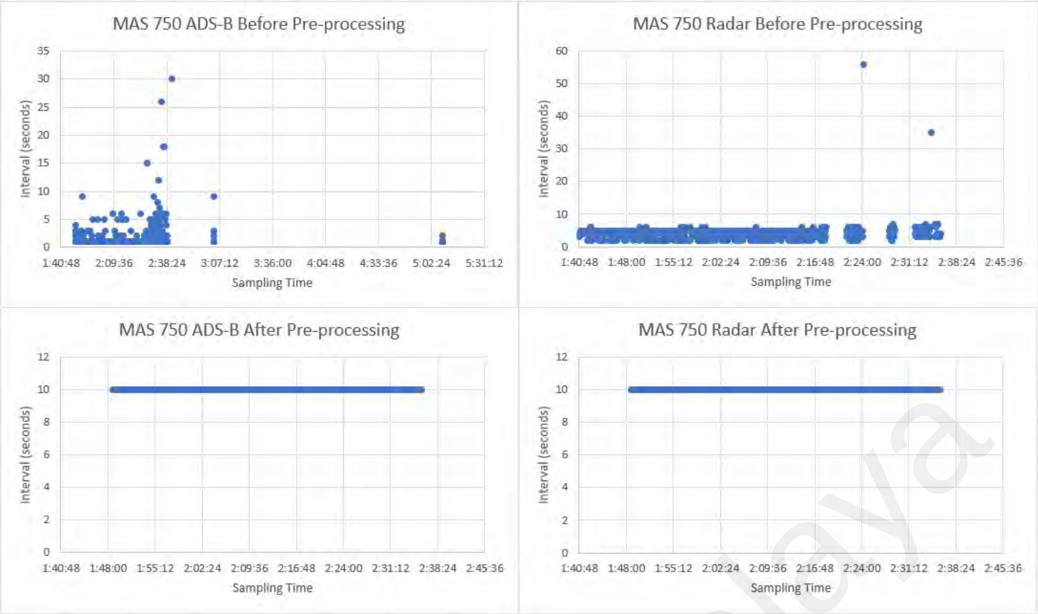

Figure 6.3: Comparison of Sampling Interval of Radar and ADS-B for MAS 750

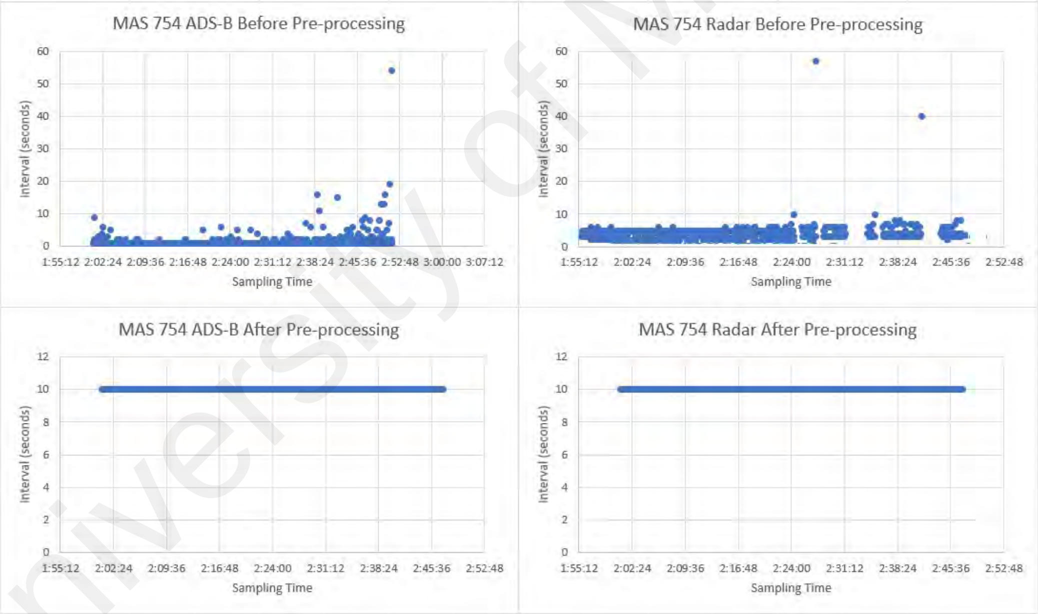

Figure 6.4: Comparison of Sampling Interval of Radar and ADS-B for MAS 754

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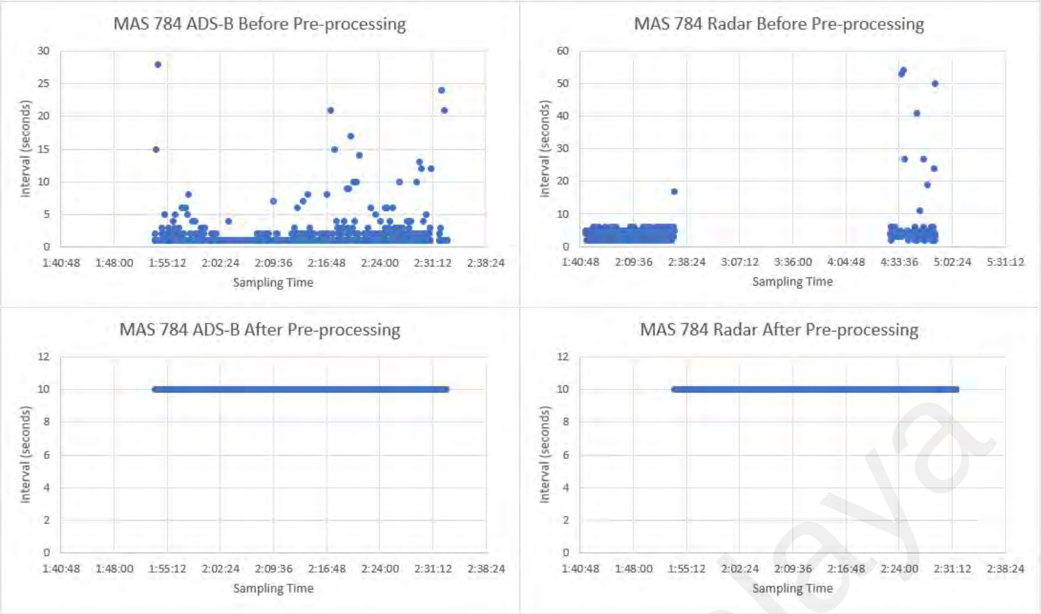

Figure 6.5: Comparison of Sampling Interval of Radar and ADS-B for MAS 784

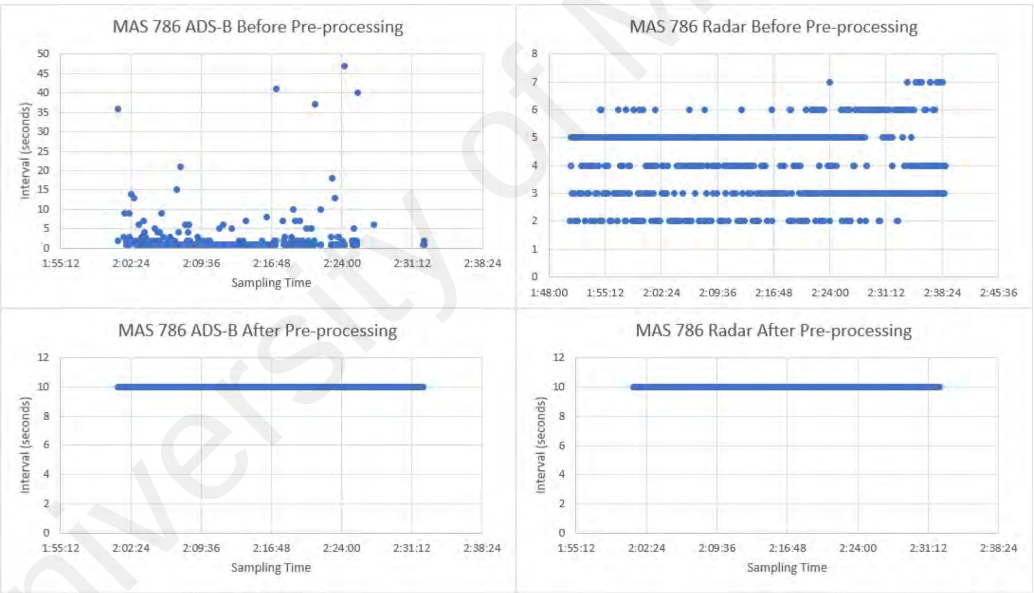

Figure 6.6: Comparison of Sampling Interval of Radar and ADS-B for MAS 786

Figure 6.1 to Figure 6.6 show that the sampling interval has been regulated to ten seconds for both radar and ADS-B measurements. The output time series from the correlation tool have the same starting and ending sampling time, with the same measurement count. Now the time series have entirely fulfilled the requirements for the correlation, which are: a) sampled within the same time frame and b) having even

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sampling interval, the time series are then cross correlated to recognize their pattern and relationship.

6.3.2 Latitude and Longitude

After slotting is done, the output time series are examined in detail for measurement quality and validity. The measurements are analyzed in terms of position jumping and disparities, relative to pre-slotting values. Theoretically, the slotting technique reduces the position jumping by taking the mean value of all measurements within the slot, and the value would not vary too much from the original measurements. For comparison of measurements, pre and post-slotting graphs of latitude and longitude against sampling time are plotted. They are superimposed to exhibit the differences for further inspection.

The results confirm the presumption discussed earlier that after slotting, position jump of time series are greatly reduced and the value remains consistent with the measurements before slotting. As explained in Chapter 4, position jumping mainly occurred in the ADS-B measurements. Figure 6.7, Figure 6.9, Figure 6.11, Figure 6.13, Figure 6.15, and Figure 6.17 clearly indicate that the number of position jumping reported by ADS-B for all tested aircraft are reduced remarkably to different extents. Additionally, from Figure 6.7, Figure 6.9 and Figure 6.11. Figure 6.13 and Figure 6.15, it is shown that certain values of position jumping is lowered and brought closer to the majority, if not eliminated.

However, there are cases where position jumping remains in the time series after slotting, such as shown in Figure 6.17. Further investigation shows that the slot where the position jump resides has only one measurement for that interval, therefore the value of the position jump is captured in the time series.

On the other hand, slotted time series of the radar show that the values of latitude and longitude remain consistent prior to slotting. Generally, the radar has a bigger surveillance

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radius than ADS-B, causing the head and tail of the radar measurements to be cut off when observing the overlap sampling period between both sensors.

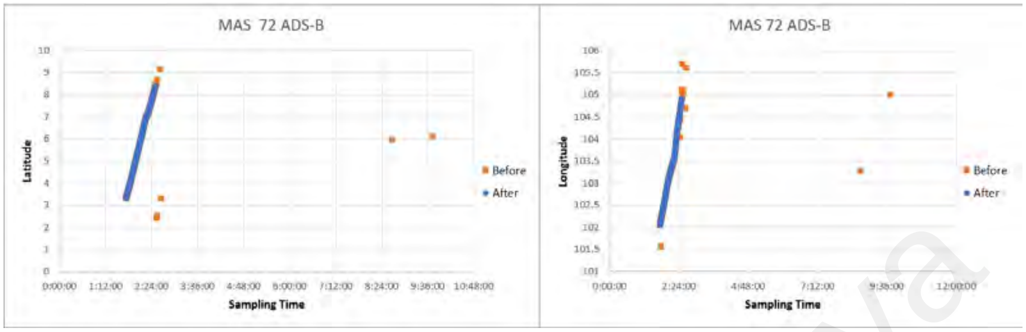

Figure 6.7: Comparison of Latitude and Longitude versus Sampling Time ADS-B for MAS 72

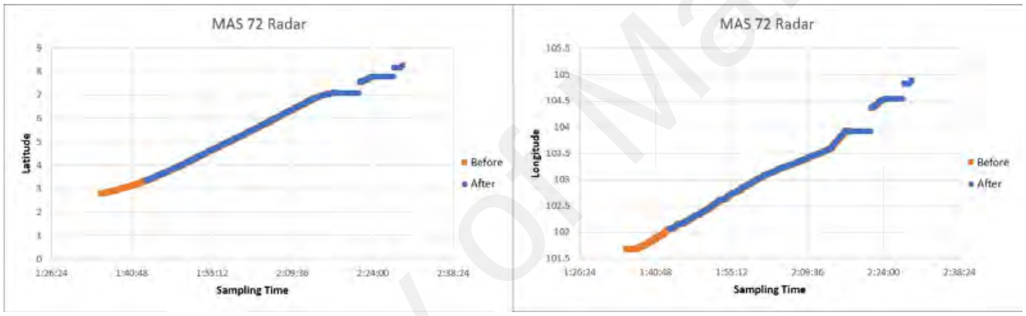

Figure 6.8: Comparison of Latitude and Longitude versus Sampling Time Radar for MAS 72

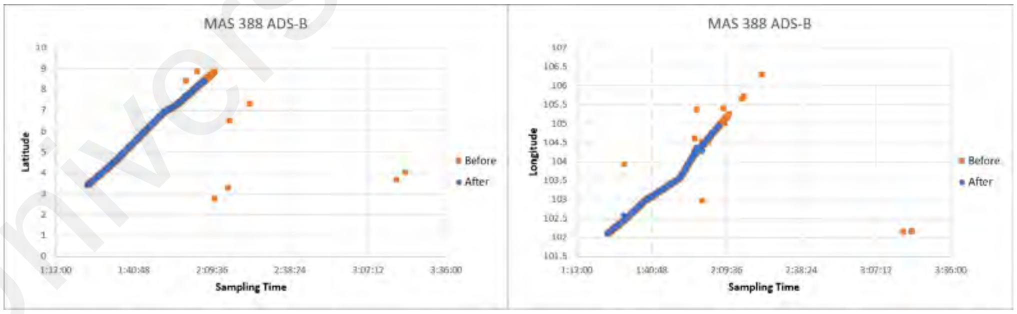

Figure 6.9: Comparison of Latitude and Longitude versus Sampling Time ADS-B for MAS 388

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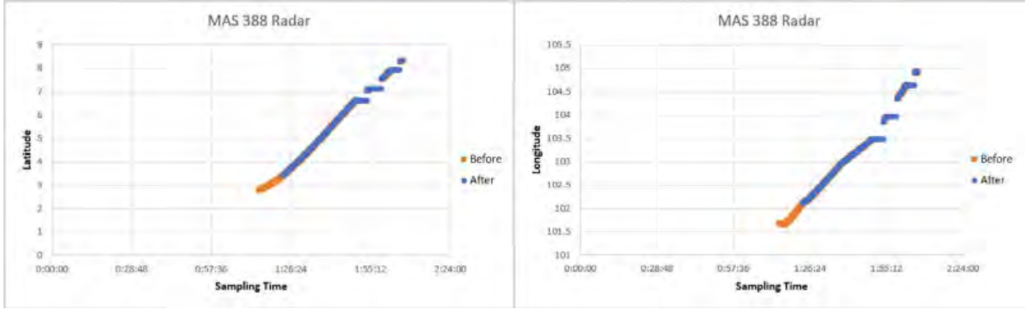

Figure 6.10: Comparison of Latitude and Longitude versus Sampling Time Radar for MAS 388

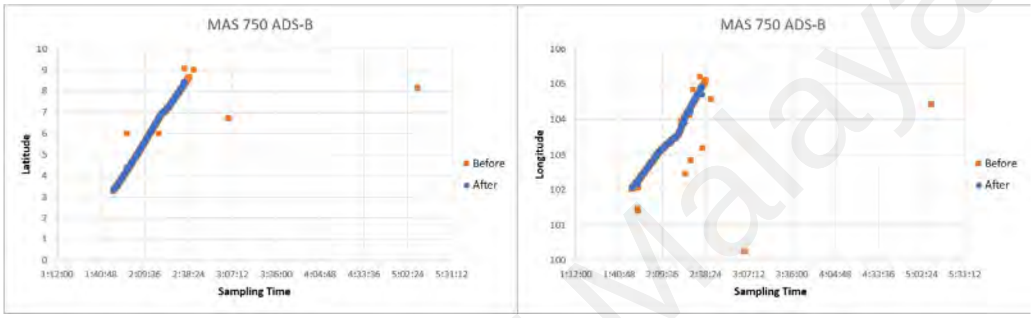

Figure 6.11: Comparison of Latitude and Longitude versus Sampling Time ADS-B for MAS 750

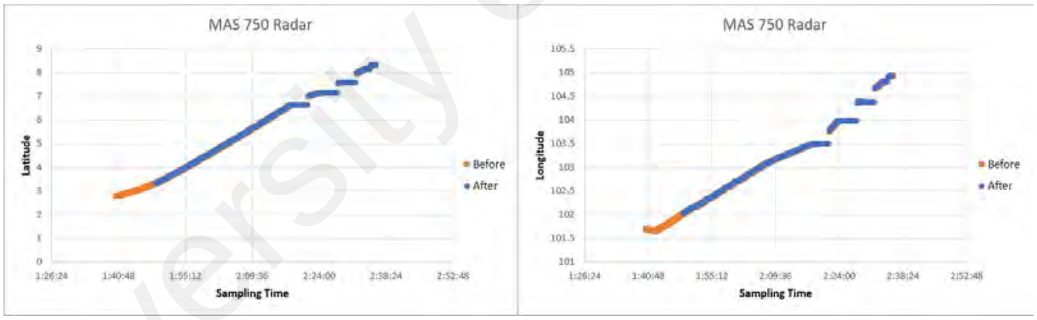

Figure 6.12: Comparison of Latitude and Longitude versus Sampling Time Radar for MAS 750

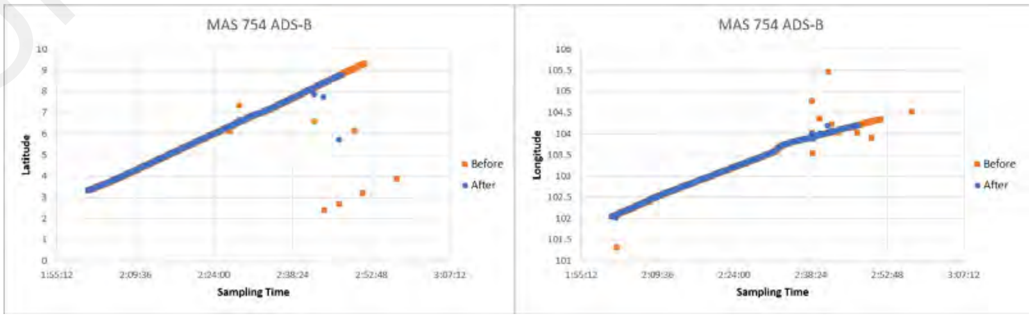

Figure 6.13: Comparison of Latitude and Longitude versus Sampling Time ADS-B for MAS 754

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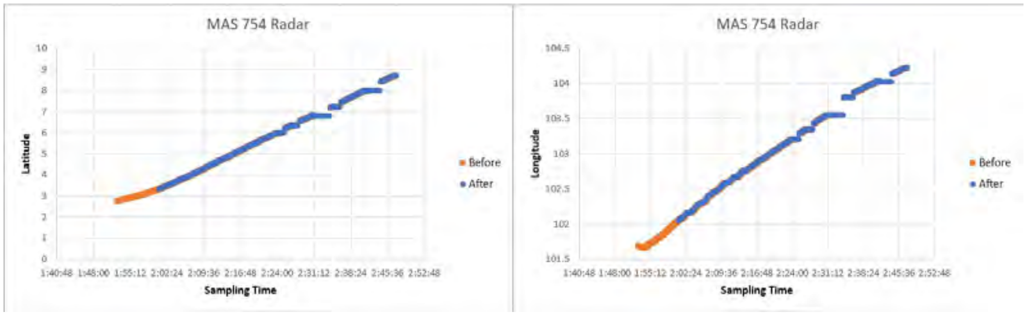

Figure 6.14: Comparison of Latitude and Longitude versus Sampling Time Radar for MAS 754

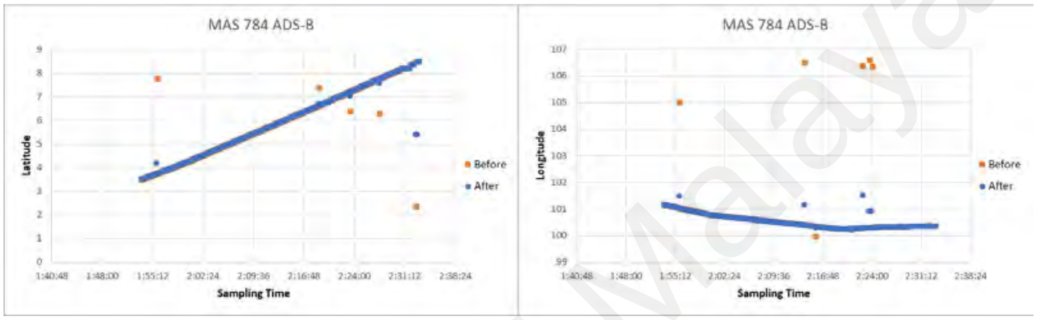

Figure 6.15: Comparison of Latitude and Longitude versus Sampling Time ADS-B for MAS 784

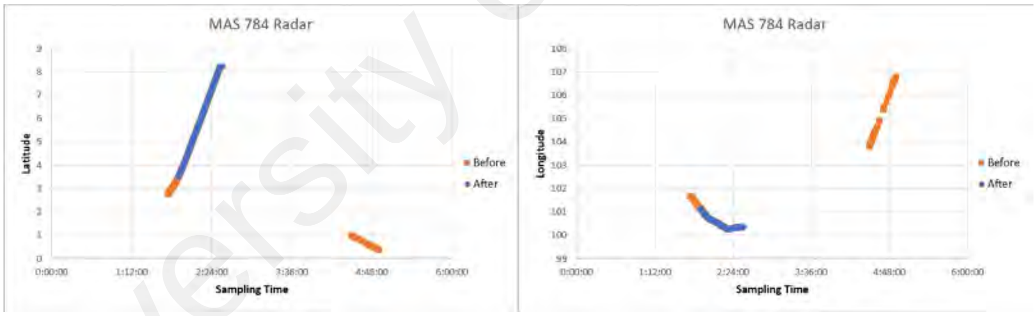

Figure 6.16: Comparison of Latitude and Longitude versus Sampling Time Radar for MAS 784

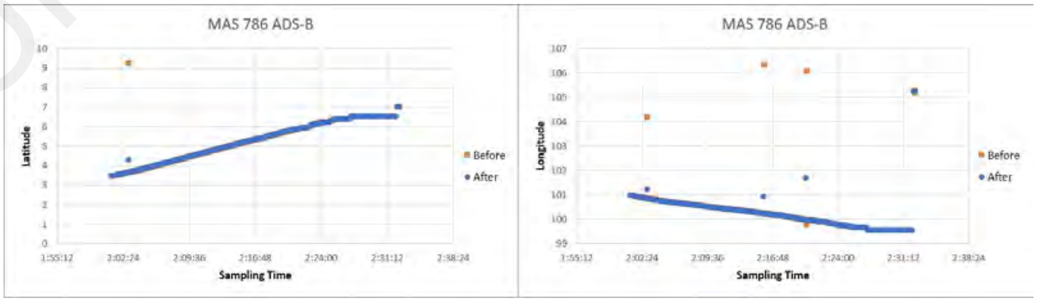

Figure 6.17: Comparison of Latitude and Longitude versus Sampling Time ADS-B for MAS 786

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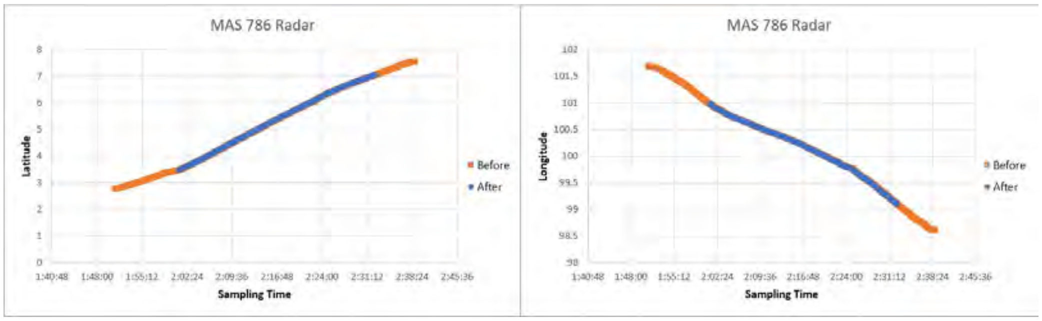

Figure 6.18: Comparison of Latitude and Longitude versus Sampling Time Radar for MAS 786

6.4 Slotted Track for Radar and ADS-B

The output slotted time series are the report tracks for radar and ADS-B sensors. These tracks are plotted on map panel as shown in Figure 6.19 to Figure 6.24. The radar track is red in color whereas ADS-B track is yellow in color. The distortions in Figure 6.22, Figure 6.23, and Figure 6.24 are caused by the outliers in ADS-B measurements, which remain in this research because the cause of outliers cannot be confirmed.

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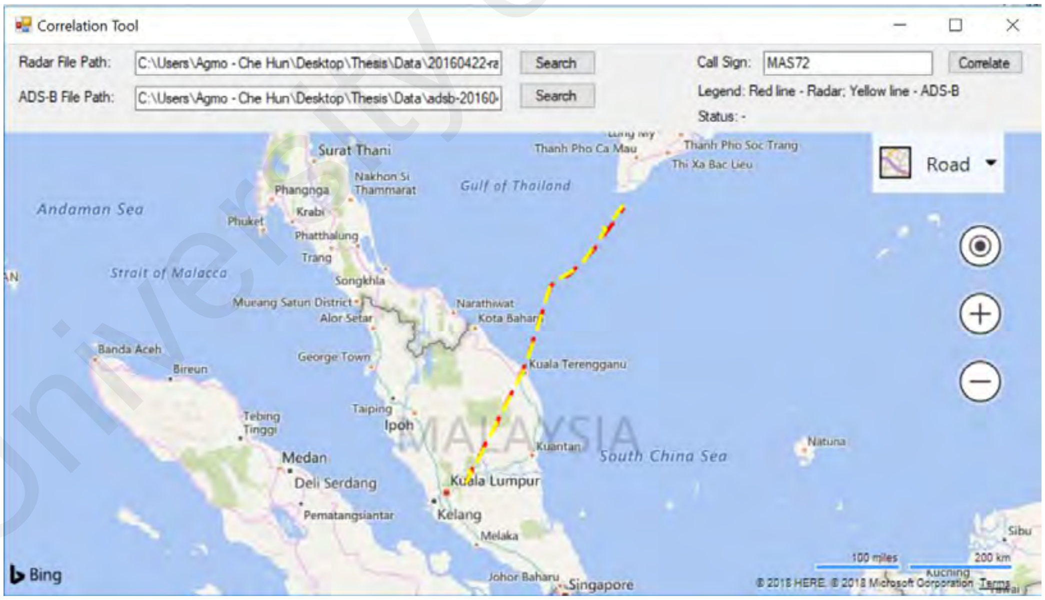

Correlation Tool

Radar File Path: C:\Users\Agmo - Che Hun\Desktop\Thesis\Data\20160422-ra

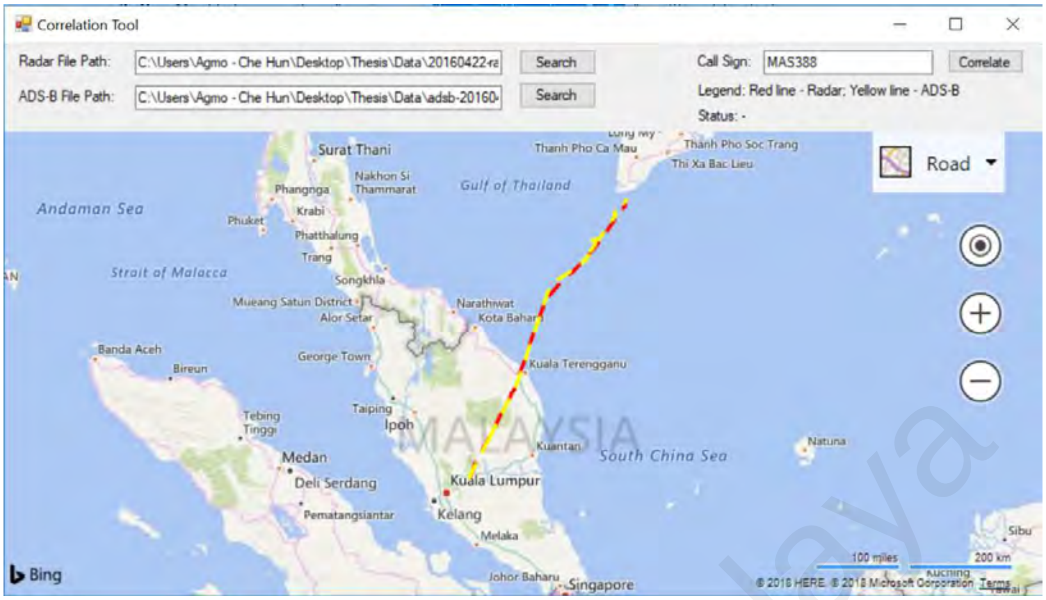
ADS-B File Path: C:\Users\Agmo - Che Hun\Desktop\Thesis\Data\adsb-20160-

Call Sign: MAS72

Legend: Red line - Radar; Yellow line - ADS-B

Status: -

Figure 6.19: Radar and ADS-B Tracks for MAS 72



Radar File Path: C:\Users\Agmo - Che Hun\Desktop\Thesis\Data\20160422-ra

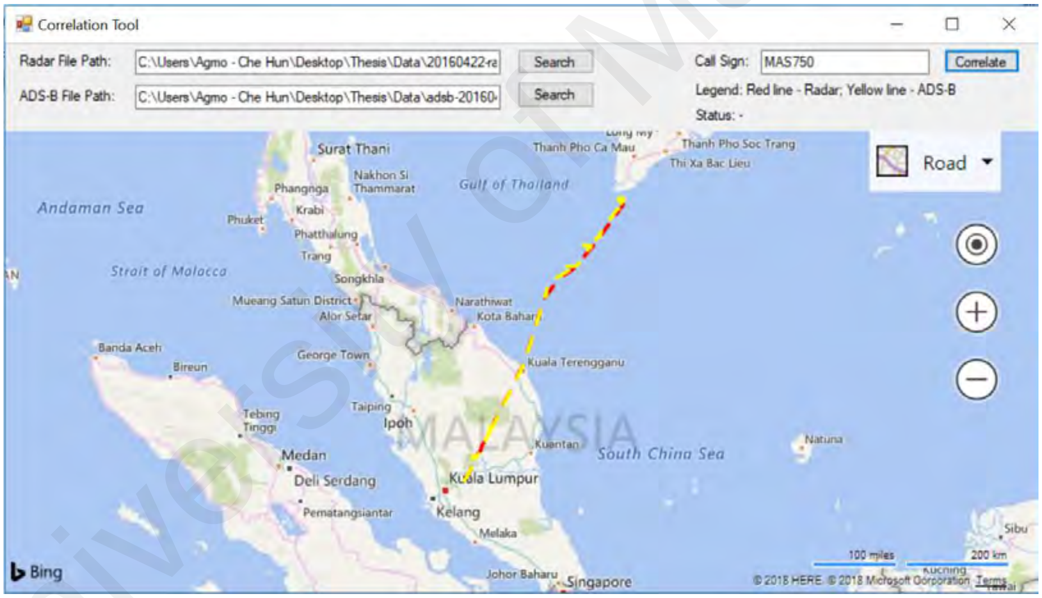
ADS-B File Path: C:\Users\Agmo - Che Hun\Desktop\Thesis\Data\adsb-20160-

Call Sign: MAS388

Legend: Red line - Radar; Yellow line - ADS-B

Status: -

Figure 6.20: Radar and ADS-B Tracks for MAS 388



Radar File Path: C:\Users\Agmo - Che Hun\Desktop\Thesis\Data\20160422-ra

ADS-B File Path: C:\Users\Agmo - Che Hun\Desktop\Thesis\Data\adsb-20160-

Call Sign: MAS750

Legend: Red line - Radar; Yellow line - ADS-B

Status: -

Figure 6.21: Radar and ADS-B Tracks for MAS 750

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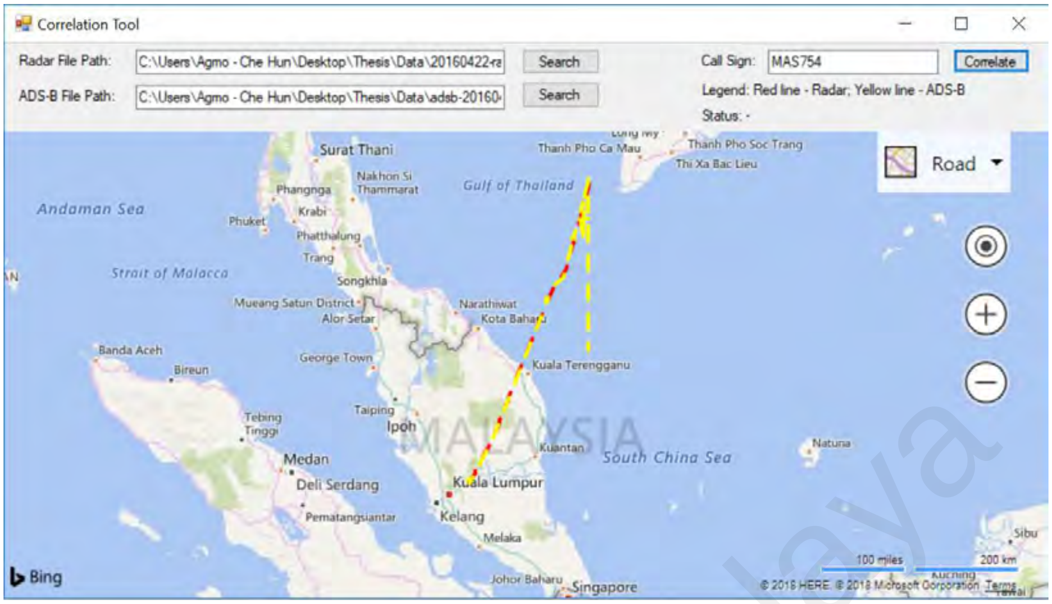


Radar File Path: C:\Users\Agmo - Che Hun\Desktop\Thesis\Data\20160422-ra

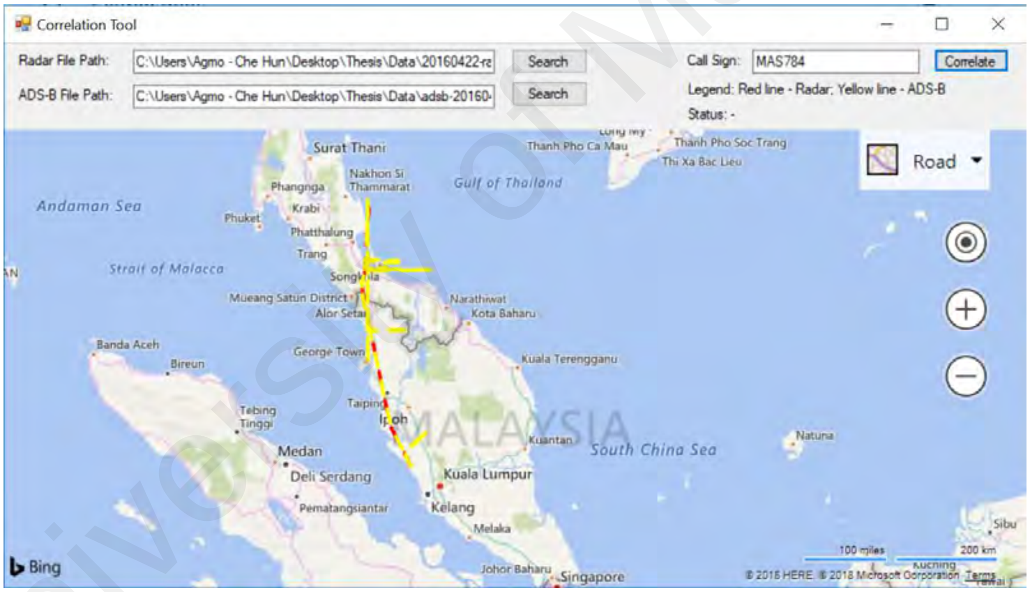
ADS-B File Path: C:\Users\Agmo - Che Hun\Desktop\Thesis\Data\adsb-20160-

Call Sign: MAS754

Legend: Red line - Radar; Yellow line - ADS-B

Status: -

Figure 6.22: Radar and ADS-B Tracks for MAS 754



Radar File Path: C:\Users\Agmo - Che Hun\Desktop\Thesis\Data\20160422-ra

ADS-B File Path: C:\Users\Agmo - Che Hun\Desktop\Thesis\Data\adsb-20160-

Call Sign: MAS784

Legend: Red line - Radar; Yellow line - ADS-B

Status: -

Figure 6.23: Radar and ADS-B Tracks for MAS 784

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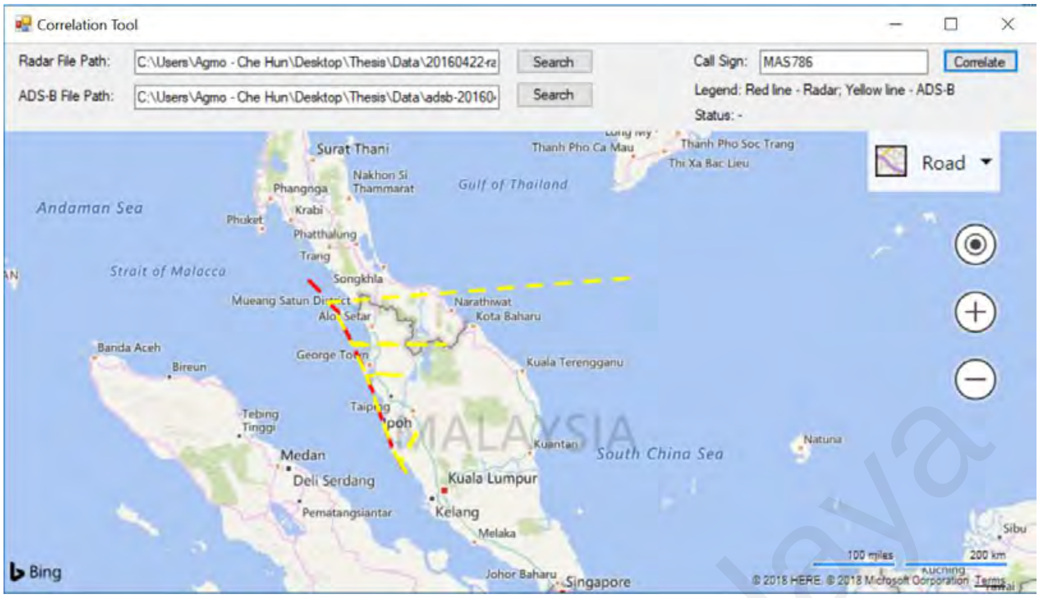

Radar File Path: C:\Users\Agmo - Che Hun\Desktop\Thesis\Data\20160422-ra

ADS-B File Path: C:\Users\Agmo - Che Hun\Desktop\Thesis\Data\adsb-20160-

Call Sign: MAS786

Legend: Red line - Radar; Yellow line - ADS-B

Status: -

Figure 6.24: Radar and ADS-B Tracks for MAS 786

6.5 Cross Correlation

The output time series from the slotting process are then channeled into cross correlation calculation. Cross correlation as explained in Chapter 5 aims to determine the relationship and pattern between the two time series.

6.5.1 Time Delay Analysis

Cross correlation is useful in determining the time delay between two time series. A time shift is introduced in one of the time series to detect if it is lagging or leading another. It is done by moving the time series to the left or right for 0 to N - 1 sampling interval. The highest correlation coefficient corresponds to the point in time where the time series are best aligned. Figure 6.25 to Figure 6.30 show the correlation coefficients for each time delay throughout the time series. All examined aircraft have high alignment between radar and ADS-B at the time delay of 0, which confirms that the slotted technique is effective in correlating measurements of radar and ADS-B. Furthermore, observations in Figure 6.25 to Figure 6.30 also show that bigger lags lead to a smaller correlation coefficient with a peak value at lag = 0.

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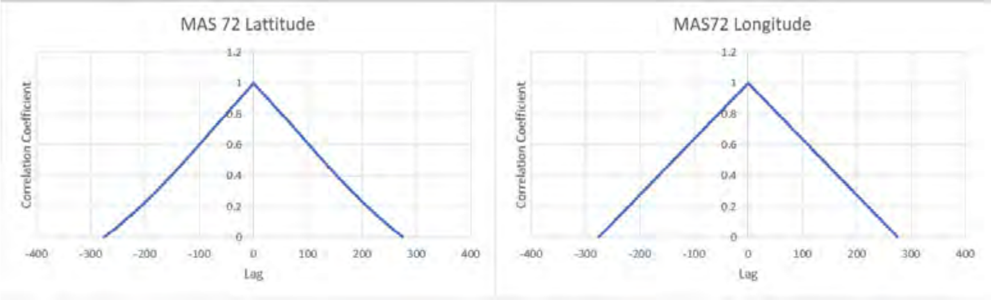

Figure 6.25: Correlation coefficient versus Lag for MAS 72

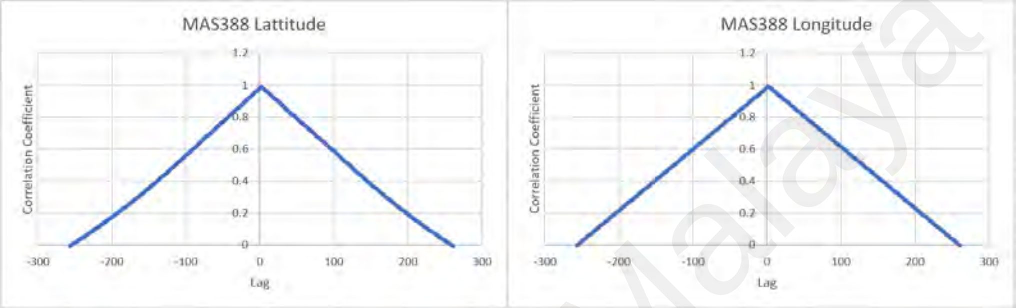

Figure 6.26: Correlation coefficient versus Lag for MAS 388

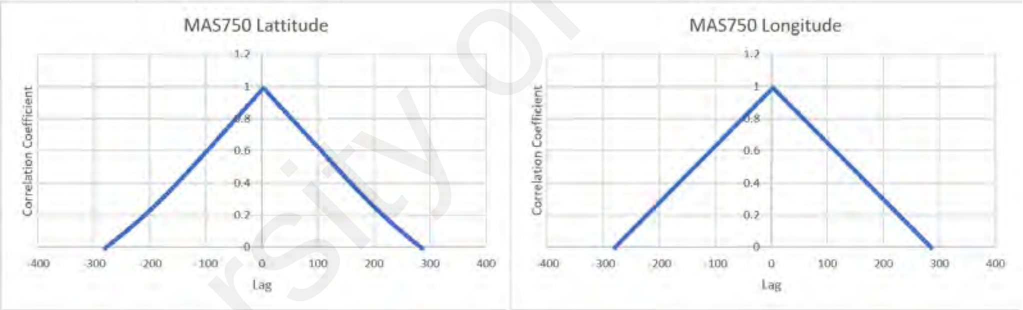

Figure 6.27: Correlation coefficient versus Lag for MAS 750

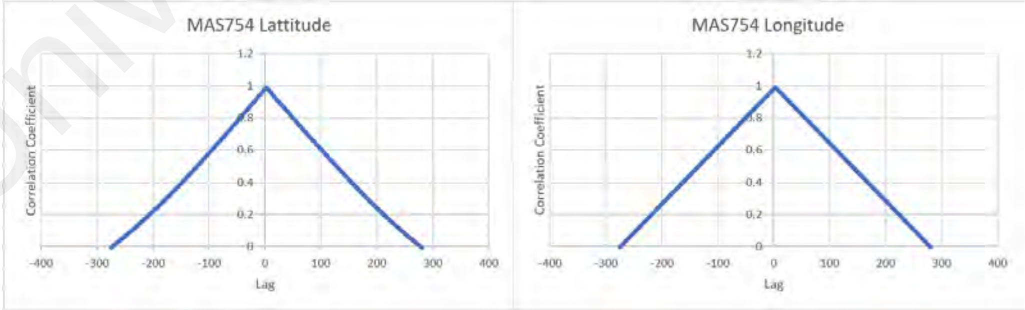

Figure 6.28: Correlation coefficient versus Lag for MAS 754

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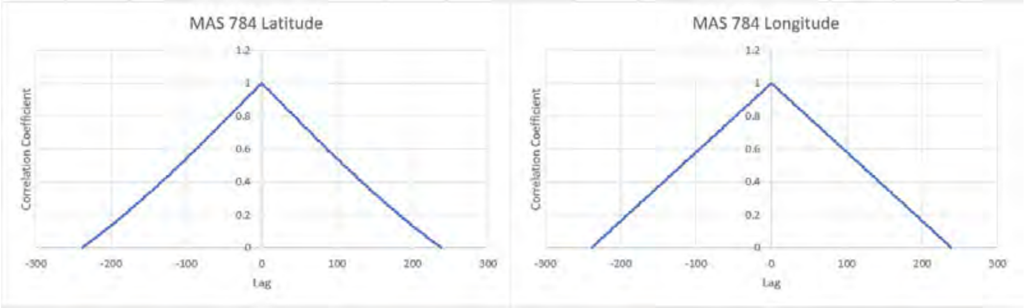

Figure 6.29: Correlation coefficient versus Lag for MAS 784

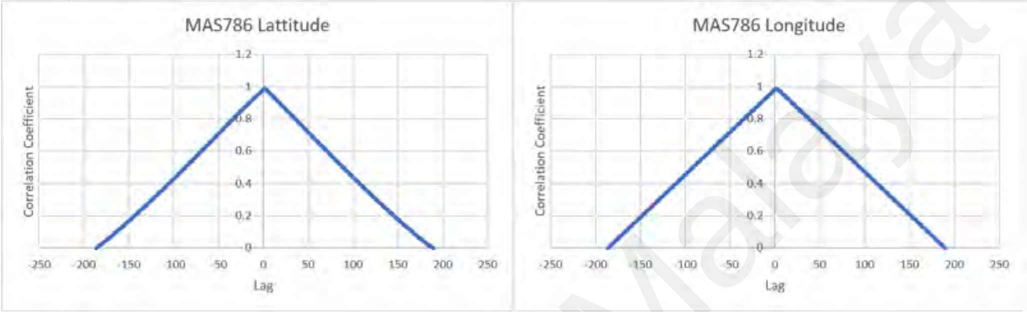

Figure 6.30: Correlation coefficient versus Lag for MAS 786

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6.5.2 Correlation Coefficient

Correlation coefficient measures the strength and direction of a linear relationship between radar and ADS-B measurements. They all assume values between ranges −1 to +1, whereby +1 indicates the strongest positive agreement and −1 the strongest negative agreement. Both slotted time series are most correlated at lag = 0 as seen in Figure 6.25 to Figure 6.30. Correlation coefficient where lag = 0 are produced from the correlation tool and presented in Table 6.2.

Table 6.2: Correlation Coefficient of Radar and ADS-B

Call Sign	**Correlation Coefficient (Latitude)**	**Correlation Coefficient (Longitude)**
MAS 72	0.999868012902438	0.999999650661124
MAS 388	0.999831813498088	0.999999641960182
MAS 750	0.999855858078629	0.999999712980813
MAS 754	0.999485083114659	0.99999989251486
MAS 784	0.999090806	0.999999390037612
MAS 786	0.999818212963105	0.999979378337871

Correlation coefficients shown in Table 6.2 are noticeably close to +1, indicating a strong positive linear relationship between radar and ADS-B measurements after the slotting process. The correlation coefficient can then be used in the regression analysis for track prediction. This is useful when one of the sensors has malfunctioned or does not report any measurements. Regression analysis can be used to anticipate the missing measurements with the presence of a correlation coefficient. It is important to highlight again that the scope of this research only covers correlation of the tracks from two different sensors.

6.6 Summary

This chapter demonstrated the testing and validation of the proposed correlation algorithm and tool. Results are verified by comparing values of the measurements count, sampling interval and validity of latitude and longitude, as well as pre and post application of slotting technique. Lastly, the correlation coefficient is examined to confirm the relationship of output time series.

The proposed correlation algorithm and tool are validated against radar and ADS-B measurements collected from CAAM. Objectives of the correlation tool are evaluated in terms of its effectiveness to transform radar and ADS-B measurements to evenly sampled time series with the same length and output time series that are correlated with each other. Results demonstrated in this chapter conclude that the correlation tool has achieved its objectives.

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CHAPTER 7: CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORK

The chapter discusses accomplishments of the research objectives defined in Chapter 1. Additionally, the limitations or drawbacks encountered while applying the proposed correlation algorithm in evaluation process are also discussed. Lastly, future work that can be conducted on the proposed correlation algorithm is presented.

7.1 Conclusion

This research has achieved the following objectives:

- Reviewed the state of art of the aircraft surveillance sensors;
- Identified, reviewed and analyzed existing multi-sensor data correlation algorithms available in the public domain;
- Analyzed characteristics of aircraft positioning data from two surveillance sensors: radar and ADS-B;
- Developed an algorithm to correlate the aircraft positioning data from the two sensors; and
- Developed a tool–Multi-sensor Data Correlator.

Based on the research and development done throughout this thesis, conclusions are drawn as follow:

- From the intensive literature review conducted in Chapter 2 to identify the characteristics and limitations of radar and ADS-B, respectively, it was found that both complement each other with strengths in different aspects such as the update rate, coverage range and accuracy of position data;
- Existing multi-radar correlation algorithms are reviewed in detail in Chapter 3. Based on the advantages of each algorithm, a list of characteristics of a high-performance correlation algorithm is derived;

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- Radar and ADS-B data collected from Civil Aviation Authority of Malaysia (CAAM) are statistically analyzed and shown in Chapter 4. Besides that, the characteristics and errors of each sensor are also examined thoroughly. It is concluded that both sensors have inconsistent update rates that serves as the main challenge in correlating them;
- A comprehensive review on the existing correlation algorithms on unevenly spaced data was conducted in Chapter 5. The slotting technique was chosen as the best solution in correlating radar and ADS-B sensors measurement data, whereby they are divided into a series of slot, and each slot is represented by the mean value of the measurements that fall within it;
- The slotting technique is included in the cross-correlation algorithm, and the results are validated in Chapter 6 in terms of sampling interval (update rate), latitude and longitude measurements, time delay applied in cross-correlation, and lastly the correlation coefficient produced from the algorithm. Improvements were seen in all aspects with the highest correlation coefficient approximate to +1, concluding that the sensors can be correlated by using the slotting technique; and, finally
- The proposed Correlation Tool development is described in detail in Chapter 5. The tool works by firstly extracting each of the sensors' measurements based on aircraft's unique call sign, followed by slotting of the measurements, cross correlating them, and lastly displaying the aircraft's track on the map panel.

7.2 Limitations and Recommendations

In this section, limitations and recommendations in correlating data from radars and ADS-B, as well as the correlation tool developed by using the slotting technique are elaborated below:

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- It has been found that position jumping or outlier measurements occurred frequently in the ADS-B data. Although the slotting technique does not eliminate position jumping, it is useful to reduce or lower its incidence. Therefore, the removal of position jumping should be introduced in the algorithm to improve its performance;
- Instead of two sensors, more should be included in the algorithm for correlation to produce more accurate results or cater for malfunctioning of any sensor;
- Measurements of integrity and accuracy for ADS-B are not considered in this research. However, these measurements can be included in future research to produce accurate and reliable correlations; and
- Map panel on the correlation tool can be plotted in real time during the slotting technique rather than after the process is completed.

7.3 Future Work

This research contributes to the improvement of ATC operations by proposing a correlation algorithm involving radar and ADS-B, and the development of a correlation tool. Further studies are proposed to enhance the multi-sensor correlation algorithm as stated below:

- In the calculation of algorithm, where sensors, especially radars fail to report any measurement due to blocking of building or mountain, the last reported position is used. However, a regression analysis can be included to anticipate changes in measurements caused by these line-of-sight issues;
- Development of data fusion algorithm to fuse ADS-B positioning with radar positioning to support the transition period before full worldwide implementation of the latter; and

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- At present, the input of radar and ADS-B measurements into the Correlation Tool is in text file. Moving forward, the input of data into the correlation tool can be improved by channeling real time measurements data directly from the sensor system.

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camparison with legacy systems. *Journal of Brazilian Air Transportation Research Society*.

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LIST OF PUBLICATIONS AND PAPERS PRESENTED

Based on the work in this thesis, two papers have been published.

- Koh, C.H. & Ali, B. S. 2016. Multi-Sensor Surveillance Data Correlation Algorithm. The 3rd International Conference on Computational Science and Technology (ICCST). Kota Kinabalu, Malaysia, November 28 – 30 2016.
- Koh, C.H. & Ali, B. S. 2018. Multi-Sensor Surveillance Data Correlation Algorithm. *Advanced Science Letters*.

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