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BACHELOR'S THESIS

STATISTICAL ANALYSIS OF ADS-B QUALITY INDICATORS OF DATA OBTAINED FROM A LOW-COST RECEIVER

By

Aghadhia Firaz Uno Kusuma

11201601013

Presented to the Faculty of Engineering

In Partial Fulfilment Of the Requirements for the Degree of

SARJANA TEKNIK

In

AVIATION ENGINEERING

FACULTY OF ENGINEERING

BSD City 15345

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APPROVAL PAGE

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STATEMENT BY THE AUTHOR

I, hereby, declare that this submission is my own work and to the best of my knowledge, it contains no material previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any other degree or diploma at any educational institution, except where due acknowledgement is made in the thesis.

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ABSTRACT

Statistical Analysis of ADS-B Quality Indicators of Data Obtained From A Low-Cost Receiver

by

Aghadhia Firaz Uno Kusuma

Triwanto Simanjuntak, PhD, Advisor

In this thesis, the author investigated the ADS-B quality indicators to see the latest status of data quality as well as the air traffic. ADS-B quality indicators determine if the data that were sent are acceptable to be used for the relevant surveillance applications. To attain such data, the author used a low-cost ADS-B receiver system that was installed at the author's home. The collecting period was executed for a total of five weeks, initiated from November 9, 2020 until December 13, 2020. The raw data was then cleaned and filtered before statistically analyzed with Python. For comparison with DO-260B minimum requirements, the author used FAA's regulation. Of the total valid messages received, 65.88% still use ADS-B version 0. Only 32.02% is ADS-B version 2 and 2.10% is ADS-B version 1. In addition, more than 50% of each ADS-B version 2 quality indicators met the minimum requirements. Thus, the results are satisfactory.

Keyword: *ADS-B, Quality Indicators, ICAO Version 0, ICAO Version 1, ICAO Version 2, FAA regulation*

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And lastly, to everyone that I have not mentioned, but supported me otherwise. Thank you so much for believing in me.

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List of Abbreviations

ATC	**A**ir **T**raffic **C**ontrol
ADS	**A**utomatic **D**ependent **S**urveillance
ANSP	**A**ir **N**avigation **S**ervice **P**roviders
ASTERIX	**A**ll **P**urpose **S**tructured **E**uerocontrol **S**urveillance **I**nformation E**X**change
FAA	**F**ederal **A**vaition **A**dministration
FIS-B	**F**light **I**nformation **S**ystem **B**roadcast
GNSS	**G**lobal **N**avigation **S**atellite **S**ystem
GVA	**G**eometrical **V**ertical **A**ccuracy
ICAO	**I**nternational **C**ivil **A**viation **O**rganization
NAC	**N**avigation **A**ccuracy **C**ategory
NACp	**N**avigation **A**ccuracy **C**ategory **P**osition
NACv	**N**avigation **A**ccuracy **C**ategory **V**elocity
NIC	**N**avigation **I**integrity **C**ategory
NUC	**N**avigation **U**ncertainty **C**ategory
NUCv	**N**avigation **U**ncertainty **C**ategory **V**elocity
NUCp	**N**avigation **U**ncertainty **C**ategory **P**osition
OSED	**O**perational **S**ervice and **E**nvironment
RTCA	**R**adio **T**echnical **C**ommision for **A**eronautics
SDA	**S**ystem **D**esign **A**ssurance
SIL	**S**urveillance/Source **I**ntegrity **L**imit
SSR	**S**econdary **S**urveillance **R**adar
TDOA	**T**ime **D**ifference **O**f **A**rrival
TIS-B	**T**raffic **I**nformation **S**ervice **B**roadcast
PSR	**P**rimary **S**urveillance **R**adar

To those who believed in me in my hardest times.

CHAPTER 1
INTRODUCTION

1.1 Background

Transportation has a critical role in supporting and facilitating various aspects of life. Advances in transportation express deeply with how we, as consumers, execute a day-to-day activity and lifestyle. One of those advancements in transportation is through air, where it was developed to strengthen things such as logistics, employment, foreign trade, tourism, and provide easy access points on a national and international level (?, ?). Before the outbreak of COVID-19, the demand for air transport is remarkably high due to its good impact on economic growth, as well as moving billions of people and goods all over the city. With an influence that strong, aircraft manufacturers had to adapt to the global demand by either producing more aircraft or increasing aircraft capacity. However, more airplanes in the sky results in a high density of air traffic, which may result a greater risk of accidents. Thus, the safety of each and one of those flights are to be considered.

With a variety of surveillance systems and infrastructure, a standard must be present. ADS-B, a surveillance technology, was intended not to replace conventional radars, but to work along with them with additional improvements in tracking aircraft around the globe. Radio Technical Commission for Aeronautics (RTCA), a non-profit association, has a mission to ensure the safety, security, and overall health of the aviation ecosystem through integrated performance standards. Their standards and guidance materials include Operational Service and Environment

Definition (OSED), Operational Safety and Performance Requirements (SPR), Interoperability Requirements (IRR), Minimum Aviation System Performance Standards (MASPS) and Minimum Operational Performance Standards (MOPS).

ADS-B standards experienced a few changes throughout the years. Three major ADS-B standards are into focus for this research, and they are DO-260, DO-260A, and DO-260B. The major difference between DO-260 and DO-260A was the split between accuracy and integrity, where the accuracy is 95% (under normal conditions) and integrity for protection against abnormal performance. During the development of DO-260, Selective Availability still exists. SA was intended to downgrade GPS signals for national security reasons until May 2000 where President Bill Clinton ordered discontinuation of SA so that civil and commercial vehicle users can receive more accurate data. Thus, RTCA decided it was necessary to make DO-260A. From DO-260A to DO-260B, the major differences was the split of quality indicators between horizontal and vertical components with the addition of a more high-quality horizontal position integrity and the ability to distinguish avionics faults and measurement integrity. These performance standards fall under Minimum Operational Performance Standards, where it was aimed to give designers, manufacturers, installers, and operators the standards needed to carry out its intended functions (?, ?). MOPS explains to the user the equipments characteristics and its requirements, equipment applications, and operational goals and provides the footing for the required performance.

Several regions in the world have already issued a mandate for the adoption of DO-260B, such as the United States by January 2020 and Europe by June 2020. Indonesia has a population of roughly 270 million people, 17,508 islands, and has an area of roughly 1,905,000 KM^2, making it the largest archipelago country in the world. In addition, aircraft crosses the Indonesian airspace every second, whether it is Indonesian-registered aircraft or aircraft from other countries that have diplomatic ties with Indonesia. Nonetheless, with different standards available means different acceptable levels come into place. Not only that, but knowing the current status of those level can be quite complex due to different standards, let alone every country has their own criteria of which standard to be implemented.

1.2 Problem Statement

In aviation, safety is the number one priority in all aspects. The ADS-B standards experienced version changes throughout the years. Performance standards were requested in the development of ADS-B. Radio Technical Commission for Aeronautics (RTCA), a non-profit Standards Development Organization issued its standard for ADS-B Version 0 called DO-260 in September 2000. It was later improved based on the users feedback and analysis. Thus, a second standard was issued in April 2003 called DO-260A for ADS-B Version 1. As of right now, the latest version is the DO-260B released in December 2009 for ADS-B Version 2. Embedded in all of the three standards are the quality indicators. Quality indicators philosophy is correlated with the ADS-B transmitting system that sends data (velocity, position, etc.) as well as the quality of those data. Once the data is transmitted, the receiving end can then decide whether the data is acceptable or not for the relevant applications.

With hundreds, if not, thousands of aircraft crossing the Indonesian airspace every day, safety among those aircraft are crucial. Based on *KP 280 Tahun 2017*, section 3.2.2 stated that in order for the ADS-B data to be used universally, it needs to transmitt in the predetermined format and characteristics of the mentioned standards. Three of the standards mentioned are DO-260, DO-260A, and DO-260B. A note was also present stating that compliance with DO-260B is much more preferred because it is the latest standard used in Europe and America. Unfortunately, the author has not found any research about the latest data quality of aircraft crossing the Indonesian airspace. This is concerning because according to

PM 81 Tahun 2017, all transport category aircraft must be equipped with ADS-B by January 1, 2020. Even with the latest version of ADS-B, the performance of it needs to be evaluated for analysis. In addition, no data are publicly available on ADS-B quality indicators over Indonesia, as well as which versions of ADS-B are mostly present. If Indonesia do prefer DO-260B as the standard for surveillance, then it should be evaluated statistically and compared with FAA's minimum requirement to see if they are met.

1.3 Research Objective

In this research, there are several objectives the author wants to inform. The primary objective is to collect ADS-B quality indicator data and analyze them. In addition, the author wants to see if the collected data meets the minimum requriement stated by FAA. The author also aims to oversee the trend of air traffic within the collecting period. Once the results and analysis are complete, the author's desires are to give regulators a picture of ADS-B data quality indicators data and ADS-B version within vicinity the of the author's home, so that a re-evaluation of surveillance regulation can be done if needed.

1.4 Research Scope

The author collects raw ADS-B data for five weeks by using a low-cost Raspberry-Pi ADS-B receiver system. The receiver will be installed at the author's home with the coordinates **6° 21' 21.204" S, 106° 43' 10.776" E**.

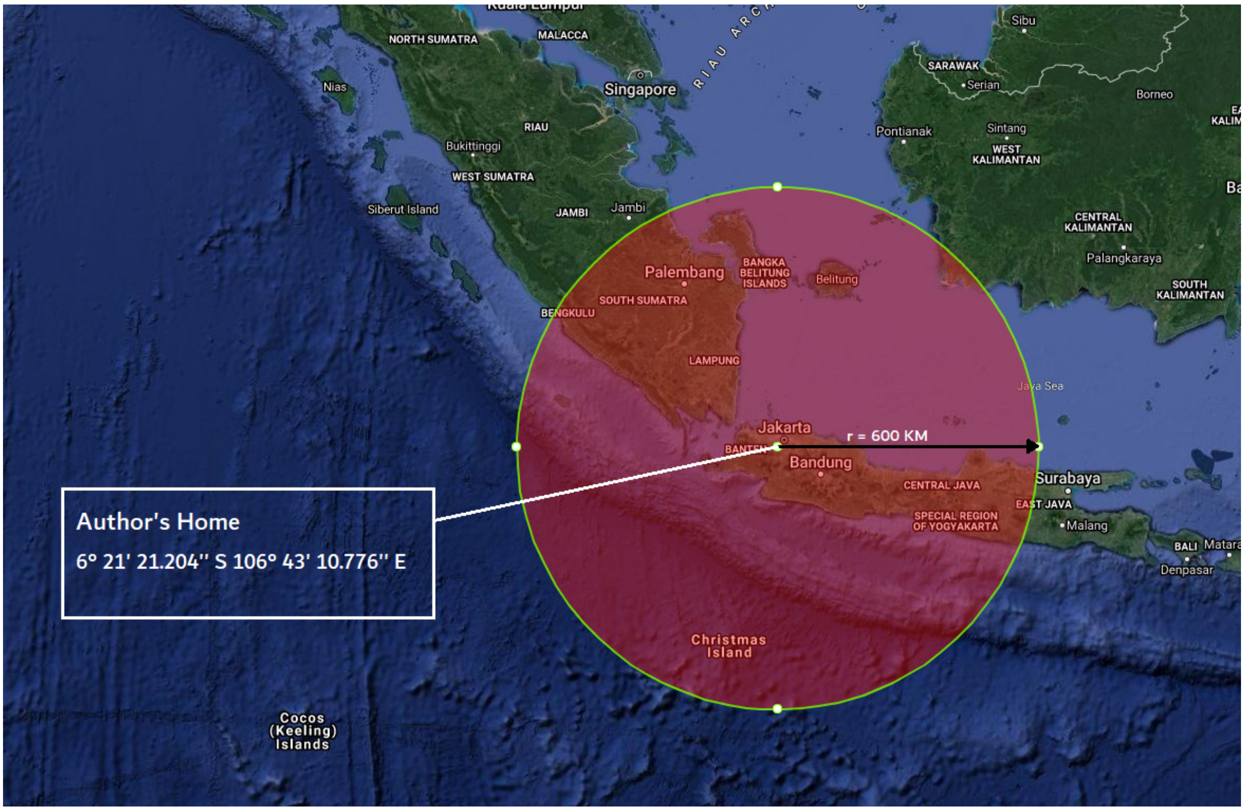

Figure 1.1: Range and location of the low-cost receiver systems

As much as the author wants a smooth and optimized data collecting process, there are limitations. One of the limitations is the Raspberry Pi 2 Model B. This model is limited with only 1GB of RAM, which means not a lot of program can run all at once. Secondly, the location of the author's home is surrounded by obstacles such as houses and high-cliffs area. In regards with acquiring the ADS-B quality indicator data, the author only uses dump1090 as a decoder from PiAware. Frequency of flights are not as many before the COVID-19 outbreak. Because of this, the author has already reached out to flight tracking agencies FlightAware and Flightradar24. However, the price they offered are beyond the author's budget; thus the author used a low-cost ADS-B receiver system instead. The author do realize there are a handful of ADS-B quality indicators. However, the author only focuses qualty indicators related to position and integrity such as NACp, NUCp, SIL, and NIC for analysis. Other factors include power outages and bad weather, which is beyond author's control. For data collection period, it is only five weeks because the author still needs to do a file clean up and statistical analysis of the data.

1.5 Significance of Study

This thesis can act as a miniature statistical study due to the fact that there is not a lot of research of ADS-B quality indicators with this approach. Not only that, but this research is a contribution to ADS-B quality indicator data for aircraft within the Indonesian airspace. The author do intend to give the complete dataset of the ADS-B quality indicator to those who requires it. As previously mentioned, the author hopes the results of this thesis could give regulators a means of re-evaluation of aviation regulation if needed.

CHAPTER 2
LITERATURE REVIEW

2.1 Overview

In general, ADS-B is quite the state-of-the-art surveillance technology. Because of its promising features, a fundamental understanding needs to be settled. These basic understanding includes what it is, how it works, the types, and the message structure of a single message. In addition, MLAT is also another surveillance technology that helps with tracking aircraft. Thus, a basic understanding in that in needed as well. Next it will the understanding of the standards for ADS-B. The standards used in this research are from RTCA, a non-profit organization that specializes in developing performance standards. They have a variety of standards that are still being implemented until today, but only three are used in this research. The differences of these standards will also analyzed in terms of the quality indicators and its capabilities offered. Not only that, how RTCA name the standards and the meanings behind each number and letter are also discussed. A side standard that the author came across was ASTERIX CAT 21, or known as All-Purpose Structured Eurocontrol Surveillance Information Exchange. This standard explains the "language" of ADS-B messages sent from an ADS-B ground station to ATC. After that, the author will cover about the ADS-B infrastructure in Indonesia and what effort has been made so far. Not only that, but from the regulation point of view as well. Since the main objective of this research is to analyze the ADS-B quality indicators, an understanding of what those quality indicators mean is essenstial.

2.2 Automatic Dependent Surveillance - Broadcast (ADS-B) Technology

ADS-B stands for Automatic Dependent Surveillance Broadcast, and it is a co-operative surveillance technology (?, ?). Automatic means it does not require an external stimulus, can be dependent on specific onboard systems (avionics), and transmits in all directions without knowing who its "listeners" are (?, ?). It is a derivative of ADS principles, where its function is to transmit data and other vital information to be used by ATC and nearby aircraft that pick up the signals. Since ADS-B equipment can transmit and receive, it is further divided into two types: ADS-B IN and ADS-B OUT. ADS-B OUT is the ability to transmit messages to other aircraft or ground stations, and ADS-B IN is the ability to send and receive transmitted signals from other aircraft (?, ?). However, there is a catch. If an aircraft wants to receive ADS-B data from other aircraft, it needs to have ADS-B IN. Most countries have mandated the use of ADS-B OUT, but it is optional to use ADS-B IN. Basically, in those messages contains positional data, the identity

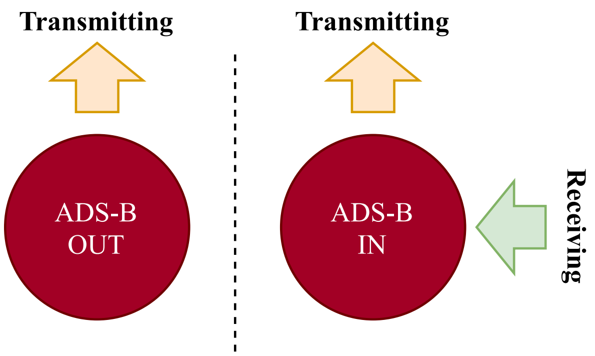

FIGURE 2.1: ADS-B types

of the aircraft (such as GIA345, LNI1191, etc.), direction and how fast the aircraft is going (velocity), and how high the aircraft is (altitude) (?, ?). This information is quite crucial to air traffic controllers because they make decisions with the help of this information. Although generally, the message contains more than just four data. It can contain flight identification, squawk codes, and others, which is further explained in the chapter.

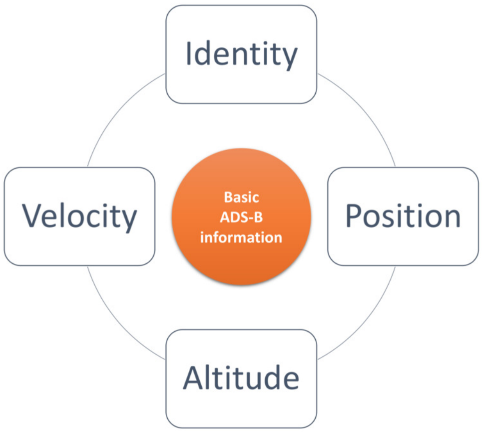

FIGURE 2.2: Four basic ADS-B data

2.2.1 Datalink System

With that being said, these messages travel through a medium called the datalink system. The data link systems are known to support ADS-B, and those are 1090 Extended Squitter, Universal Access Transceiver, and Very High-Frequency Datalink Mode 4. The 1090 Extended Squitter or widely known as 1090ES, operates on the 1090 MHz frequency. ADS-B messages are transmitted through this datalink through an aircraft transponder. 1090 ES also supports the Mode-S transponder, as well as it is accepted worldwide in the general and commercial aviation world (?, ?). For the Universal Access Transceiver or UATm, it operates on 978 MHz frequency. A unique transceiver is mandatory because it needs to be able to both transmit and receive information, hence Universal Access Transceiver. As of now, only the United States and China use this datalink system (besides 1090ES). The FAA wanted was worried there would be congestion in 1090MHz, so they included FIS-B and TIS-B to encourage people to move to UAT. FIS-B or Flight Information

Services Broadcast is a broadcasting service that transmits aeronautical information like weather and restricted areas, and TIS-B or Traffic Information Broadcast provides traffic reporting services to aircraft equipped with ADS-B IN (?, ?). FIS-B and TIS-B are available in UAT, but for aircraft that operates in 1090MHz it only has TIS-B. Very High-Frequency Datalink Mode 4 operates on 118–136.975 MHz frequency, and in this range of frequency, it is usually used for voice communications (?, ?). Thus, a special kind of radio is required for VDLm4. VDLm4 also support services mentioned before, which are TIS-B and FIS-B. VDLm4 was tried in Sweden and Russia but received little attention.

2.2.2 Flow of ADS-B

Next is about the overall flow of how an ADS-B works. Assuming it is using a 1090 MHz datalink system, it is divided into three sections: ground, air, and space (Table **??**). In the ground section, it consists of surveillance radars such as Secondary Surveillance Radar, Multilateration, Primary Surveillance Radar, ATC center, and ADS-B ground stations. Radars on the ground (SSR, MLAT receivers, PSR) will receive signals from a non-equipped ADS-B aircraft and ADS-B equipped aircraft. For the ADS-B ground stations, it will also receive data from ADS-B equipped aircraft. Both ADS-B ground stations and other forms of radars will send those data to ATC to be used for air traffic management purposes. In the air section, aircraft that are both equipped with ADS-B IN and OUT will be able to see each others data, such as their directions, vertical speed, and intentions. Aircraft that is not equipped ADS-B but have a transponder will still be able to transmit its position to ground radars and nearby aircraft. If that nearby aircraft is ADS-B equipped, it will see the non-ADS-B aircraft as potential traffic with the help of TCAS (?, ?). In the space section lies the satellite system for navigation, that is the Global Navigation Satellite System (GNSS), which generally consists of GPS from the United States, GLONASS from Russia, and GALILEO from the European Union. These satellites send positional data to aircraft equipped with ADS-B, which will be used for surveillance purposes along with the phases of flights.

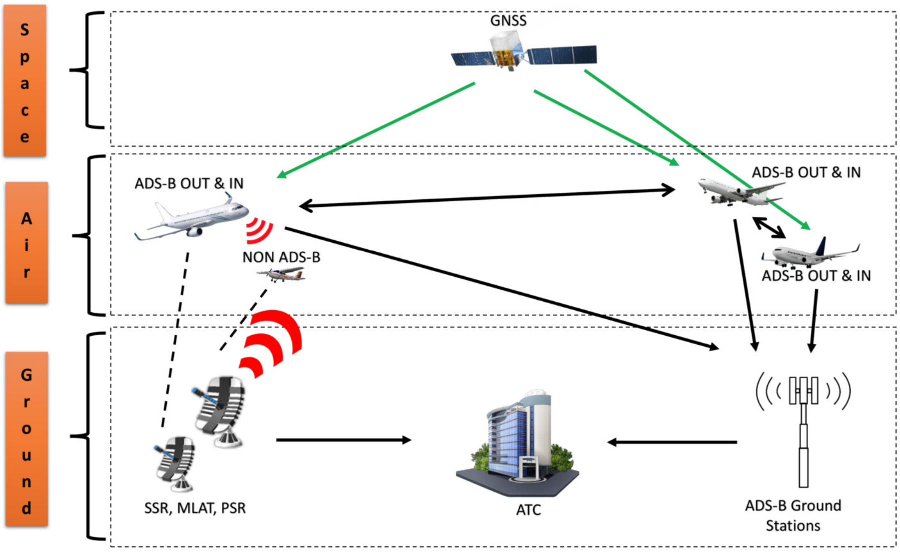

FIGURE 2.3: The flow of ADS-B divided into segments

According to *KP 280 Tahun 2017*, ADS-B data needs to be in a certain format for it to be able to be used internationally. The formats are defined under several ADS-B standads, but unfortunately it is rather quite difficult to find the comeplete reference. However, for it to be usable by ATC, the ADS-B transmitter must transmitts the following minimum data set:

- Position
- Position Integrity Information
- Pressure Altitude
- Aircraft Identification
- Version Number
- SIL
- NACp

2.2.3 ADS-B Message Structure

Since ADS-B necessary foundation has been stated, it is time to get into a more detailed section of ADS-B, which is the ADS-B message structure. In this segment, there are plenty of things to cover. A single ADS-B message is 112-bits long and can be sliced into five crucial parts: the downlink format (DF) field, capability field (CA), aircraft address field (AA), the message or data field, and parity or identity field (PI) (?, ?). Each and one of those fields have essential functions in a single ADS-B message.

DF (5)	CA (3)	AA (24)	DATA (56)	PI (24)

Figure 2.4: Five sections of an ADS-B message structure

Downlink Format

Starting with the downlink format field, it is five bits long and acts as a descriptor. There are various types of downlink formats such as downlink format 17, downlink format 18, downlink format 19 and 20. A Mode S transponder uses downlink format 17 while a non-transponder based ADS-B and TIS-B equipment uses downlink format 18(?, ?). Because each number of downlink format correspond with a specific type of equipment, it can be used as a filter.

Capability Field

The next field is called a capability field. This field starts form bit 6 until bit 8 (3 bits long). The Capability Field reports the capability of the ADS-B transmitting system based on a Mode-S transponder. It is available for Downlink Format 17 and Downlink Format 18.

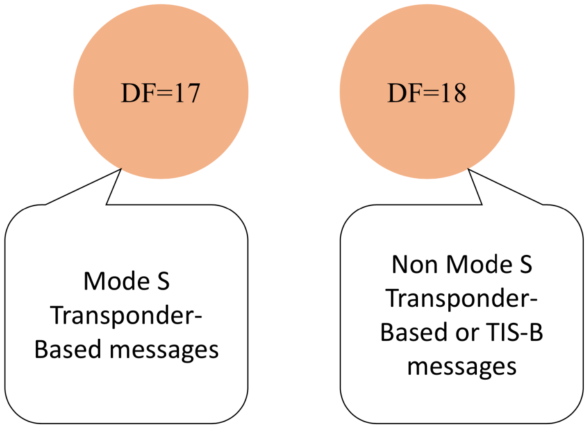

FIGURE 2.5: The difference between Downlink Format 17 and Downlink Format 18

Coding	Definition
0	Level 1 transponder
1-3	Reserved
4	Level 2 and beyond transponder, have the ability to set CA to 7, and on-ground
5	Level 2 and beyond transponder, have the ability to set CA to 7, and airborne
6	Level 2 and beyond transponder, have the ability to set CA to 7, and either on-ground or airborne
7	Signifies the downlink request value is 0, or flight status is 2,3,4, or 5, and either airborne or on the ground

TABLE 2.1: CA Field code definitions

Aircraft Address

Aircraft address starts from bit 9 until 32 (total of 24 bits). Its function is to give a unique ICAO address to an aircraft. It is also knows as hex code, and it is embedded in every aircraft which tells their corresponding country and operator.

An example of an ICAO address is 4840D6. This identifies as a Fokker 70 aircraft with the registration of PH-KZD. In Indonesia, the ICAO address usually starts with 8A.

Data Segment

The data segment starts from bit 33 until bit 88. In order to know the content inside the ADS-B message, it needs to read the first 5 bits of the data segment called Type Code(?, ?). For example, type code 1 until 4 is about aircraft identification, type code 5 until 8 is about the surface position, type code 9 until 18 is about the airborne position (with barometric altitude), type code 19 is about airborne velocity, type code 20 until 22 is about the airborne position (with GNSS height), type code 23 until 27 is reserved for future uses, type code 28 is about aircraft status, type code 29 is about target state and status information, and lastly type code 31 which is about aircraft operation status.

In bits 38 until 40, it is used to identify aircraft or vehicle types through four ADS-B Emitter Category Sets namely ADS-B Emitter Category Set A, ADS-B Emitter Category Set B, ADS-B Emitter Category Set C and ADS-B Emitter Category Set D (?, ?). Each category has a coding value of 0 through 7, except Category Set D where it only has a coding value of 0 until 2. For ADS-B Emitter Category Set A, code 0 means no ADS-B emitter information, codes 1,2, 3, and 5 refers to light, small, large, and heavy aircraft based on its weight, code 4 refers to a high-vortex large aircraft such as the Boeing 757, code 6 refers to a high-performance aircraft that goes beyond 400 knots and more than five times the gravitational force, and lastly code seven which refers to a rotorcraft like a helicopter. For ADS-B Emitter Category Set B", code 0 means no information is given, code 1 refers to a glider or a sailplane, code 2 refers to a lighter-than-air aircraft, code 3 refers to a skydiver, code 4 refers to an ultralight aircraft, code five is reserved for further uses, code 6 refers to an unmanned aerial vehicle, and lastly, code 7 refers to a trans-atmospheric vehicle. For ADS-B Emitter Category Set C, code 0 means no ADS-B information given code 1 refers to an emergency vehicle, code 2 refers to a service vehicle, code 3 refers to a point obstacle, code 4 refers to a cluster obstacle, code 5 refers to a line obstacle, and code 6 and 7 are reserved for future uses. For ADS-B Emitter Category Set D, there are only codes of 0 and 1. The code 0 refers to no ADS-B information is given, and code 1 is reserved for future uses.

Type Code	Content
1 - 4	Aircraft Identification
5 - 8	Surface Position
9 - 18	Airborne Position (with Barometric Altitude)
19	Airborne Velocities
20 - 22	Airborne Position (with GNSS Height)
23 - 27	Reserved
28	Aircraft Status
29	Target State and Status Information
31	Aircraft Operation Status

TABLE 2.2: ADS-B message type based on its Type Code

Coding	Definition
0	No ADS-B emitter category information
1	Light (<15.500 lb)
2	Small (15.500 to 75.000 lb)
3	Large (75.000 to 300.00 lb)
4	High-vortex large (aircraft such as B-757)
5	Heavy (>300.000 lb)
6	High-performance (>5g acceleration and >400 knots)
7	Rotorcraft

TABLE 2.3: ADS-B emitter category set “A”

Coding	Definition
0	No ADS-B emitter category information
1	Glider/Sailplane
2	Ligter-than-air
3	Parachutist/Skydiver
4	Ultralight/Hang-glider/Paraglider
5	Reserved
6	UAV
7	Space/Trans-atmospheric vehicle

Table 2.4: ADS-B emitter category set “B”

Coding	Definition
0	No ADS-B emitter category information
1	Surface Vehicle - Emergency vehicle
2	Surface Vehicle - Service vehicle
3	Point Obstacle (includes tethered ballons)
4	Cluster Obstacle
5	Line Obstacle
6	Reserved
7	Reserved

Table 2.5: ADS-B emitter category set “C”

Coding	Definition
0	No ADS-B emitter category information
1	Reserved

Table 2.6: ADS-B emitter category set “D”

Parity Field

Parity or identity field starts from bit 89 until bit 112. It is the last 24-bit part of the ADS-B message structure. Basically, a remainder is generated from the sender side and the receiver side will validate the arithmetic message. In other words, it is a redundancy check to validate the contents of the ADS-B message (?, ?).

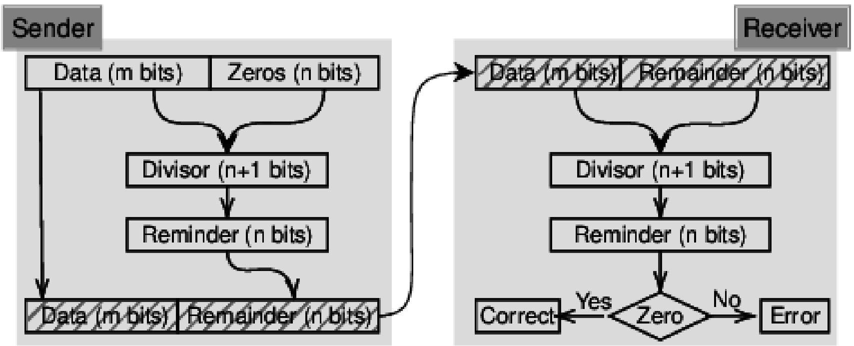

FIGURE 2.6: Flow of CRC error check (?, ?)

2.3 Multilateration

Multilateration is a set of surveillance equipment that consists of four ground stations able to give an accurate location of an aircraft by using a method known as Time Difference of Arrival. When an aircraft passes by an airport with MLAT ground stations installed, signals from the aircraft are emitted and received by the ground stations. It is worth to note that these signals are received at different timestamps (usually fractional) by each MLAT antennas; thus it is this time difference that allows the position of the aircraft to be calculated by advanced processing units. Then, aircraft reports will be created to be sent to a surveillance data processor, which will output track reports to the ATC display system. The time difference from three antennas can have hyperboloids, where the point of intersection is the aircraft's position. This phase can be called *Hyperbolic Positioning* (?, ?). Ideally, a 3-dimensional position can be determined with four MLAT ground stations (?, ?). More than four MLAT ground stations available means that extra information that could serve to validate measurements.

Compared to ADS-B, MLAT can be considered either passive or active. By being passive, ground stations will listen for emitted signals from aircraft, while active means it interrogates the aircraft. Passive systems are best for regions that mandates Mode-S transponders or ACAS in aircraft avionics, while active systems do not require a moving part, much simpler, and cheaper maintenance cost. Not only that, MLAT uses its own measurement of position (independent) and ADS-B uses onboard navigation based on GPS (dependent) in terms of position source. MLAT does not require any additional avionics, but the minimum avionic type to working with MLAT is a Mode A/C transponder for interrogation requirements (?, ?). Unlike traditional rotating radars, MLAT is able to achieve a higher update rate, usually every second. It is also low in ground equipment and lifecycle cost, as well as elemental to ADS-B capability. An MLAT system has the following components:

1. A transmitting subsystem
2. Optional Intelligent Interrogation
3. A receiving antenna array subsystem
4. A central processor

Criteria	**ADS-B**	**MLAT**
Ground Equipement	Single ground station for coverage	Multiple ground stations for coverage
Position Source	via datalink, usually based on GPS	own measurement of position
Operational Principle	Passive	Passive or Active
Equipage	Needs ADS-B capable for Mode-S transponder	Needs Mode-S or Mode A/C transponder
Coverage	As defined by ground station antenna and terrain	Tailored by ground station deployment
	Ground communication network is needed for each GS	

Table 2.7: ADS-B and MLAT comparison

Multilateration is beneficial to the Air Traffic Management system. Combined with ADS-B technology, it can reduce a controllers workload, increase safety, improve some limitations of traditional surveillance radar, increase airport capacity, and reduce infrastructure costs. It is also beneficial to airspace that does not have radar coverage. According to ICAO, MLAT specific applications are as follows:

1. Airport surface surveillance
2. Situational awareness
3. Airport low visibility operations
4. Parallel runway approach monitoring
5. Noise monitoring data provision
6. Airport usage data
7. Aiways usage data
8. Flight following
9. Enhanced ATS situational awareness
10. Enhanced overall flight data and improved SAR activity

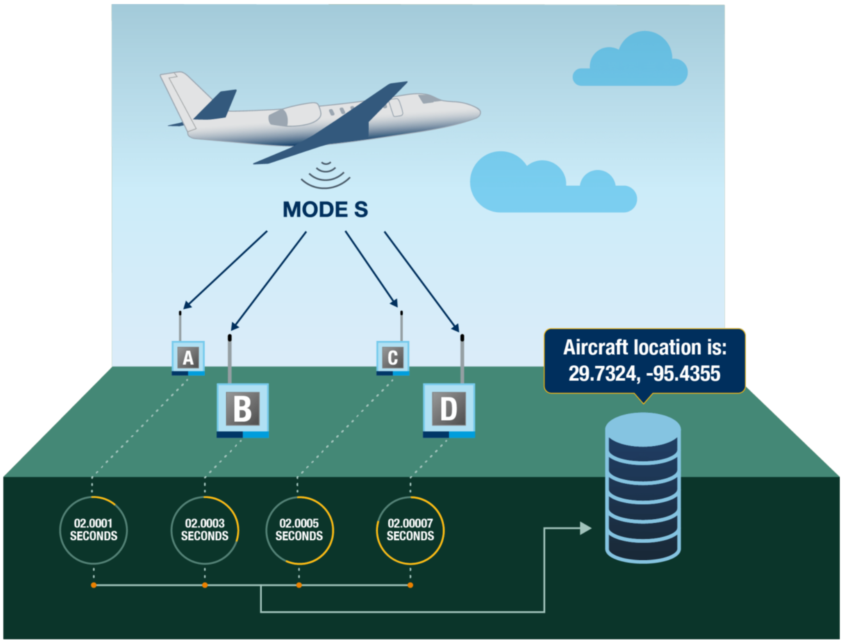

Figure 2.7: Time difference of arrival (?, ?)

2.4 ADS-B Standards

ADS-B experienced many changes throughout the years. Because of those various changes, a technical guideline was needed to adapt to such changes and meet the minimum operational requirements. Based in Washington D.C., United States of America, Radio Technical Commission for Aeronautics published several types of standards. Their standards fall into several categories: Operational Services and Environment Definition (OSED), Operational, Safety and Performance Requirements (SPR), Interoperability Requirements (IRR), Minimum Aviation System Performance Standards (MASPS) and Minimum Operational Performance Standards (MOPS). The three standards will be mentioned in this thesis are called DO-260, DO-260A, and DO-260B. Another term to go by is ADS-B Version 0 (DO-260), ADS-B Version 1 ADS-B Version (DO-260A), and ADS-B Version 2 (DO-260B). These three standards fall under MOPS. MOPS itself is aimed to give designers, manufacturers, installers and operators the standards needed to carry out its intended functions (?, ?).

2.4.1 Document History and Nomenclature

DO-260 (ADS-B version 0) was published in September 2000. It was later improved based on users feedback and analysis. Thus, a second version of the standard was published in April 2003 called DO-260A (ADS-B Version 1). Later down the timeline, DO-260A Change 1 was published in June 2006 and DO-260A Change 2 in December 2006. The term 'Change' contains only editorial changes, clarifications, and corrections, but no changes in specification wise. Next comes DO-260B (ADS-B Version 2) published in December 2009, followed by DO-260B Corrigendum 1 issued in December 2011. The term 'Corrigendum' means it is a supplemental information to DO-260B. It contains typographical errors, corrections to test procedures, and notes that help to clarify procedures. The corrigendum does not affect desired performance, nor does it affect the compliance of any equipment.

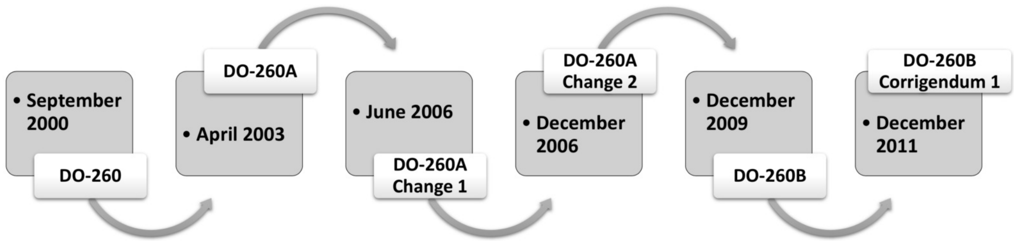

FIGURE 2.8: Evolution of RTCA DO-260 standards

Regarding the naming of the standards, '*DO*' refers to the word '*Document*,' and the numbers (260) are assigned sequentially or the next available number. The alphabetical letter such as '*A*' in DO-260A refers to the consecutive changes in specifications of the system. Moreover, the term '*Change*,' as previously mentioned, refers to editorial changes, clarifications, and corrections. The process of how a standard is published are as follows (?, ?):

1. A request from aviation industries or government agencies determine the need for a specification plan and guidance.
2. The request is then submitted to the Program Management Committee in RTCA.
3. PMC will confirm the need for a new document and publish "Terms of Reference" that will define the document and the next available number.
4. The task of generating the document will be assigned to a Special Committee (SC).

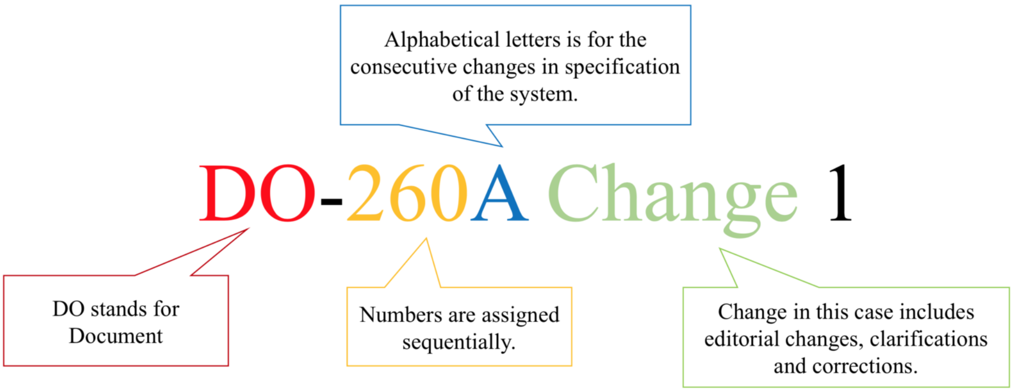

FIGURE 2.9: RTCA standard nomenclature

2.5 All Purpose Structured Eurocontrol Surveillance Information Exchange (ASTERIX)

ASTERIX CAT 21 is a data format standard used to transfer ADS-B data from ADS-B ground stations to an air traffic management system, which will then go through the air traffic controllers processing and display system (?, ?). There are three versions of ASTERIX, version 0.23, version 1.0, and version 2.1. Version 0.23 was issued in November 2003 and embedded in DO-260 at the time. As the standards by RTCA evolved, so does ASTERIX data format. Version 1.0 was issued in August 2008 and fully incorporated in DO-260A, while version 2.1 was issued in May 2011 and also fully incorporated in DO-260B. In 2005, the Asia Pacific region used ASTERIX V0.23 as the baseline for sharing ADS-B data. It proved beneficial because it provided crucial information for ATC services such as 3 and 5 nautical miles separation. ASTERIX V0.23 can support DO-260, DO-260A, and DO-260B ADS-B ground station and avionics for essential ATC services, but could not support some capabilities offered by DO-260A and DO-260B (?, ?).

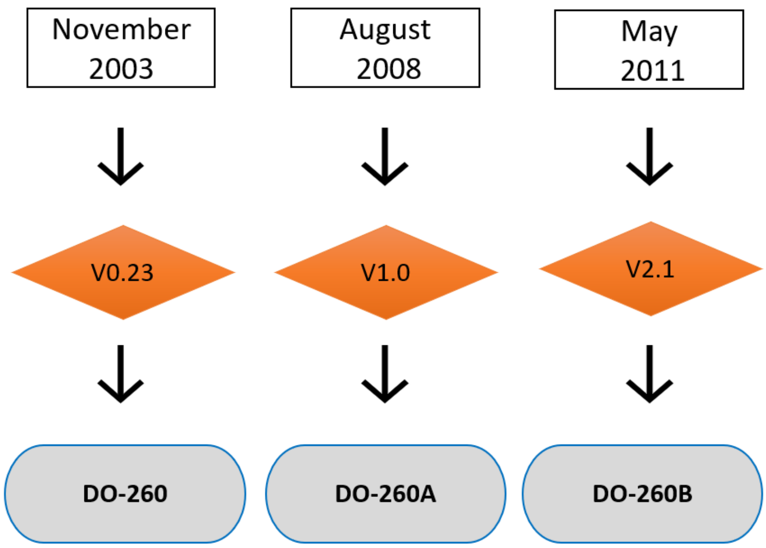

FIGURE 2.10: Timeline of ASTERIX development

ASTERIX CAT 21 was developed to be able to support various data links. Therefore, there are data fields that are optional and mandatory. The generation of ASTERIX at an ADS-B ground station is divided into four groups:

- Mandatory items (group 1), where all the data listed under this group must be present during transmission.
- Desirable items (group 2), wherefrom an operational perspective, is useful to have the data under this list.

- Optional data (group 3), where here it may or may not be needed, depending on if the data are available from aircraft or operational needs.
- Future data (group 4), where this group only provides information for future adaptability and possible cost-effectivity.

2.5.1 Mandatory Data Items

The mandatory data items in ASTERIX CAT 21 during transmission must include data source identification, which identifies the source of data. Next is the time of day to know data that are too old and the time of applicability of position. After that is the target report descriptor, which indicates if a report is a duplicate, on the ground, a simulated target, a test target, or a real target. Next is the target address, which is used for reports or to report linkage during ATC tracking. After that is the figure of merit, where positional data that does not meet the minimum requirement should be discarded. Last is the position in WGS84 coordinates, which is used for position reports. Which versions of ASTERIX CAT 21 supports the described data items can be seen on table **??**.

Description	V 0.23	V 2.1
Data Source Identification	x	x
Time of Day	x	
Time of Applicability of Position		x
Target Report Descriptor	x	x
Target Address	x	x
Figure of Merit/Quality Indicators	x	x
Position in WGS-84 Coordinates	x	x

Table 2.8: Mandatory ASTERIX CAT 21 data items

2.5.2 Desirable Data Items

The desirable data items in ASTERIX CAT 21 includes aircraft operational status in teh case of a Resolution Advisory (RA) event. Next is the emitter category, in which it defines the aircraft or vehicle type. After that is geometric altitude, which can be useful for Required Vertical Separation Minima or RVSM. Next is the flight level, which is vital for ATC because it tells the altitude of the aircraft. After that is the barometric vertical rate and geometric vertical rate, both are used for predictive tools and safety nets. The ground vector are provided vectors to support the extrapolation of positional data to the time of display. Target identification is the callsign or flight identification of an aircraft. Lastly, target status is used in the case of an aircraft emergency; so that ATC knows what type of emergency it is.

Description	V 0.23	V 2.1
Aircraft Operational Status		x
Emitter Category	x	x
Geometric Altitude/Height	x	x
Flight Level	x	x
Barometric Vertical Rate	x	x
Geometric Vertical Rate	x	x
Ground Vector	x	x
Target Identification	x	x
Target Status	x	x

TABLE 2.9: Desirable ASTERIX CAT 21 data items

2.5.3 Optional Data Items

Optional data items in ASTERIX CAT 21 include the time of report transmission. With this, ATC can receive the time of applicability. Next is the time of day accuracy, which refers to the maximum errors in a day. Velocity accuracy refers to position quality affected when using a GPS. Time of applicability of velocity refers to a velocity data time out in ground stations. The time of message reception of velocity refers to the same message as a position in ASTERIX. Track number is a 24-bit code that could be used as a false track number. Trajectory intention is defined in DO-260, and selected altitude could be used to detect pilot errors during the selection of heading or altitude. Service identification is a type of service. Service management is an update rate and time of message reception of position and velocity is to support MLAT system processing by a receiver. MOPS version is useful for statistics on equipage, and Mode 3/A code can be used for legacy ATC system that does implement flight identification. The rate of turn is to determine the rate of turn in an aircraft, and message amplitude is suitable for technical analysis. ACAS resolution advisory, receiver identification, and data ages are part of the optional data items. Airspeed, true airspeed, and magnetic heading are only sent in the absence of a ground vector information. The met report, final state selected altitude, roll angle, and WGS84 position are also optional data items. Which versions of ASTERIX CAT 21 supports the described data items can be seen on table **??**.

Description	V 0.23	V 2.1
Time of Report Transmission		x
Time of Day Accuracy	x	
Velocity Accuracy	x	
Time of Applicability of Velocity		x
Time of Message Reception of Velocity		x
Track Number		x
Trajectory Intent	x	x
(intermediate) Selected Altitude	x	x
Service Identification		x
Service Management		x
Time of Message Reception of Position - High Res		x
Time of Message Reception of Velocity - High Res		x
MOPS Version	x	x
Mode 3/A Code		x
Rate of Turn	x	x
Surface Capabilities and Characteristics		x
Message Amplitude		x
Mode S MB Data		x
ACAS Resolution Advisory Report		x
Receiver ID		x
Data Age		x
Air Speed	x	x
True Air Speed	x	x
Magnetic Heading	x	x
Met Report	x	x
Final-State Selected Altitude	x	x
Roll Angle	x	x
Position in WGS-84 High Res		x

Table 2.10: Optional ASTERIX CAT 21 data items

2.6 ADS-B Quality Indicators

DO-260B is the latest version at the moment. Of course, its predecessors, DO-260A and DO-260, contributed substantially to the latest standard right now. Note that each version of standards has its specifications in terms of minimum performance requirements and how it should behave under certain conditions. Thus, there are some differences between the ADS-B document versions. One thing that stands out the most are the quality indicators. ADS-B quality indicators are quite complex. They are expressions of credibility as well as reliability, but in the form of integrity and accuracy reports. Every ADS-B message contains some sort of data (information). However, each message has a quality for the data being sent. Once the message is transmitted along with the quality of the data, the receiving end can decide whether it is good enough to be used in air traffic management.

Several quality indicators are essential to the quality of the data being sent. Those quality indicators are Navigation Uncertainty Category for Velocity (NUCv), Navigation Uncertainty Category for Position (NUCp), Navigation Accuracy Category for Velocity (NACv), Navigation Accuracy Category for Position (NACp), Navigation Integrity Category (NIC), Navigation Integrity Category barometric (NICbaro), Surveillance Integrity Level (SIL), Source Integrity Level (SIL), Source Integrity Level supplements (SILsupp), System Design Assurance (SDA), and Geometric Vertical Altitude (GVA). Each of the following ADS-B quality indicators serves a purpose.

In DO-260, NUCp and NUCv are present. During the development of DO-260, Selective Availability (SA) for GPS was turned on. Selective Availability was intended to downgrade GPS signals for national security reasons. Therefore, this affected civilian GPS because both horizontal and vertical plane accuracy to be very poor. In May 2000, President Bill Clinton of the United States ordered the discontinuation of Selective Availability, so that civil and commercial vehicle or aircraft users can receive more accurate data. Because Selective Availability was turned off, RTCA upgraded DO-260 into DO-260A. The significant difference between DO-260 and DO-260A is the split between accuracy (assuming it is 95 % accuracy under standard conditions) and integrity (protection against abnormal conditions). In DO-260A, new quality indicators are found from the split, namely NIC, NIC supplements, NACp, NACv, and SIL. After DO-260A comes the more improved version DO-260B. In DO-260B, another split happened , but mostly correlated with the horizontal and vertical component of the quality indicators. It also enhanced resolution to horizontal position integrity as well as the capability to differentiate measurement integrity from avionics faults. Here in DO-260B, new quality indicators emerged called System Design Assurance and Geometric Vertical Accuracy.

2.6.1 Navigation Uncertainty Category

Starting with Navigation Uncertainty Category, where accuracy and integrity are both combined into a single quality indicator. Navigation Uncertainty Category is further divided into two classes, Navigation Uncertainty Category for Position (NUCp) and Navigation Uncertainty Category for Velocity (NUCv). NUCp is made up Horizontal Protection Level (integrity) and Horizontal Figure of Merit (accuracy). Here HPL is computed by the GNSS and in theory, a 100% containment limit in the horizontal plane. It helps to determine the separation between two aircraft and HFOM with a 95% positional determines the separation that pilots should be more cautious of. In HFOM, is further divided into a vertical and horizontal radius of containment. Radius containment, usually denoted as Rc, is a statistical radius that within a flight, there is a 95% probability the aircraft is within the radius of its original stated position. NUCps values depend on what Type Code it refers to. For NUCp airborne position with barometric altitude, it is

Type Code 9 until 18. The values start 0 through 9, where HPL and RCu get more accurate as of the value increases. For an airborne position with GNSS height, it is Type Code 20 until 22. The values are 0, 8, and 9. The higher the NUCp value, the more accurate it is. For surface position, it is Type Code 5 until 8. The NUCp values start at 6, 7, 8, and 9. The higher the NUCp value, the more accurate the position report. Navigation Uncertainty Category for Velocity is used to indicate the uncertainty of horizontal and vertical speed (rate). NUCv falls within Type Code 19, which means it is about airborne velocity message. It is divided into two parameters called Horizontal Vertical Error (95%) and Vertical Velocity Error (95%). The NUCv values start from 0 until 4, where the higher the value, the more accurate the velocity report. This quality indicator is only available in DO-260.

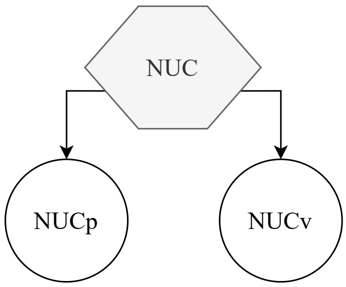

FIGURE 2.11: Navigation Uncertainty Category

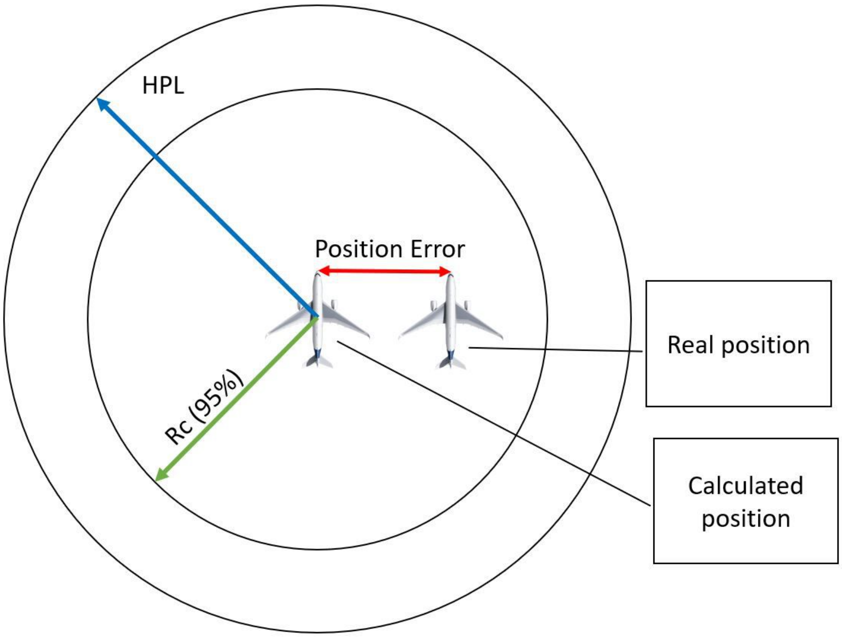

FIGURE 2.12: NUCp paramters

NUCp	HPL (m)	Rc Horizontal (m)
0	> 37040	> 18520
1	< 37040	< 18520
2	< 18520	< 9260
3	< 3704	< 1852
4	< 1852	< 926
5	< 926	< 463
6	< 370	< 185
7	< 185.2	< 93
8	< 25	< 10
9	< 7.5	< 3

TABLE 2.11: Airborne position with barometric altitude (Type Code = 9 - 18)

NUCp	HPL (m)	Rc Horizontal (m)	Rc Vertical (m)
0	> 25	> 10	> 15
8	< 25	< 10	< 15
9	< 7.5	< 3	< 4

Table 2.12: Airborne position with GNSS height (Type Code = 20 - 22)

NUCp	HPL (m)	RCu (m)
6	> 185.2	> 93
7	< 185.2	< 93
8	< 25	< 10
9	< 7.5	< 3

Table 2.13: Surface position (Type Code = 5 - 8)

NUCv	HVE 95% (m/s)	VVE 95% (m/s)
0	Unknown	Unknown
1	< 10	< 15.2
2	< 3	< 4.5
3	< 1	< 1.5
4	< 0.3	< 0.46

Table 2.14: NUCv figure of merit

2.6.2 Navigation Accuracy Category

Navigation Accuracy Category, where it is further divided into two classes called Navigation Accuracy Category for Position and Navigation Accuracy Category for Velocity. NACp is based on two parameters called Estimated Position Uncertainty (EPU) and Vertical Estimated Position Uncertainty (VEPU). NACp announces the 95% accuracy limits for the horizontal position (EPU) and vertical position (VEPU). NACp is reported so that surveillance applications can determine whether the reported position is acceptable or not. The values for NACp starts at 0 until 15, where values 0 through 11 has its figures and values 12 through 15 is reserved for future purposes. The higher the NACp value, the more accurate it is. Navigation Accuracy Category for velocity is based on Horizontal Figure of Merit (HFOMr) and Vertical Figure of Merit (VFOMr). Previously in ADS-B Version 0, it is called NUCv. The values remain the same as in DO-260, only renamed differently.

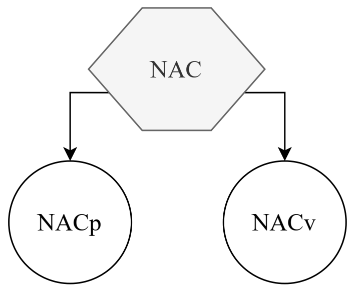

Figure 2.13: Navigation Uncertainty Category

NACp	95% HFOM and VFOM (m)
0	≥ 18520
1	< 18520
2	< 7408
3	< 3704
4	< 1852
5	< 926
6	< 555.6
7	< 185.2
8	< 92.6
9	< 30 and VEPU < 45
10	< 710 and VEPU < 15
11	< 3 and VEPU < 4
12-15	Reserved

TABLE 2.15: NACp values

NACv	HFOMr 95% (m/s)	VFOMr 95% (m/s)
0	Unknown	Unknown
1	< 10	< 15.2
2	< 3	< 4.5
3	< 1	< 1.5
4	< 0.3	< 0.46

TABLE 2.16: NACv values)

2.6.3 Surveillance / Source Level Integrity

Surveillance Integrity Level is based on two parameters called Radius of Containment and Vertical Protection Limit. It is used to determine the probability of exceeding the reported Radius of Containment and Vertical Protection Limit without giving any warnings or alerts. In DO-260A, Surveillance Integrity Level is still dependent on Vertical Protection Limit. If the Vertical Protection Limit could not be determined, then it must be set to zero (?, ?). Surveillance Integrity Limit has a value of 0 through 3, where the unit for it is either per hour or per sample. In DO-260B, it is renamed as Source Integrity Level. In this version, it is only dependent on the reported horizontal position (Rc). Also, it added SIL supplement, which only has a value of 0 and 1. The zero or one value determines whether the unit is in per hour or per sample. Other than that, its function remains the same.

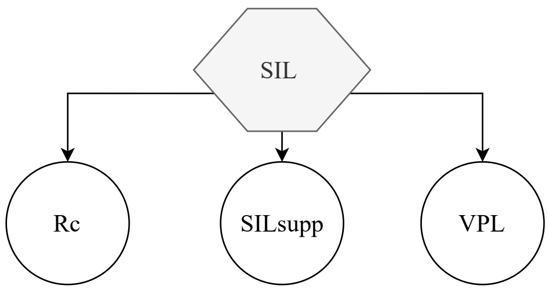

FIGURE 2.14: Navigation Uncertainty Category

SIL	RCu	VPL
0	0	0
1	$< 1\times10^{-3}$	$< 1\times10^{-3}$
2	$< 1\times10^{-5}$	$< 1\times10^{-5}$
3	$< 1\times10^{-7}$	$< 2\times10^{-7}$

TABLE 2.17: Values for Surveillance Integrity Level

SIL	Probability of Exceeding RCu
0	$< 1\times10^{-3}$ or unknown
1	$\leq 1\times10^{-3}$
2	$\leq 1\times10^{-5}$
3	$\leq 1\times10^{-7}$

TABLE 2.18: Values for Source Integrity Level

SILsupp	Definition
0	Probability of exceeding NIC Rc based on “flight per hour”
1	Probability of exceeding NIC Rc based on “flight per sample”

TABLE 2.19: SIL supplement bit to define unit

2.6.4 Navigation Integrity Category

Navigation Integrity Category is based on four parameters. The Radius of Contamination, Vertical Protection Limit, Navigation Integrity Category Supplement Bits, and Navigation Integrity Category Barometric. Navigation Integrity Category Barometric (NICbaro) indicates whether or not the barometric pressure altitude has been cross-checked with another source of pressure altitude,a nd only available in DO-260B. Navigation Integrity Category Barometric has a coding value of 1 and 0, where 0 means the barometric altitude has not been cross-checked and 1 being cross-checked. In ADS-B Version 1, NIC is first introduced here in order to address more uncertainty levels. Within NIC, there are two different levels in Type Code 7 for surface position messages, and 11, 13, and 16 for airborne position messages. Thus, NIC Supplement Bits (NICsupp) is present to help differentiate which level it refers to. In Ads-B Version 2, the two levels are divided again. Now it is called NIC Supplement A (NICa), NIC Supplement B (NICb), and NIC Supplement C (NICc). For NICa, it is located in Type Code 31 about the operational status message. For NICb, it is located in Type Code 9 through 18, and it is about airborne position message. Lastly, NICc is located in Type Code 31, where it is about an operational status message but a different message bit from NICa. The NIC values start from 0 through 11, whereas the value increases the level of Radius of Containment gets smaller. In this figure, as you can see, is an elliptical boundary containing the horizontal Radius of Containment (95%), the vertical Radius of Containment (95%), and the containment region. Take a famous flight route as an example, from Soekarno-Hatta International (IATA Code: CGK) Airport to Juanda International Airport (IATA Code: SUB). The route takes roughly 1 hour and 35 minutes. The 95% here means that through the 1 hour and 35 minutes of flight, there is a 95% probability that the aircraft is within the radius of containment. As for the rest, there is always a 4.99% chance that the aircraft will go out of the containment region.

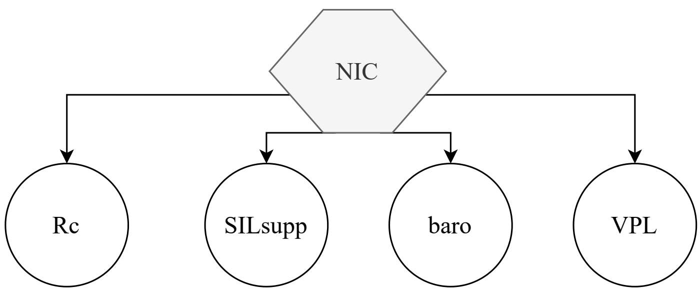

Figure 2.15: Navigation Integrity Category

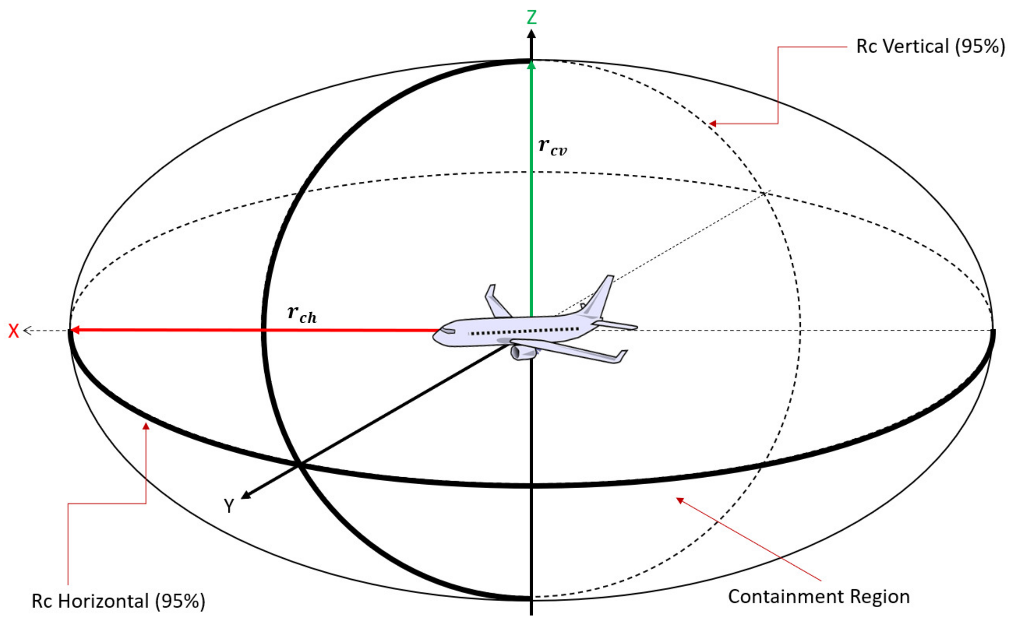

FIGURE 2.16: Vertical and hoorizontal radius of containment for NIC

NIC	Rc (m)	Rc Vertical (m)
0	> 37,040 or unknown	
1	<37,040	
2	<14,816	
3	<7,408	
4	<3,704	
5	<1,852	
6	<1,111	
7	<370	
8	<185.2	
9	<75	<112
10	<25	<37.5
11	<7.5	<11

TABLE 2.20: Values of NIC for version 1

NICbaro	Meaning
0	Barometric altitude has not been crosschecked
1	Barometric altitude has been crosschecked

TABLE 2.21: Values of NICbaro for version 2

2.6.5 Geometric Vertical Accuracy

Geometric Vertical Accuracy was only introduced in ADS-B Version 2. As previously mentioned, ADS-B Version 2 was about the split between the horizontal and vertical components. GVA here is aimed for ADS-B applications, where it indeed relies on the accuracy of the geometrical vertical position aspect. The benefits of GVA is that it can help analyze if the mismatch between geometric and pressure altitude is affected by either the barometric altitude system or GPS receiver. An example of the application is the Required Vertical Separation Minima. The GVA field shall be set using the Vertical Figure of Merit (VFOM) 95% from the GNSS position source used to encode the geometric altitude field in the airborne position message. In addition, it includes the probability of transmitting false or misleading latitude, longitude, velocity, or associated accuracy and integrity metrics.

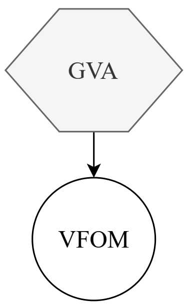

FIGURE 2.17: Geometric Vertical Accuracy

GVA	Meaning
0	Unknown or >150 m
1	$\leq$ 150 m
2	$\leq$ 45 m
3	Reserved

TABLE 2.22: Values of GVA in version 2

2.6.6 System Design Assurance

System Design Assurance (SDA) is an ADS-B quality indicator where it gives indications about the probability of a malfunction in the ADS-B system that could potentially cause false position reports. It includes a position source, ADS-B equipment, and any intermediary devices that process data. Note that during the installation of System Design Assurance in aircraft, it is possible to use a preset if it does not use multiple position sources. Otherwise, the system (avionics) must be able to change and adjust the System Design Assurance by itself. The values for System Design Assurance starts from 0 until 3, where 0 means it is unknown or no safety effect, 1 refers to a minor supported failure condition, 2 being paramount, and 3 hazardous. The unit for the probability of undetected fault is in per flight hour. As for the software and hardware design assurance level, the SDA value of 0 is not available, minor has a grade of D, major has a grade of C, and hazardous has a grade of B. In the United States, the Federal Aviation Administration has been developing a program called the Next Generation Air Transportation System (NextGEN). NextGEN was intended to improve safety and support environmental movements by changing how the National Airspace System works. The FAA thought that it was time to upgrade ground-based surveillance and navigation to airborne-based surveillance systems. Not only that, but NextGENalso also aims to upgrade ATC radar-based technology to more satellite-derived location technology. Moreover, to fulfill, ADS-B technology and infrastructure is believed to be an essential key component in the succession of the program. One of the minimum technical performance requirements in NextGEN is that the System Design Assurance level must have an equal or more than the value of 2.

SDA	**Failure Condition**	**Probability of Undetected Fault**	**Design Assurance Level**
0	Unknown/ no safety effect	$>1\times10^{-3}$ per flight hour/unknown	Not Avail
1	Minor	$\leq 1\times10^{-3}$ per flight hour	D
2	Major	$\leq 1\times10^{-5}$ per flight hour	C
3	Hazardous	$\leq 1\times10^{-7}$ per flight hour	B

Table 2.23: Values of SDA in version 2

2.6.7 Capability Differences between the ADS-B Standards

Aside from the ADS-B quality indicators perspective, the standard documents have other capabilities stated as well. Starting with the capability of transmitting the length and width of the aircraft. It is only available in ADS-B Version 1 and ADS-B Version 2. For the indication of capabilities, it allows ATC to anticipate an in-trail procedure clearance. The in-trail procedure is one of the ADS-B applications where ITP-equipped aircraft use the ADS-B location report to change altitude without having to be blocked by the standard separation rules. Indication of capabilities is available on all ADS-B standard versions. Status of Resolution Advisory is to allow ATC to know whether pilots were alerted about a potential conflict. This is available on all ADS-B standard versions. GPS offset is to generate alerts on airport surface movement control such as the Advanced Surface Movement Guidance and Control System (A-SMGCS). It is only available on ADS-B Version 1 and ADS-B Version 2. Intention refers to the usage of the trajectory prediction algorithm. It is only available on ADS-B Version 1 and ADS-B Version 2. For Target Status capability, it is so that ATC can know what mode the aircraft is in. This capability is only available on ADS-B Version 2. Resolution Advisory, or widely known as RA, are advisories given to the pilots by Airborne Collision Avoidance System (ACAS).

Capability	DO-260	DO-260A	DO-260B
Length / Width of Aircraft		✓	✓
Indication of Capabilities	✓	✓	✓
Status of Resolution Advisory	✓	✓	✓
GPS Offset		✓	✓
Intention		✓	✓
Target Status			✓
Resolution Advisory			✓
Mode A	✓	✓	✓

*Reprocessed by author

FIGURE 2.18: Difference in capabilities of ADS-B standards

To sum up the difference between DO-260, DO-260A, and DO-260B, each capability and ADS-B quality indicators are both critical points to the standards. Both aspects provide a purpose and meaning to the corresponding ADS-B standards. Each ADS-B standards are uniquely made and improved based on stakeholder feedback and the continuous evolution of ADS-B technology. Starting with Navigation Uncertainty Category, it was first introduced in DO-260 as the baseline of quality indicators, and this baseline was used until DO-260A. As for Navigation Accuracy Category for Position, Surveillance/Source Integrity Level, and Navigation Integrity Category, it was meant to replace NUC in DO-260. Mode A Code presence in DO-260A and DO-260B is to support air traffic infrastructure legacy. The revision of the Surveillance Integrity Category to become Source Level Integrity as well as the addition of System Design Assurance in DO-260B is meant to separate the reports to reflect equipment certification levels, as well as the capability in detecting navigation source faults. The addition of ADS-B IN bits in DO-260B shows the enhancement in the receiver for both UAT IN and 1090 Extended Squitter IN. There are also changes to the Target State Report in DO-260B, and this is to better synchronize with aircraft data. The offer of a non-diverse antenna options for small aircraft in DO-260B can lower the cost of equipage. Next is the revision on latency requirement, redefining of TCAS status bits, new guidance on how to determine Navigation Accuracy Category for Velocity, and how to select the best position/state vector sources. All of those act as part of the enhancement in DO-260B. Transmission rates to Mode A are changed in DO-260B to improve squitter and efficiencies. Moreover, the ability to send trajectory change reports and GPS offsets in DO-260A and DO-260B. For GPS offset in DO-260B, it states by how much the offset is.

Capability	DO-260	DO-260A	DO-260B
NUC	✓	✓	
Mode A Code		✓	✓
NACp		✓	✓
SIL		✓	✓
NIC			
Revise SIL to become Source Level Integrity and added SDA			✓
Revise NIC/NAC/SIL and added GVA			✓
Added ADS-B IN bits			✓
Changes to the Target State Report			✓
Offer non-diversity antenna options for small aircraft			✓

*Reprocessed by author

Figure 2.19: Summerized differences

Capability	DO-260	DO-260A	DO-260B
Revise latency requirement			✓
New guidance on how to determine NACv			✓
New guidance on how to select the best position/state vector sources			✓
Changes to the Mode A Code transmission rates			✓
Redefine TCAS status bits			✓
Fixes and improvement to the NIC reporting and modified surface movement field for airport surface.			✓
Ability to send trajectory change report		✓	✓
GPS Offset		✓	✓

*Reprocessed by author

FIGURE 2.20: Summerized differences

2.7 DO-260B-Compliant Aircraft

Modifying an aircraft to be DO-260B compliant requires several upgrades to the aircraft avionics and external add-ons. In general, to be DO-260B compliant, the aircraft needs to have dual GPS receivers or Multi-Mode Receivers, GPS status annunciators, a compliant DO-260B ATC transponder, installation kit and wirings to connect the sensors to transponders, and a GPS antenna. Examples of DO-260B compliant transponders are TPR-901 Collins Aerospace transponder, NXT-800 L3H Avionics transponders, and XS-950 ACSS transponder. One of Indonesias airline is in the process of upgrading its aircraft to be DO-260B compliant. The aircraft type is a Boeing 737-500 Classic Series. They upgraded their aircraft by installing two TPR 901 ATC/Mode S Transponder from Collins Aerospace, two 1203C GPS/SBAS Sensor from FreeFlight Systems, two external GPS/SBAS Antenna from Sensor System, one Annunciator Panel/GPS Status from Aircraft Systems and Manufacturing, and 1203C Installation Kit from Aircraft Systems and Manufacturing.

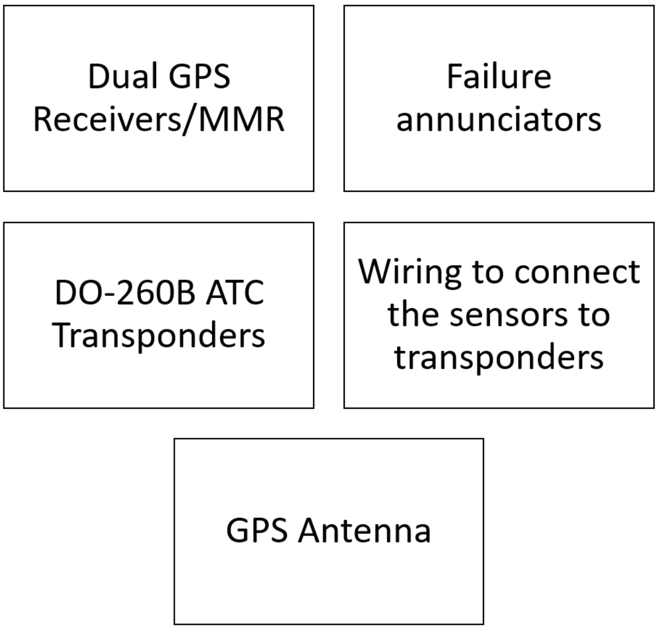

FIGURE 2.21: DO-260B aircraft modifications

Item	Qty	Manufacturer
TPR-901 ATC/MODE S Transponder	2	Collins Aerospace
Model 1203 GPS/SBAS Sensor	2	FreeFlight Systems
GPS/SBAS Antenna	2	Sensor System
Annunciator Panel, GPS status	1	ASM Inc.
FreeFlight 1203C Installation Kit	1	ASM Inc.

TABLE 2.24: Modifications for Boeing 737-500 from airline X

2.8 Overview of ADS-B Adoption in Indonesia

2.8.1 Regulation Perspective

In Indonesia, regulation and infrastructure helsp with the development of ADS-B technology and its applications. As to the regulation, Act No. 1 Year 2009 acts as the umbrella for aviation in Indonesia. In Act No. 1 Year 2009, Article 269, Section B, about the objective of flight navigation, stating that flight efficiency should be established. In support of that, Article 287, Section C states that air traffic services should provide useful guidance and information for the sake of flight safety and efficiency. Next comes the Ministerial Regulation Year 2015. This regulation refers to the Civil Aviation Safety Regulation (CASR) Part 92, discussing the general operating flight rules. Here it does not mention RTCA DO-260 documents, but it does mention equipping ADS-B for each airspace class. In referring to CASR Part 91, Section 91.226, it is stated, "An aircraft carrying ADS-B transmitting equipment for operational use in Indonesian airspace must comply with the requirements in FAA TSO-C116b, or CASA AUS ATSO-C100a, or ATSO-C1005a, or other standards acceptable by DGCA." However, this Ministerial Regulation was revised and renewed with the Ministerial Regulation No. 81 year 2017. Next comes Ministerial Regulation No. 48 Year 2017 that concerns CASR Part 171, which is about Aeronautical Telecommunications Service Providers. Under CASR Part 171.015, it specifies about a group of surveillance facilities, which includes Primary Surveillance Radar (PSR), Secondary Surveillance Radar (SSR), Multi-Mission Surveillance Radar (MMSR), Multilateration (MLAT), ADS-B, ADS-Contract, Surface Movement Radar (SMR), Precision Approach Radar (PAR), Air traffic Control Automation, Advanced Surface Movement Guidance and Control System (ASMGCS), and Automatic Identification System (AIS). After that is the Ministerial Regulation No. 89 Year 2017 that replaced Ministerial Regulation No. 94 Year 2015. Here the regulation declares that all

Transport Category Aircraft *must* possess ADS-B equipment by January 1, 2020. Not only that, but it also declares that by January 1, 2030, all category aircraft *must* have ADS-B equipment. In regards to ADS-B equipment, it must comply with the minimum requirements stated in DO-260 (ADS-B Version 0), DO-260A (ADS-B Version 1), or DO-260B (ADS-B Version 2). Next is the Decree of the Director General of Air Transportation No. 103 Year 2015, which discusses technical specifications on the aviation telecommunication facility. It also gives a brief explanation of surveillance facilities, including about ADS-B stating that its processing capability must comply with DO-260, DO-260A, and DO-260B. After that comes Decree of the Director General of Air Transportation No. 280 Year 2017, an Advisory Circular (AD) on the airworthiness approval of ADS-B equipment. Here, it is peculiar on how users that implement DO-260, DO-260A, and DO-260B should handle such requirements stated in those standards.

2.8.2 Infrastrcture Perspective

From the infrastructure perspective, Indonesia has two Flight Information Region named Jakarta FIR and Ujung Pandang FIR. Both FIRs has an area of roughly 5,193,252 KM^2. For air traffic before the emergence of Coronavirus, it was about 9,900 aircraft movements per day. Within the two FIRs, it is further divided into Flight Service Stations. For Jakarta FIR, there are four Flight Service Stations called Medan FSS, Palembang FSS, Jakarta FSS, and Pontianak FSS. For Ujung Pandang FIR, there are ten Flight Service Stations called Bali FSS, Banjarmasin FSS, Balikpapan FSS, Kupang FSS, Ujung Pandang FSS, Manado FSS, Ambon FSS, Biak FSS, Merauke FSS, and Jayapura FSS.

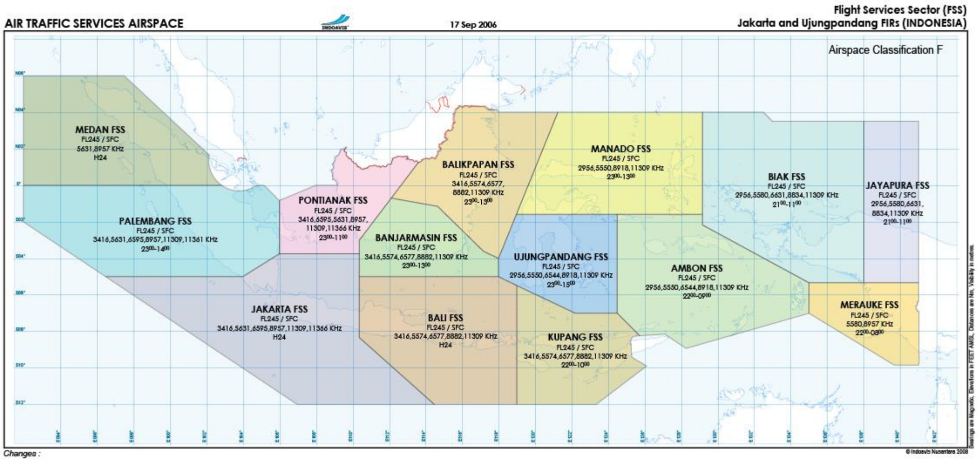

FIGURE 2.22: Flight Information Region of Indonesia

As of 2018, there are 31 ADS-B ground stations spread across Indonesia. According to Mr.Yudi from *Badan Pengkajian Dan Penerapan Teknologi* (?, ?), Indonesia needs at least 1000 ADS-B-based navigation devices due to vast and stretching geographical features. Starting with Sumatra, there are four ADS-B ground stations located in Aceh, Medan, Pekanbaru, and Palembang, with two additional ground station to the right of Sumatra, Metak, and Natuna. Moving down to Java, there are five ADS-B ground stations located in Jakarta, Cilacap, Semarang, Surabaya, and Kintamani. Above Java, Kalimantan has five ADS-B ground stations located in Pontianak, Pangkalan Bun, Banjarmasin, Balikpapan, and Tarakan. To the right of Kalimantan, Sulawesi has five ADS-B ground stations located in Manado, Palu, Malino, Makassar, and Kendari. Beneath Sulawesi, Nusa Tenggara islands, has three ADS-B located in Waingapu, Alor, and Kupang. In Maluku and North Maluku, there are a total of three ADS-B ground stations located in Galela, Ambon, and Saumaki. For West Papua and Papua, there are a total of four ADS-B ground stations located in Sorong, Biak Timika, and Merauke.

FIGURE 2.23: Map of ADS-B across Indonesia

Indonesia was committed to upgrading its surveillance system to achieve a means of safety and efficiency of flight navigation and tracking. To reach such ambition, Indonesia created its first ADS-B Task Force on May 22, 2014. Their main tasks were to discuss the issue regarding ADS-B implementation. By July 24, 2014, the Indonesian Directorate General of Civil Aviation published an Aeronautical Information Publication (AIP) Supplement No. 10/14 for ADS-B implementation in Indonesia (Tier 2). It was effective on September 18, 2014, at 19:00 UTC until June 25, 2015. On February 4, 2015, DGCA issued a circular letter to Indonesian airlines about the minimum standards for ADS-B equipment, which had to comply with DO-260 at the minimum. The circular letter also requested that airlines collect transponder and GNSS receiver models, as well as their part numbers for documentation purposes. A second task force was created on April 9, 2015, to discuss status updates of ADS-B implementations, the concept of operations, and preparations for publishing a new AIP. On April 30, 2015, an AIRAC AIP Supplement Nr. 08/15 about ADS-B implementation in Indonesia specifically for Air Traffic Service Surveillance Separation. Then on May 25, 2017, an AIP Supplement Nr. 18/17 was issued to further expand the implementation of ADS-B ATS Surveillance Separation from FL245 until FL600. Lastly, November 2019 marks the time where Indonesia has completed upgrading its ADS-B ground stations to be compliant with DO-260B minimum standard.

Indonesia has successfully created its ADS-B ground stations. Badan Pengkajian Dan Peneparan Teknologi and Perseroan Terbatas Industri Telekomunikasi Indonesia worked together to make the ADS-B ground station and give it the code AGS-216. It has been certified by the Ministry of Transportation and built based on international standards. Thus, making it on par with other ADS-B manufacturers such as Thales. The benefit of AGS-216 is that it can increase situational awareness for both ground controllers and pilots, increase surveillance coverage area, low-cost maintenance, fast support and response due to local-made technology, the ability to cover an area with a radius of 450 KM in every direction, accommodating up to 500 aircraft, small electrical needs thus it can use solar power panels, and simple installation process. The AGS-216 has specifications as follows:

Parameter	**Specifications**
Processed Signal	1090ES Mode S (DF=17, DF=18)
Input Voltage	18-30 VDC
Power Consumption	24 Watts
Update Rate	1 sec
Reception Range	>250 NM
Target Capacity	300 targets
Latency	<500 ms
Report Generation	ASTERIX CAT 21 ver 0.23 and 2.1
MOPS Compliance	DO-260, DO-260A, DO-260B

Table 2.25: AGS-216 specifications

2.9 Previous Similar Works

The author do realize that there are other studies involving with ADS-B data. One study that caught the author's interest was initiated by I Gede Suryadharma Susila, in which he focused on air traffic flow behavior over a specifc time (?, ?). In his research, he used a Raspberry Pi 3 Model B+, 1090MHz ADS-B antenna, and other supporting hardwares in order to get ADS-B data. With the help of dump1090 stream parser, the received data was further filtered. With a collecting period of one month, he was able to receive 23 parameters (columns) and 89,338,383 of data (rows). However, a thermal problem was encountered on the Raspberry Pi and the RTL dongle during the data collection. Other problem was a lot of the data have empty values. Another study that caught the author's attention is by Yazfan Tabah Tahta Bagaskara, in which he focused on flight path reconstruction based on ADS-B data with Kalman filter (?, ?). In his research, the ADS-B data were received from opensky-network.org, a non-profit community-based receiver network. Initially, Bagas wanted to utilize Gede's data. However, the parameters that were needed is not complete such as NIC (ADS-B quality indicator), which indicates the error of the position information.

Overall, both research involves ADS-B data. If recalled, the current research's main objective is to acquire ADS-B quality indicator data, which previous similar works did not have. Compared with Gede's research, the author used Raspberry Pi 2 Model B, one generation lower than what he used (Table **??**). The difference between the two is that Gede's Raspberry Pi has a more advanced processor. Nonetheless, the performance of Raspberry Pi 2 Model B is still reliable based on the identical number of aircraft tracked daily (figure **??** and figure **??**). Another difference is that Gede placed the receiver components outside, exposing to outside environment. On the contrary, the current resesarch's author placed all of the receiver system inside his room (except antenna), where room temperature is almost constant. Thus, this helps with the thermal problem previously encountered by Gede, with the addition of a mini fan to further cool the temperature. The author was also able to receive more ADS-B parameters, a total of 43 where some of them are the ADS-B quality indicators (Table ??). In addition, of the 23 ADS-B paramters received from Gede's work, 16 of them are the same and present in the current work. A customized statistics was also accessable via FlightAware dashboard, where it tells the user about the number of aircraft tracked (daily), position sources, antenna's coverage graph, and number of positions and aircraft received per hour. The current author also uses an updated version of ADS-B decoder and parser. Compared with Bagas' research, the major difference is here the author does not use a dummy quality indicator for NIC because the actual ADS-B quality indicator was received real-time.

The strength in Gede's work is he was able to analyze in depths the behavior of air traffic by Flight Level as well as its longitue and latitude. His paper could act as a prototype study for those who wishes to study air traffic density with similar approach. The only weakness of Gede's work is that his data have a lot of empty values, with only 17.42% that has altitude, longitude, and altitude. According to Gede, the cause of that could be the dump1090 stream parser as to why the information is not filled 100%. To those who wishes to use a similar approach, he recommends to use a better receiver hardware as well as a better parser. Not only that, he also recommends a hardware that has good durability. Compared with the current research, the current author was able to use an improved decoder and parser (Table ??). However, the current author was unable to use a better version of Raspberry Pi and the data collection period is roughly the same. Durability problem was also encountered byt the current author as the Raspberry Pi would sometimes freeze on its own.

Category	**Current Work**	**Previous Work 1**
Duration of Data	Five weeks	1 month
ADS-B Parameters	43	23
Quality Indicators	Yes	None
Source of Data	OpenSky Network Kit	OpenSky Network Kit
Decoder	PiAware dump1090	dump1090 stream parser
Parser	In-house "aircraft.JSON" parser	dump1090 stream parser

Table 2.26: Research comparison (?, ?)

Category	**Raspberry Pi 2 Model B**	**Raspberry Pi 3 Model B+**
Processor	Cortex-A7 quad-core ARM @ 900MHz	Cortex-A53(ARMv8) 64-bit SoC @ 1.4GHz
Memory	1GB RAM	1GB LPDDR2 SDRAM
Ethernet	Yes	Yes
GPIO	40-pin	40-pin
HDMI Port	Yes	Yes
CSI	Yes	Yes
DSI	Yes	Yes
MicroSD slot	Yes	Yes
Graphics Core	VideoCore IV 3D	1080P30 Encode/Decode
USB Port	4	4

Table 2.27: Raspberry Pi specification comparison

CHAPTER 3
RESEARCH METHODOLOGY

In conducting this research, the author has to go through several processes to achieve the objectives. Research methodology describes the process by which to formulate the problems and objectives; thus, data can be obtained for analysis. Moreover, research methodology emphasizes the research strategy as well as determining the data sources. For this thesis, the methodology consists of several aspects.

3.1 Problem Statement

Where there is technology, a standard is also in place. The RTCA committee has published minimum operational performance standards for ADS-B called DO-260, DO-260A, and DO-260B. Inside those standards are the quality indicators, which are, philosophically, telling the integrity and accuracy of the data being sent. Air traffic is still active even during the pandemic. Initially, the author wanted to see if the air traffic within the Indonesian airspace had already complied with the FAA minimum performance values. However, there was a lack of statistical data analysis of ADS-B quality indicators in Indonesia. Additionally, DO-260B is the preferred standard, yet the percentage of which ADS-B version mostly used is still unknown.

3.2 Literature Study

Before diving deep into the technical aspect of this research, fundamental knowledge is needed. A thorough study of ADS-B is important such as how it works, its types and architecture, and why it is needed in the first place. Next, the author learned about the standards and how it was made, what teams are involved, reasons why it was made, and ASTERIX documentation for data transfer between ground stations and ATC. After that, the author analyzed the differences between ADS-B minimum operational performance standards published by RTCA. Here, the author inspects key points, namely the ADS-B quality indicators capabilities and purpose from each standard version, the new addition of ADS-B quality indicators, and other capabilities offered aside from ADS-B quality indicators. Then, from the airborne section point of view, determining what modifications needed to be done to an aircraft to comply with the latest standard. Finally, the author studied the ADS-B adoption in Indonesia, divided into two perspectives, regulations and the infrastructure. For the regulation studies, it was worth knowing the timeline of ADS-B regulations in Indonesia. From very general to very specific rules of ADS-B implementations. Additionally, the author studied the regualtion published by the FAA regarding the airworthiness approval of ADS-B. For infrastructure studies, the author researched the Indonesian airspace's size and its daily air traffic movement. Also, knowing how much ADS-B ground stations are available and its location across Indonesia. The author also realizes the collaboration between BPPT and INTI in creating locally-made ADS-B ground station codenamed AGS-216. Lastly, the author compared to previous similar works by Gede and Bagas, taking into account the results achieved by them and what can be improved.

Diving into a more technical area, the author realized software and hardware are involved. Raspberry Pi 2 Model B is one of the hardware that was used in this research. Thus, a thorough study of what and how a Raspberry Pi works was a must. Not only that, but the software needed to be installed in Raspberry Pi was also studied, called Raspberry Pi OS. The installation guide for this was available on the Raspberry Pis official website. Furthermore, FlightAware was also involved because of its open-source software (PiAware) for tracking and dumping aircraft data. Thereby, the author reviewed all the features FlightAware gave to its users was essential to optimize data collection further.

3.3 Computational Tool

3.3.1 Python

Python was a programming language used in various applications due to its flexibility. It can conduct from simple to complex functions, considered highly interactive, and able to give programmers “opinions” on syntax errors. This programming language has been widely used worldwide, such as OS developers, data scientists, and financial firms. The community for Python is still active; thus, updates or troubleshooting was very possible. Python was used in this research to help ease the process of acquiring data as well as creating basic statistical graphs.

3.3.2 Matplotlib

Matplotlib as one of Pythons library used to create good quality data visualizations. This library is useful in academic writing or presentations due to its flexibility in manipulating data instantly. Matplotlib can be used to plot 2D and 3D plots in many formats (?, ?). Because of its flexibility, many scientists used this to visualize their data.

3.3.3 Pandas

Pandas was another useful Python's package that the author relied on the most when doing the research. It is also an open source package that used for it capability in data analysis/manipulation tool. It provided a fast, flexible, and expressive data structures that are designed to be easy and intuitive for the users (?, ?). The usage of this package led to the ease of the author to process arrays with much degree of effectiveness, and with the conjunction of NumPy, the author gained more flexibility to manipulate the arrays with ease. The data that were processed with the help of this package became more intuitive and neat for the author to see, use, and process. In addition this package also gave the author some degree of ease to post-process the processed arrays.

3.4 Data Collection

The process of collecting and analyzing data for research is called data collection. In this phase, a researcher can call back his or her hypothesis, combined with the collected data. It is also considered the most critical process of research. A researcher has to make sure that the data collected is reliable in order for decisions to be made. There are various ways of collecting data, such as questionnaires, interviews, reports, existing data, observation, focus groups, and combination research.

This thesis will use a low cost Raspberry-Pi ADS-B receiver system to collect quality indicator data for only five weeks. The low-cost OpenSky Network Kit Raspberry-Pi ADS-B receiver is a state-of-the-art, easy to install, receiver system. This receiver will be installed at the authors home (**6° 21' 21.204" S, 106° 43' 10.776" E**) and collect data from November 9, 2020 until December 13, 2020. While the receiver is collecting data, the author will investigate for the value of the quality indicators, specifically (NUCp) for ADS-B Version 0, Navigation Integrity

Category (NIC) for ADS-B Version 1 and 2, Surveillance/Source Integrity Level (SIL) for ADS-B Version 1 and 2, Navigation Accuracy Category Position (NACp) for ADS-B Version 1 and 2. Once the raw data is achieved, the author will inspect the data and remove any duplicates. Assuming that there will be plenty of data to be analyzed, the author has to define what data is determined as valid or not. Only until then, the author will continue to analyze the data statistically and give a picture of the latest air traffic status as well as the quality of those ADS-B messages.

3.4.1 Raspberry Pi

The Raspberry Pi, a compact single-board computer about an average phone size, was initially designed to motivate young people to code (?, ?). Created by the Raspberry Pi Foundation in the United Kingdom, the device has similar capabilities as a computer. It can browse, play videos, programming, and even play games. Communities have been and still is, creating their project ranging from robotics to even a mousetrap.

There are several Raspberry Pi generations available today. The first generation is called Raspberry Pi and has four published models:

1. Model B (launched in 2012)
2. Model A (launched in 2013)
3. Model B+ (launched 2014)
4. Model A+ (launched 2014)

As time passes by, each model received improvements such as ethernet capability and upgraded GPIO. The first model (Model B) had a RAM of 256 megabytes and a 700 megahertz quad-core. The next family of Raspberry Pi is called Raspberry Pi 2. In this generation, there is only one model launched in 2015, and that is Model B. It has a 900 megahertz quad-core and 1 gigabyte worth of RAM. After that comes the Raspberry Pi Zero generation, launched in 2015 and 2017 with its two models, Model Zero and Model W/WH. Then comes the Raspberry Pi 3 family. Here it has three models launched in 2016 and 2018 named Model B, Model A+, and Model B+. Finally, the newest generation of raspberry computer is called Raspberry Pi 4. Launched in 2020, the Raspberry Pi 4 has one model, but with RAM choices such as two gigabytes, four gigabytes, and eight gigabytes.

Raspberry Pi 2 Model B

Model B belongs to the Raspberry Pi 2 family. This model was meant to replace the Raspberry Pi Model B+. From a similarity point of view, it has the same size and shape, same four mounting holes position, same USB, Ethernet, A/V, HDMI, microSD and microUSB slot position, and same camera, display, GPIO slot position. Thus, cases for Raspberry Pi Model B+ should work for Raspberry Pi 2 Model B. Contrarily, the major difference is that it includes a quad-core ARM Cortex-A7 processor and one gigabyte of RAM. With this processor type, performance is expected to be better than its previous Raspberry Pi generation. Because the processor is improved, it needs a higher power draw. The Model B in idle draws 200 milliamps. During heavy processing tasks, it will draw at least 650 milliamps at 5 voltage. Full features of Raspberry Pi 2 Model B include the following:

- 900 MHz quad-core ARM Cortex-A7 CPU
- 1 GB RAM
- VideoCore IV 3D graphics core
- 100 Base Ethernet
- Four USB ports

- Full-size HDMI output
- Four-pole 3.5 mm jack with audio output and composite video output
- 40-pin GPIO header
- Camera interface
- Display interface
- MicroSD card slot

3.4.2 Raspberry Pi OS

The Raspberry Pi OS is a free software operating system used for Raspberry Pi hardware (?, ?). In previous years, the name Raspbian was correlated with the Raspbian core and its 32-bit characteristic. Ever since the 64-bit version came out, it does not use the Raspbian core anymore. Thus, it changed the name to Raspberry Pi OS in support of both 64-bit and 32-bit versions. Mike Thompson and Peter Green created this software. The Raspberry Pi OS comes with more than 35,000 packages and easy-install software for Raspberry Pi computers. The software itself is based on Debian, an open-source Linux-based operating system created by a group of people. Debian could run on almost all types of computers.

3.4.3 PiAware

PiAware is an open-source software created by FlightAware, a digital aviation company that focuses on flight tracking and data collecting (?, ?). This software enables any user with the right hardware and programming skills to transmit ADS-B and Mode-S data to FlightAware. When an aircraft is being tracked, the signals sent will be received and displayed on FlightAware's map interface to view its parameters such as speed, heading, aircraft identification, and altitude on a local network.

Note that this software is for those who already possess Raspberry Pi and an ADS-B receiver.

3.4.4 Setting Up the Receiver

The low-cost OpenSky Network Kit and Raspberry-Pi ADS-B receiver system came with several devices. The following are the hardware that contributed to the data collection:

1. Raspberry Pi 2 Model B
2. Raspberry Pi case
3. Raspberry Pi power supply
4. 64GB MicroSD Card
5. A WiFi dongle
6. USB extension with slots
7. A Mouse
8. A Keyboard
9. An HDMI cable
10. Display interface
11. 1090 MHz professional A3-ADS-B antenna
12. Antenna mounting brackets
13. RTL-SDR RTL2832U R820T2 TCXO radio receiver dongle
14. 15 m low loss coax cable

15. A mini fan

16. A phone with internet package

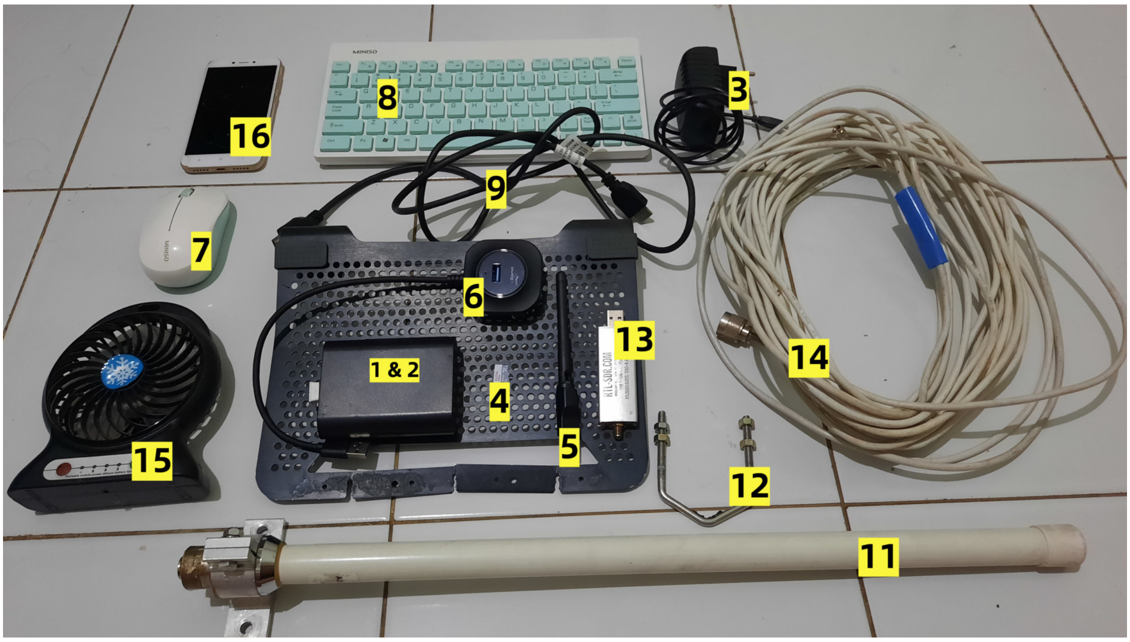

FIGURE 3.1: Hardwares involved in data collection

FIGURE 3.2: Display monitor and set up

Assembling the receiver system must be in a careful manner. The following are steps the author took in setting up the receiver system:

1. Gathered all the necessary tools and items such as a scissor, cutter, zip ties, ladder, double tape, $\frac{1}{2}$ inch pipe clamps, gypsum nails, double-foam tape, hammer, and an unused broomstick.

2. Surveyed the top of the observation room and determined the hole for the cable and made the hole.

3. Set the ladder into the right position and climbed up to the roof, bringing all the necessary tools and items. A local craftsman was also helped with the process.

4. Carefully walked towards the highest part of the roof.

5. Determined the optimal location to install the used broomstick as the foundation for the 1090 MHz A3-ADS-B antenna.

6. Carefully held the used broomstick in position while the local craftsman hammered the $\frac{1}{2}$ inch pipe clamps into place.

7. Checked the broomstick is sturdy and balanced.

8. Cut the double foam tape and placed it on the base of the antenna. This was also done for the top of the broomstick.

9. Positioned the antenna near the top of the broomstick and enclosed it with the steel bracket. Tightened the bracket with four nuts.

10. Used zip ties to add extra strength and minimize wobbliness.

11. Opened Google Map to retrieve coordinates of the house for parameter input.

12. Used a tape measure to estimate the height from the base of the antenna to the base of the roof.

13. Connected the N-male part of the cable to the antenna.

14. Added double-tape around the N-male to prevent water diffusion from rain so it is secure.

15. Searched the right roof tile to slide for the cable to go in. Local craftsman helped with this process.

16. Inserted the other end of the cable and slid back the once-moved roof tile.

17. Double-checked everything is tight and secure before coming down the ladder.

18. Used a tape measure to estimate the rest of the height, which was from the base of the roof to the ground.

19. Pulled the end of the cable through the pre-made hole very slowly until the comfortable length is achieved.

20. Plugged in the WiFi dongle, USB extender with slots, USB Bluetooth for keyboard and mouse, HDMI cable, and power supply to the Raspberry Pi.

There are several ways to install Raspberry Pi OS, and one of them is by using an operating system installation manager called NOOBS. For installing Raspberry Pi OS, it is recommended to download straight from the Raspberry Pi official website. There, under the tab “Downloads,” several options are available. It is recommended that beginners choose “NOOBS,” an easy operating system installer. Inside NOOBS contained the Raspberry Pi operating system and LibreELEC. Not only that, but it also provided another alternative operating system that can be downloaded from the internet. The offline and network install NOOBS file size was about two gigabytes. After completing the download, it was essential to format the MicroSD card before extracting the NOOBS files. Once formatting was done, remove the files from NOOBS, copy the files, and paste them onto the MicroSD card that was once formatted. Then, once the pasting process is done, it was safe to eject the MicroSD card and insert it into the Raspberry Pi computer board. Next, the Raspberry Pi computer board is powered up, and a choice will be displayed. In this step, click the checkbox for Raspbian, then proceed to install. It took some time during this installation process.

Before installing PiAware, Raspberry Pi OS must be installed. It is recommended to install PiAware straight from their official website. On the FlightAware website, the installation was under the “ADS-B” tab, then the “PiAware” tab. Next was executing the following commands in the terminal:

wget `https://flightaware.com/adsb/piaware/files/packages/pool/piaware/p/piaware-support/piaware-repository_4.0_all.deb`

```
sudo dpkg -i piaware-repository_4.0_all.deb
```

Next, the following command line will execute the download and installation of PiAware, as well as the required attributes for the Raspberry Pi:

```
sudo apt-get update
sudo apt-get install piaware
```

After that, to enable automatic PiAware updates, execute the following commands. Although these are optional and disabled by default:

```
sudo piaware-config allow-auto-updates yes
sudo piaware-config allow-manual-updates yes
```

Then, to install an ADS-B receiver software dump1090, execute the following commands:

```
sudo apt-get install dump1090-fa
```

Finally, once that installation is complete, it is safe to reboot the Raspberry Pi with the following command:

```
sudo reboot
```

FlightAware offered a special benefit to those who are willing to become a feeder for them. A feeder, in this case, means that someone is helping to add coverage and actively receiving ADS-B data from their local area. There are many benefits to becoming a feeder; among them is FlightAwares Enterprise Account, which included unlimited flight alerts, registration or tail numbers, full-screen maps without ads, multilateration results, and others. One of FlightAwares features was being able to see a flights details. An example is a Citilink flight from Ujung Pandang to Jakarta with flight number QG7343. A user can replay the flight and see the flight profile, which is the altitude versus speed graph in feet and miles per hour, respectively. From the graph, the user is able to see the correlation between altitude and the aircrafts speed at a certain phase of flight. The user could also see the aircrafts past flights that include the date, its departure origin, destination, aircraft, and duration of each flight.

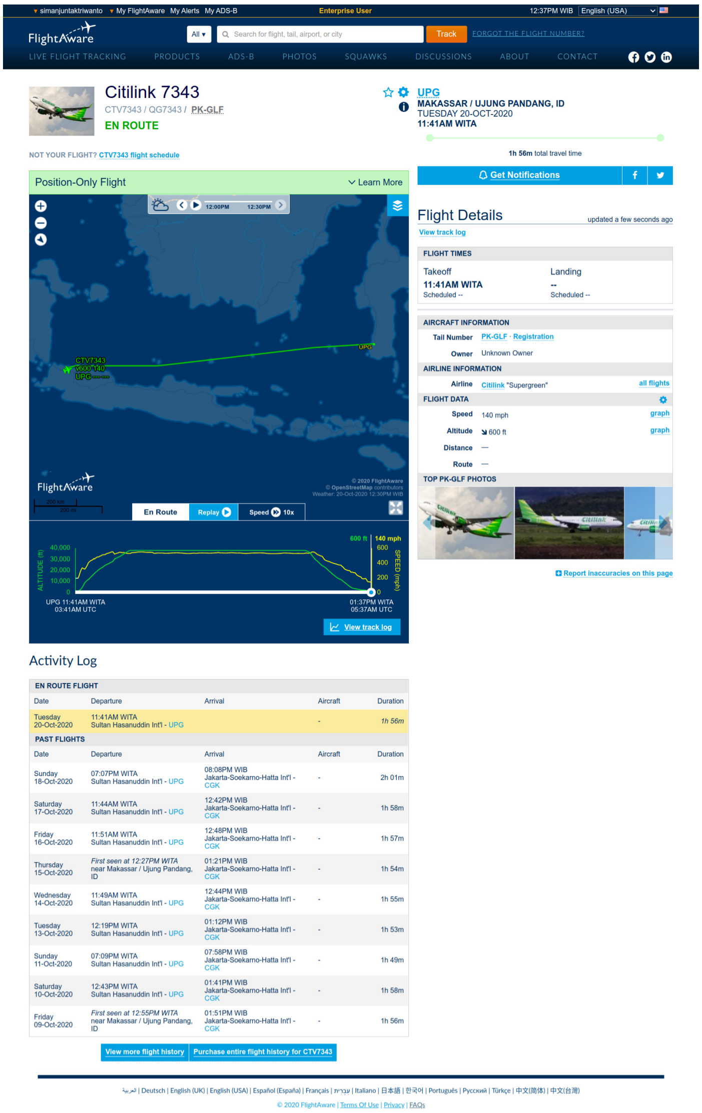

FIGURE 3.3: Flight profile

The author directed his attention to the FlightAware user dashboard, which can be accessed by logging in the account details. The author focused on the gray gear icon in the user dashboard, which lead to site configuration. In site configuration, there are many selections suchlike setting the site name, precision on the coverage map, outage emails, nearest airport, receiver location, PiAware software auto-update option, Mode-S Multilateration option, antenna coordinates and height, device commands, and the receiver log. Firstly, the author set the site name and selects the precision on the coverage map to 'exact.' After that, the author set the outage emails to 'notify after 12-hour outage' and the nearest airport to Pondok Cabe (IATA: PCB, ICAO: WIHP). Next was setting the PiAware auto-update to 'allow' and Mode S Multilateration to 'MLAT enabled.' Lastly, the author set the receiver location and height. Here, the author selected 'manually enter location' and inputs the receivers longitude and latitude recorded during the installation phase on the roof, which was -6.35589, 106.71966. The author also set the antennas height above ground level, which was estimated around six meters.

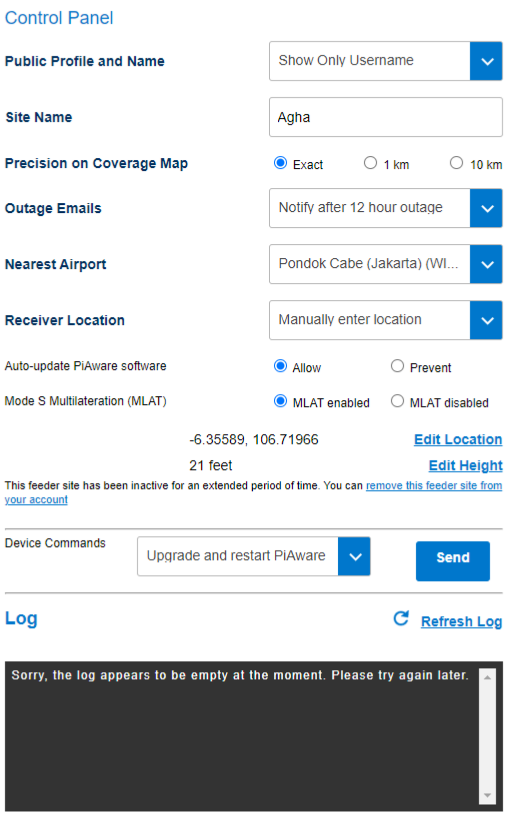

FIGURE 3.4: Site configuration

Other various information s also available on the user dashboard. Starting with a graph consisting of aircraft reported combined from the authors site and all sites.

In this graph, the author can see any differences in the number of tracked aircraft from the authors site versus all other sites daily. Next came the coverage graph comprised of the antennas 360-degree coverage. In the graph, it ias divided into cardinal, ordinal, and secondary intercardinal directions. It is further divided into its range, starting from <50 miles, then 50 to 100 miles, then 100 to 150 miles, then 150 to 200 miles. If a position is recorded, it filled up the area from light blue to dark blue. The darker the color, the more position is recorded in that specific range and direction. The coverage graph also had a sub-information in the form of a bar chart. There, it gave the author information of positions reported by distance from the receiver. Next is the hourly received reports composed of time of the day and date. Here, it gave the author information regarding the number of positions and aircraft reported at a specific time and date. Like the coverage graph, it filled up from light to dark blue squares. The darker the color, the more position, and aircraft reported. Lastly is the position reported table and graph, whereof the total positions reported, how much is from ADS-B Mode-S, MLAT, and others. From it, a graph was available to give visualization on a daily basis.

Afte the enterprise account is set up, the author headed over to SkyAware to see the display of captured traffic. Here the author was able to see a table on the right side of the map, showing a list of aircraft captured along with its parameters such as callsigns, squawk codes, altitude, speed, and ICAO 24-bit address. Also, the total aircraft captured is displayed as well as how many of them have position parameters. When an aircraft was selected (in this case BTK6375), details namely regarding the aircrafts location, speed, altitude, direction, navigation, tracking information, and accuracy came up.

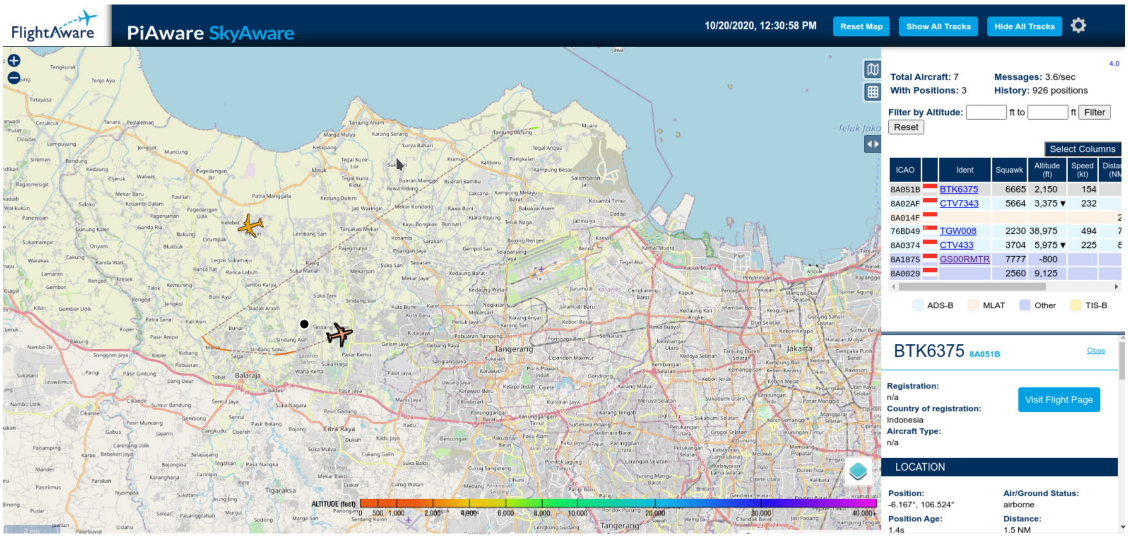

FIGURE 3.5: SkyAware display

For location, it stated the aircrafts position in longitude and latitude, the age of the reported position, air or ground status, and its distance. Next, the speed section stated the aircrafts groundspeed (knots), its indicated airspeed, true airspeed, and Mach number. After that, the altitude section described the aircrafts barometric altitude, barometric vertical rate, geometric altitude, and geometric vertical rate. Then, the direction section stated the aircrafts ground track, magnetic heading, true heading, track rate, and roll. Navigation section described the aircrafts selected altitude, its selected heading, modes, and its QNH. After that, the tracking information described the aircrafts source of information, its ADS-B version, aircraft category, squawk code, messages, RSSI, last seen, and last position in seconds. Lastly, the accuracy section had the ADS-B quality indicators. Those indicators include NACp, SIL, NACv, Rc, and NICbaro.

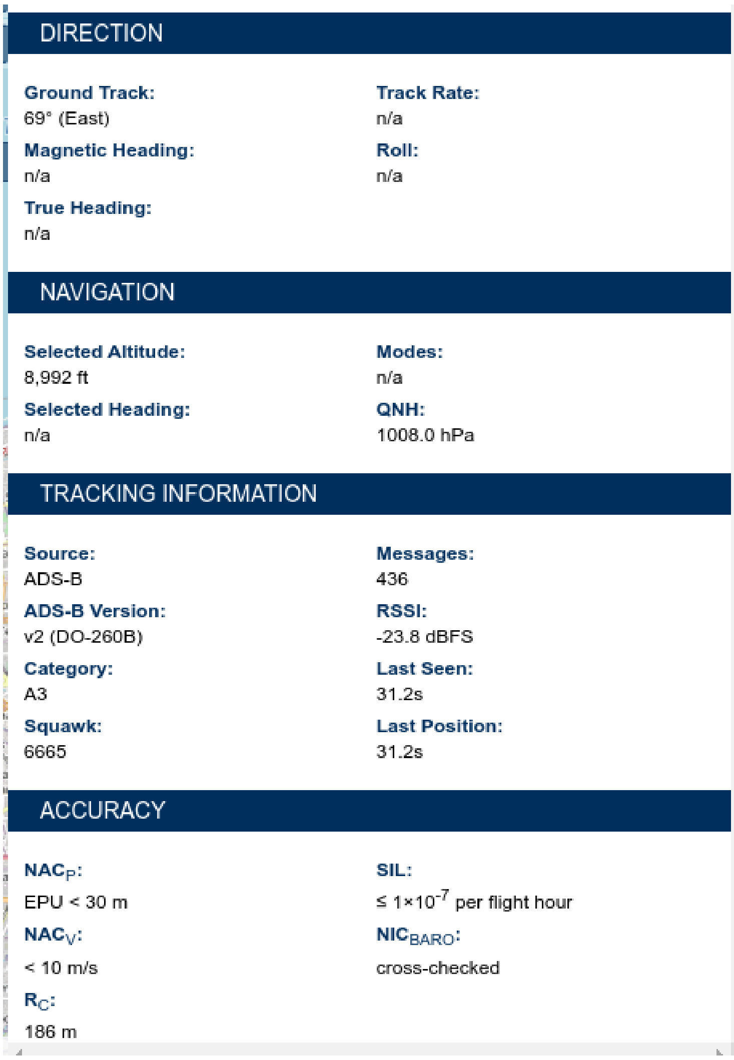

Figure 3.6: PiAware parameters

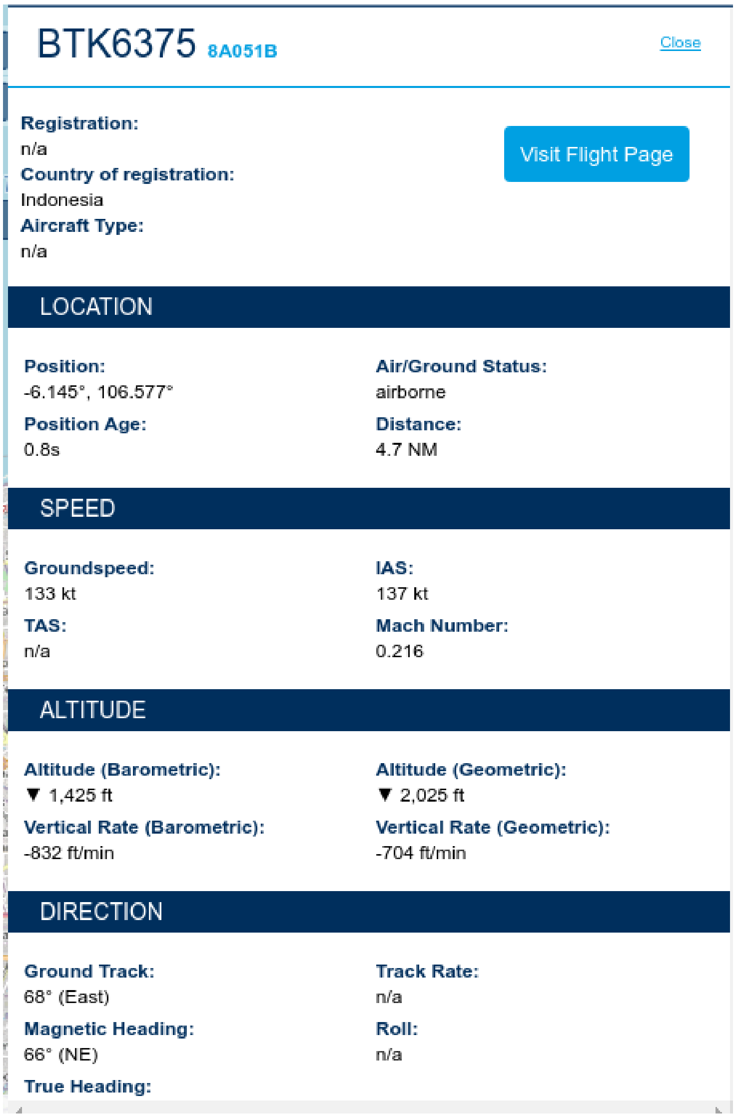

Figure 3.7: PiAware parameters

3.4.5 Data Acquisition

In this research, the author acquired the necessary in two ways, and that through the FlightAware user dashboard and a parser. From the FlightAware user dashboard, the author is able to get a customized statistics on the captured air traffic. Also, the receiver's status was also present. The author checked the customized statistics from the user's dashboard ever day, and move the data to Excel where it will be used later for analysis. A scheduler (parser) was made with Python to acqurie ADS-B quality indicators and ADS-B version. Mainly, this program was to ease the workload of the author and to keep the data organized. All data was backed-up to a cloud and another computer in the case of unwanted events.

Overall, the scheduler starts by opening the terminal and executing the following commands:

```
cd newadsb
python scheduler.py
```

Once the commands has been executed, it will start the dump1090 provided by FlightAware. Dump1090 is a program that can decode ADS-B data and sends the data to the FlightAware server via an encrypted channel. Next, it will create a directory in "newadsb" with a name already predetermined along with a time stamp. After that, it will fetch "aircraft.JSON" from PiAware and store it in the latest directory inside "newadsb" with a new name and time stamp. Before the program fetches a new data from "aircraft.JSON" and stores it in "newadsb," it will wait for five seconds before it fetches new data again. Along the process, it will also check if the program is still running. Otherwise, it will end the program only if the author closes the terminal, a power outage, or any other kind of event that disrupts the program.

3.5 File Clean Up

With the scheduler running, the author tried to achieve an uptime of 100%. However, this was rather difficult to achieve because there are factors that affected the program, thus results in the termination of the program itself. These factors came in the form of power outages, unresponsive Raspberry Pi system, connection anomalies, and no reports being received. When one of those events occurs, the

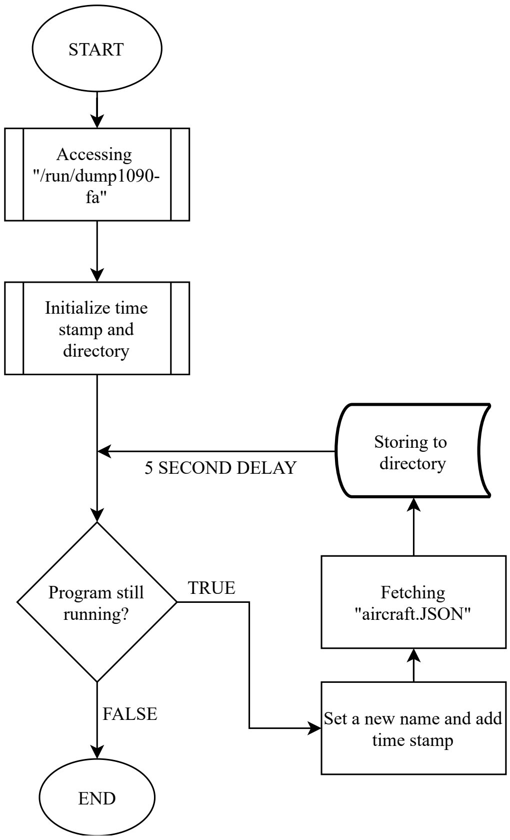

FIGURE 3.8: Flow of scheduler

author waited for an addition of two minutes before unplugging the power supply and plugging it back in. Be that as it may, the author does learn that with only one gigabyte of RAM available in the Raspberry Pi 2 Model B, only one program could run, and that was the scheduler. This was to avoid unwanted occurrences such as an unresponsive system, which leads to restarting the Raspberry Pi. Also, the author backs up the data to multiple media for redundancy.

In general, after the five week worth of collecting raw data, it went through a parsing process and eventually getting the desired ADS-B quality indicator data. After that, it was analyzed statistically with Python. The author emphasizes that FlightAware does not provide such parsing software to its enterprise users for the data that has been acquired. Thus, codes were created to parse those data.

First, all the folders taken from one of the backup media are listed. Because it was already set as a JSON file from the scheduler program, it listed all of them and removed empty files. Sometimes during data collection, empty JSON files appeared because there are no aircraft captured by the antenna. This phenomena happened mostly during midnight, and thus, a file is still fetched but with zero kilobytes of information, hence, an empty file. Next, it the author used Pythons JSON module to load the file. After that, it parsed and normalized the JSON file with Pandas and eventually saving it to data. Until here, it checked and see if there are anymore JSON file that needs to be parsed and normalized. It kept doing this until Pandas have organized all the files before moving on to the next process. Assuming all the files have been parsed and normalized, raw duplicates were removed and the data frame was ready to be exported as CSV for further analysis.

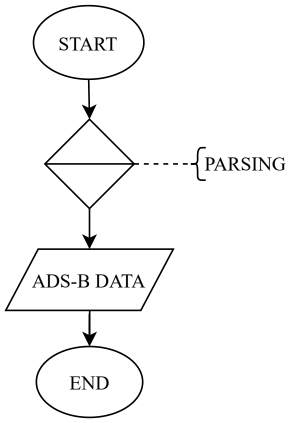

FIGURE 3.9: Acquiring ADS-B data

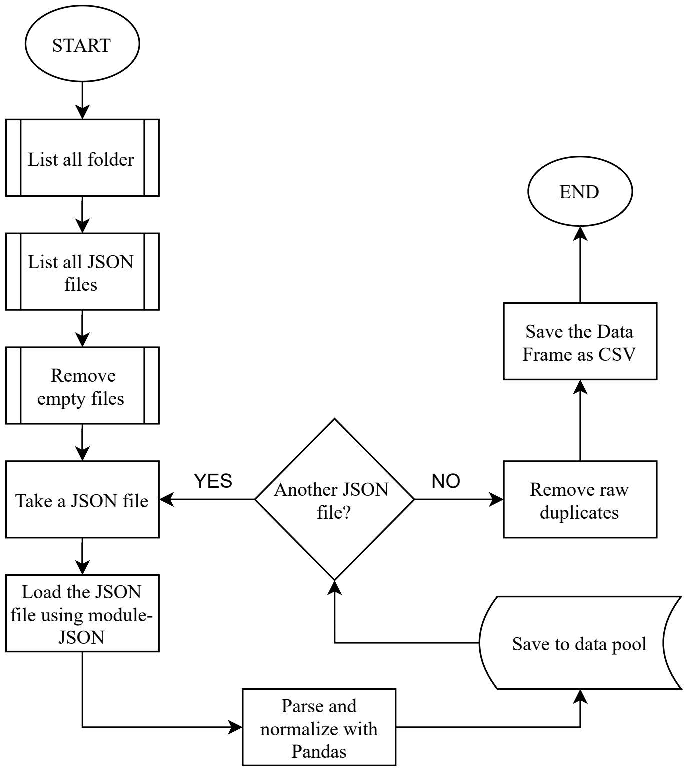

Figure 3.10: Parsing aircraft JSON files

CHAPTER 4
RESULTS AND DISCUSSIONS

4.1 Overview of Data Collection

The process of data collection initiated on Monday November 9, 2020 at 00:00 A.M. local time and ends on Sunday December 13, 2020 at 11:59 P.M. local time. Ideally, the total duration for this data collecting phase should be three to six months with hopes of achieving 99.9% uptime. However, since time is limited, it ws only for five weeks. There were some occurances that affected the data collection process. Thus, offline statuses occured on November 9, 2020 at the hours between 2:00 and 7:00 local time and November 11, 2020 between 3:00 and 6:00, and between 10:00 and 12:00 local time. Offline status also happened on November 19, 2020 between 5:00 and 6:00, and between 7:00 and 8:00. On November 22, 2020, it occured between 3:00 and 4:00, and between 6:00 and 8:00 on November 25, 2020. Lastly, it also accoured on December 2, 2020 between 8:00 and 9:00, and between 8:00 and 9:00 on December 5, 2020 local time. As a result, by calculating the total downtime within five weeks:

$$DP = \frac{n}{m} \cdot 100 \tag{4.1}$$

where,

- n is the total downtime in hours
- m is the total monitored time hours

Thus, the total downtime received is:

$$\Rightarrow DP = \frac{17}{839} \cdot 100 \Rightarrow 2.026\% \approx 2.03\% \tag{4.2}$$

With 2.03% as the downtime, the actual uptime percentage is as follows:

$$UP = 100\% - DP \tag{4.3}$$

where,

- DP is the downtime percentage

Thus, the actual uptime achieved is:

$$\Rightarrow UP = 100\% - 2.03\% \Rightarrow = \mathbf{97.97\%} \tag{4.4}$$

4.1.1 Description of the Collected Data

During the parsing process the total files that were processed is 568,374 files with three empty files. Thus, the actual parsed files are 568,371 files. After the whole process of parsing was done, the author received the raw version in a CSV format. From the raw version, the total raw data is 3,242,130 rows with a file size of 622 megabytes.

The table **??** is the result of the 568,371 files that has been parsed. Overall, it has a total of 43 parameters present. As previously mentioned, the total count of the data is 3,242,130 rows, which can assumed as 100%. There are only several parameters that are 100% in count and they are hex, mlat, tisb, messages, aseen, and rssi. However, there was also a paramater with he lowest count and that is true_heading, with only 33 counts out of 3,242,130 (.00108%).

Data	Count	Percentage	Uniqueness	Mean	Min	Max	Unit
hex	3,242,130	100%	1019	-	-	-	-
flight	1,661,949	51.26%	1642	-	-	-	-
alt_baro	2,168,486	66.88%	-	-	-	-	ft
alt_geom	1,861,052	57.40%	-	-	-975	125,400	ft
gs	2,060,810	65.56%	-	-	-	-	kt
track	2,060,810	65.56%	-	-	-	-	deg
geom_rate	1,664,385	51.33%	-	-	-	-	ft/min
squawk	1,624,554	50.11%	-	-	-	-	-
category	2,779,029	85.72%	8	-	-	-	-
nav_qnh	1,427,100	44.02%	-	-	-	-	hPa
nav_altitude_mcp	1,433,300	44.21%	-	-	-	-	-
lat	1,959,812	60.45%	-	-	-8.665187	-4.579285	DD
lon	1,959,812	60.45%	-	-	1.050007	1.081760	DD
nic	1,959,812	60.45%	-	7	0	10	-
rc	1,959,812	60.45%	-	-	0	3,704	m
seen_pos	1,959,812	60.45%	-	-	-	-	sec
ADS-B version	3,004,178	92.6%	-	-	-	-	-
nac_p	2,048,734	63.19%	-	8	0	10	-
nac_v	2,068,052	63.79%	3	0	0	2	-
sil	2,048,734	63.20%	4	0	0	2	-
sil_type	3,140,277	96.86%	3	-	-	-	-
mlat	3,242,130	100%	-	-	-	-	-
tisb	3,242,130	100%	-	-	-	-	-
messages	3,242,130	100%	-	-	-	-	-
seen	3,242,130	100%	-	-	-	-	sec
rssi	3,242,130	100%	-	-	-3.2	-0.9	dBFS
ias	1,222,089	37.69%	-	-	240	699	kt
tas	1,189,544	36.69%	-	-	520	668	kt
mach	1,221,224	37.67%	-	-	0.1	0.8	-
track_rate	1,093,511	33.73%	-	-	-	-	deg/sec
roll	1,178,860	36.36%	-	-	-	-	deg
mag_heading	1,225,840	37.81%	-	-	-	-	-

baro_rate	1,556,554	48.01%	-	-	-	-	ft/min
emergency	564,818	17.42%	2	-	-	-	-
nav_heading	348,422	10.75%	-	-	-	-	-
nic_baro	680,737	21%	2	-	-	-	-
gva	587,294	18.11%	3	2	0	2	-
sda	587,575	18.12%	-	2	0	3	-
nav_altitude_fms	86,662	2.67%	-	-	-	-	-
true_heading	33	.00108%	-	-	-	-	-

Table 4.1: Parameters of the collected raw data.

After that raw data has been received, the author further filters the data in order to do some statistical analysis. However, because there are so many data, a justification defining the rows as valid or not is needed. Thus, the author decided that a row is valid if it had the value 0, 1, or 3 for the column (parameter) ADS-B version. This is because the author aims to do a statistical analysis based on each ICAO ADS-B version (DO-260, DO-260A, and DO-260B).

4.2 Aircraft Reported

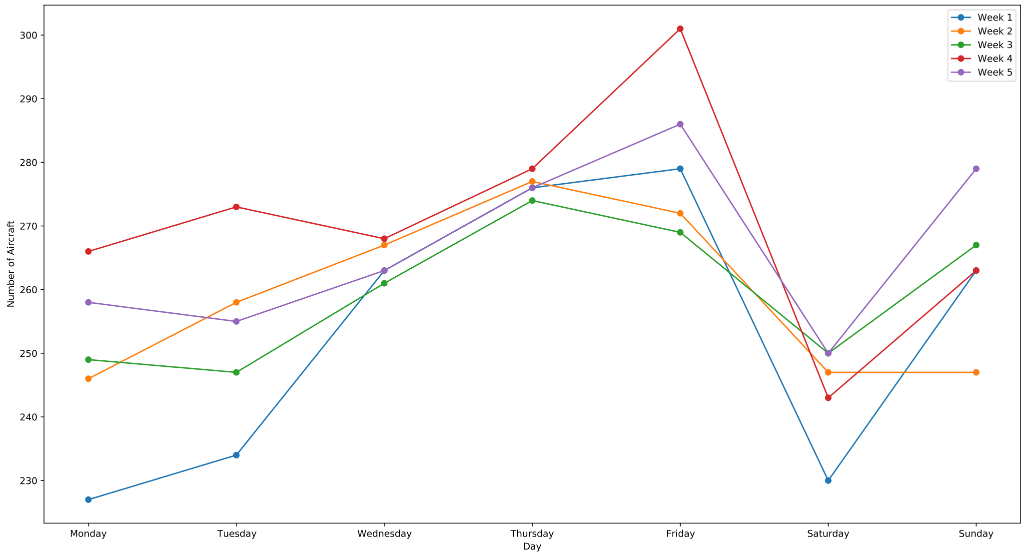

FIGURE 4.1: Total daily number of aircraft for all sites

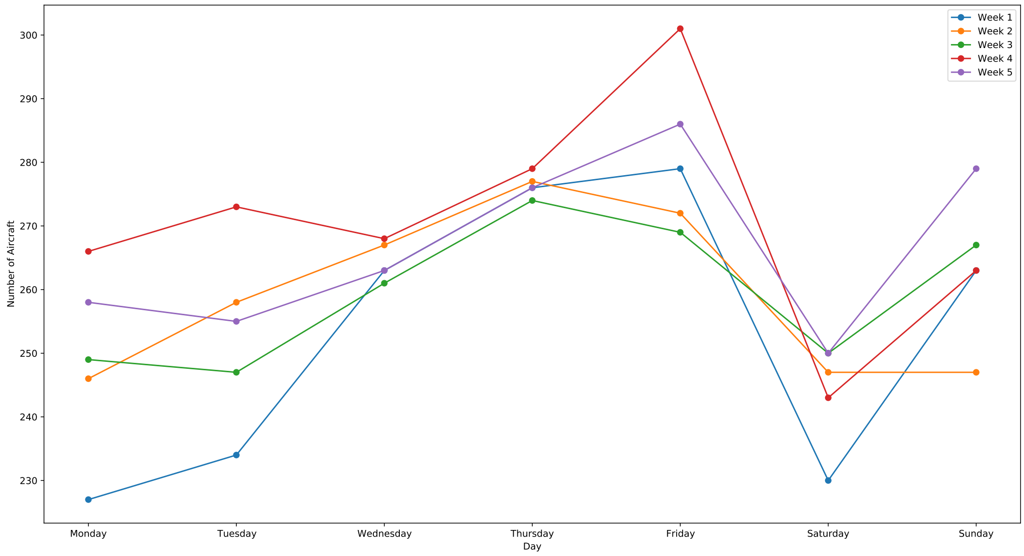

FIGURE 4.2: Total daily number of aircraft for author's site

The line graphs above illustrates the number of aircraft reported daily for all site and the author's site. For this case, all site (Fig. ??) refers to other users within the area that are also capturing aircraft positions. On the other hand, the author's site (Fig. ??) straightforwardly refers to the author himself. Since the data collection is five weeks in total, the data points are color coded in blue, orange, green, red, and purple in accordance to each week, respectively. It is worth noting that the values for both graphs are the same throughout the week. This indicates that the antenna are working properly just like the other sites within the area.

In figure ?? and ??, week one experienced a steady climb from Monday to Tuesday before rocketing upward on Wednesday. Then, it gradually climbs until Friday before taking a steep fall on Saturday. Lastly, it soars sharply on Sunday. Continuing to week two, the number of aircraft reported falls substantially until Tuesday before inreasing modestly upto Thursday. Then, it drops gradually on Friday and falls sharply on Saturday before leveling out on Sunday. Next, week three experienced a slight drop from Monday to Tuesday, then increasing steadily upto Thursday. After that, it drops slowly on Friday and plummets sharply on Saturday before climbing again on Sunday. On week four, the number of aircraft reported is close to 270 on Monday and increased ever so slightly on Tuesday. It then dropped downward on Wednesday before soaring substantially upto Friday. Then, it suddently sink on Thursday before climbing upward on Sunday. Lastly, week five started with almost 260 of aircraft reported and dipped slightly on Tuesday. Then, it climbed consistently until Friday before falling down on Saturday. Then, the number of aircraft reported soared upward on Sunday.

Conclusively, there are patterns that can bee seen on both graphs. The first one is that there is positive trend of increased number of aircraft reported from Monday to Thursday. Then, from Thursday to Friday only week one, four, and five experienced a gain in number of aircraft while week two and three experienced a drop. However, the author realizes that within all five weeks, the number of aircraft reported experienced a steep dive on every Saturday.

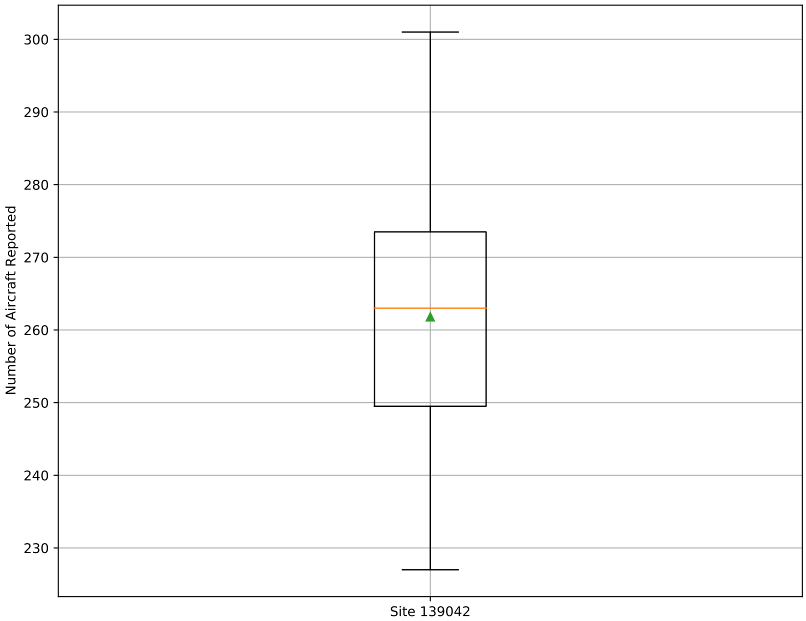

FIGURE 4.3: Box plot of daily reported aircraft

As for the box plot (Fig. ??), it represents the distribution of data, in this case, the number of aircraft reported daily. The 25th percentile of the data lies just below 250 aircraft, while the 75th percentile is just above 270 aircraft on a daily basis. As for the 50th percentile, or known as the median, is denoted as an orange line. The median is slightly below 265 aircraft. For the minimum number of aircraft reported daily, it is 227, whereas the maximum number of aircraft reported daily is 301. With an average number of aircraft captured daily about 262, the standard deviation of the data is 16.24.

4.3 Hourly Received Reports

In this section, there graphs illustrates the relationship between the number of detected aircraft or received positions with hour of the day. Starting from 00:00 until 23:00 local time (UTC+07:00), where data points corresponds to each hour. Also, the lines are color coded according to what day it is of the week.

Period	Hourly Received Reports
Week 1	234,354
Week 2	275,336
Week 3	213,340
Week 4	222,014
Week 5	217,856
Total	1162900

TABLE 4.2: The sum of received reports for eah week

4.3.1 Week One

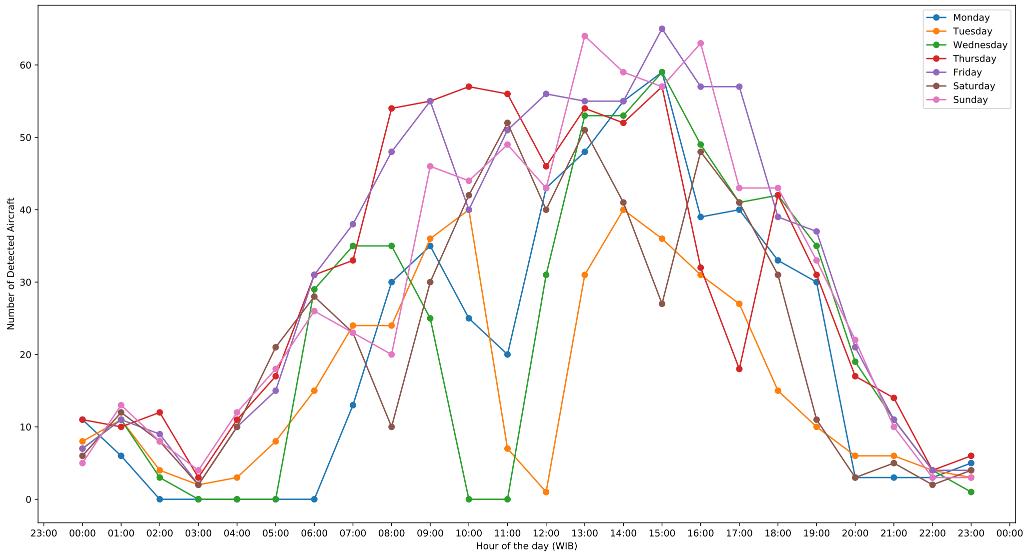

FIGURE 4.4: Number of detected aircraft per hour for week one

For figure ??, it represents the number of detected aircraft per hour. Overall, the authors realizes that the lowest point of air traffic happened around 3:00 in the morning, while the highest point of air traffic is between 13:00 and 16:00 in the afternoon for week one. At midnight, the number of aircraft detected is less than ten for Tuesday, Friday, Saturday, and Sunday. Except for Monday and Thursday, the number of aircraft reported is more than ten. From there, a positive slope occured from midnight to 01:00, except for Monday and Thursday where it experienced a decline in number of aircraft. Then, all days faced a significant drop from 01:00 to 03:00. For Monday and Wednesday, there are a few data values that are compeltely zero in number of aircraft due to offline status of the antenna. These happened between 02:00 and 06:00, and between 10:00 and 11:00 local time. Nonetheless, from 03:00 upto 11:00, there is an overall trend of increased number of air traffic substantially before dipping down at 12:00. After that, it rises moderately from 11:00 to 15:00 and 16:00 in the afternoon before plummeting down to almost completely zero air traffic at 22:00 and leveling out at 23:00 at night.

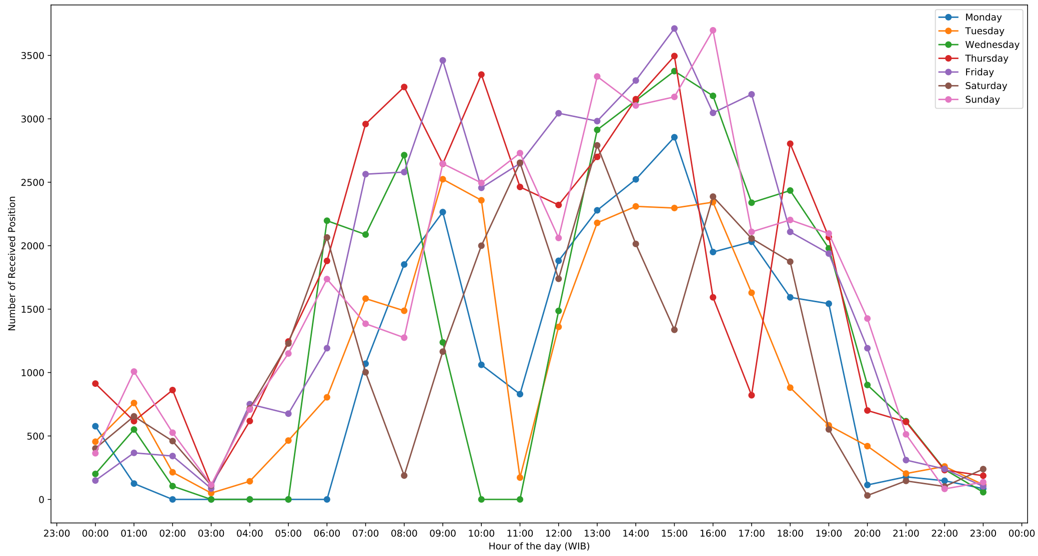

Figure 4.5: Number of received aircraft positions per hour for week one

As for figure ??, it represents the number of received positions from aircraft per hour. Overall, the lowest point of received positions is at 3:00, while the highest point of received positions is at 15:00 and 16:00 in the afteroon. At 00:00, the number of received positions started out less than 500 for Tuesday, Wednesday, Friday, Saturday, and Sunday. As for Monday and Thursday, it started out more than 500 of received positons. From there, all days experienced a significant drop at 3:00 in the morning. After that, the trend sky rocketed between 3:00 to 9:00 in the morning before dipping slightly around 11:00 and 12:00. There are soem data points where the values are zero within this week due to offline status, as previously mentioned before. From 12:00 to 16:00, position reports gained quite a lot before diving down to less than 500 reported positions at 23:00.

4.3.2 Week Two

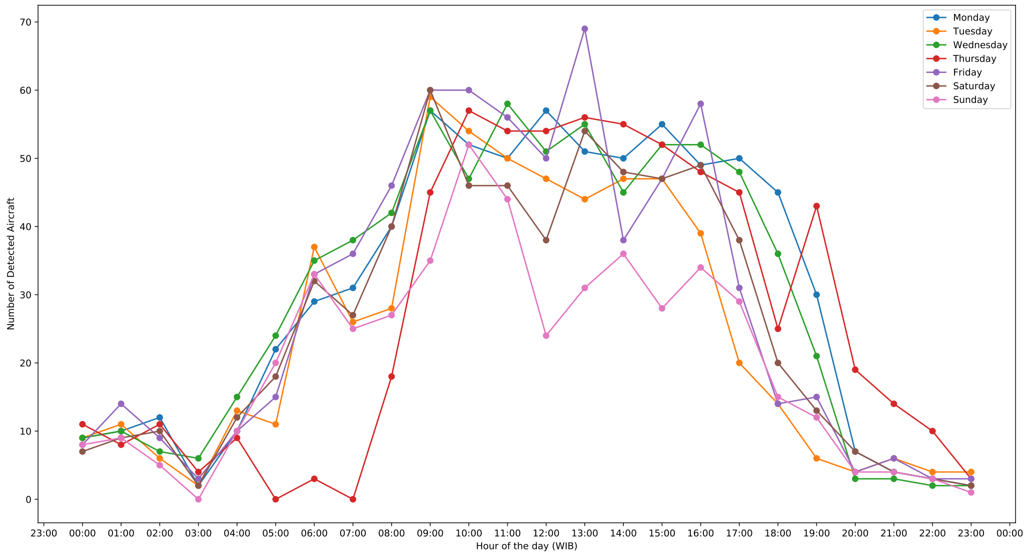

FIGURE 4.6: Number of detected aircraft per hour for week two

For figure **??**, it represents the number of detected aircraft per hour in week two. Overall, the lowest point of air traffic for week two lies at 3:00 on a Sunday, and highest point at 13:00 on a Friday. At midnight, the number of detected aircraft is less than ten for all days except Thursday. Then, from 00:00 to 02:00, it increases in number moderately before falling down at 03:00. After that, the number of detected aircraft for most days leaped upward until 09:00. However, for Thursday it experienced a few offline status before rocketing upward in number of detected aircraft. From 9:00 to 17:00, air traffic decreased gradually for all days except for Sunday, where it experinced a sudden drop 12:00 and fluctuates from 14:00 to 17:00. At 17:00 to 20:00, air traffic took a sharp dive and then leveling out until 23:00.

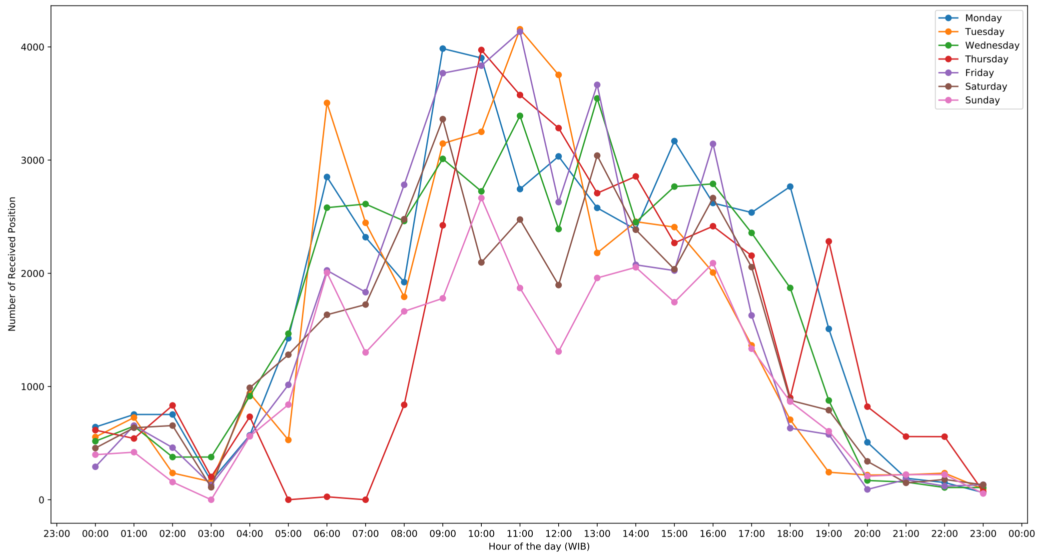

FIGURE 4.7: Number of received positions per hour for week two

With figure **??**, it represents the number of received positions per hour in week two. Overall, the lowest point of received positions is at 03:00 on a Sunday, and highest point at 11:00 on a Tuesday. At midnight, the number of received positions started out less than 1000 for all days. Then, from midnight to 02:00, Monday, Thursday, and Saturday increased slightly while Tuesday, Wednesday, Friday, and Sunday dropped. At 03:00, all days encountered a deep fall except Wednesday where it levels out. From 3:00 to 11:00, the number of received position and experienced an upward trend. However, as previously mentioned, Thursday experienced a few offline status before leaping dramatically. Then, from 11:00 to 20:00, position reports starts to fall significantly before leveling until 23:00.

4.3.3 Week Three

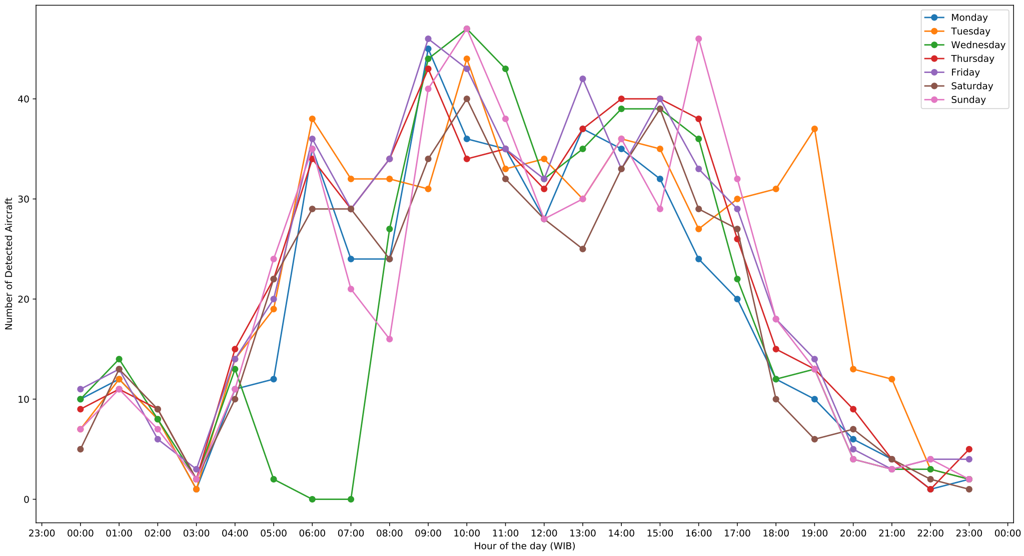

FIGURE 4.8: Number of detected aircraft per hour for week three

The following figure ?? represents the number of detected aircraft per hour in week three. Overall, the high points of air traffic lies 10:00 for Wednesday and Sunday, and 16:00 on a Sunday. At midnight, the number of detected aircraft is less than ten for all days except Friday. Then, from 00:00 to 01:00, air traffic increased quite a bit before plunging down to almost zero at 03:00. After that, air traffic rose dramatically upto 06:00 and then dipping down from 07:00 through 08:00. However, for Wednesday it experienced a few offline status before rising again at 08:00. From 08:00 to 15:00, air traffic fluctuated for all days before plummeting down to almost zero traffic at 22:00. Then, air traffic levels out until 23:00 for all days except Thursday, where it rises moderately. Overall, the air traffic in this week is much more uniform from 00:00 to 06:00 than previous weeks. The low points of air traffic lies at 03:00 for Monday and Tuesday, and 22:00 for Monday and Thursday.

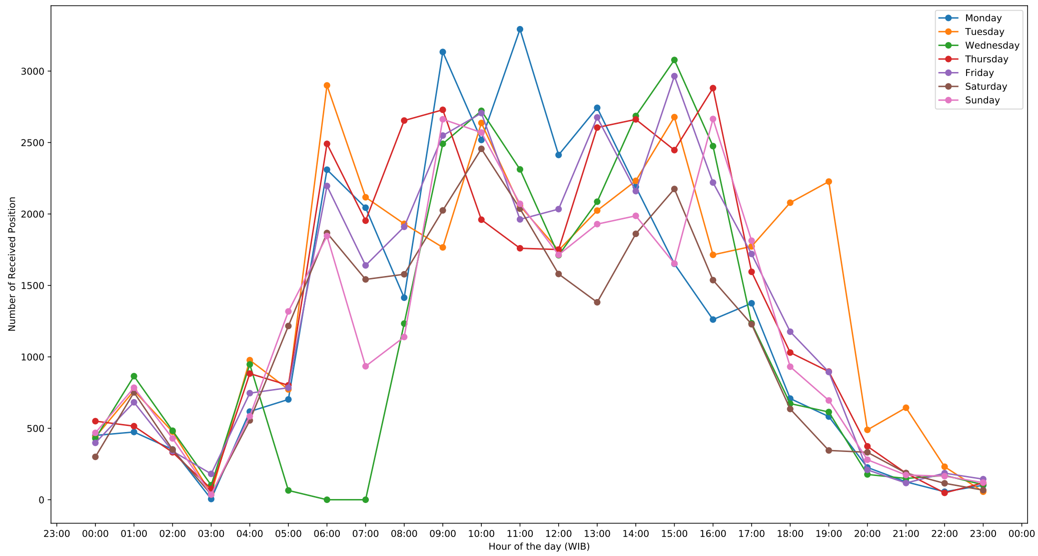

Figure 4.9: Number of received positions per hour for week three

As for figure **??**, it represents the number of received positions per hour in week three. Overall, it seems the lowest number of received poitions is at 03:00 on a Monday, whereas the highest is at 11:00 on a Monday also. At 00:00, the number of received positions started out less than 500 for all days except Thursday. Then, from midnight to 01:00, it rose significantly before falling down in numbers at 03:00. For Monday and Thursday, the numbers leveled out before droppin down at 03:00. After that, position reports leaped sharply, but fluctuactes as time passes by. Although, as previously mentioned, Wednesday experienced an offline status from 06:00 to 07:00. By 16:00 and 17:00, the number of received positions sunk dramaticaly and then leveling out until 23:00.

4.3.4 Week Four

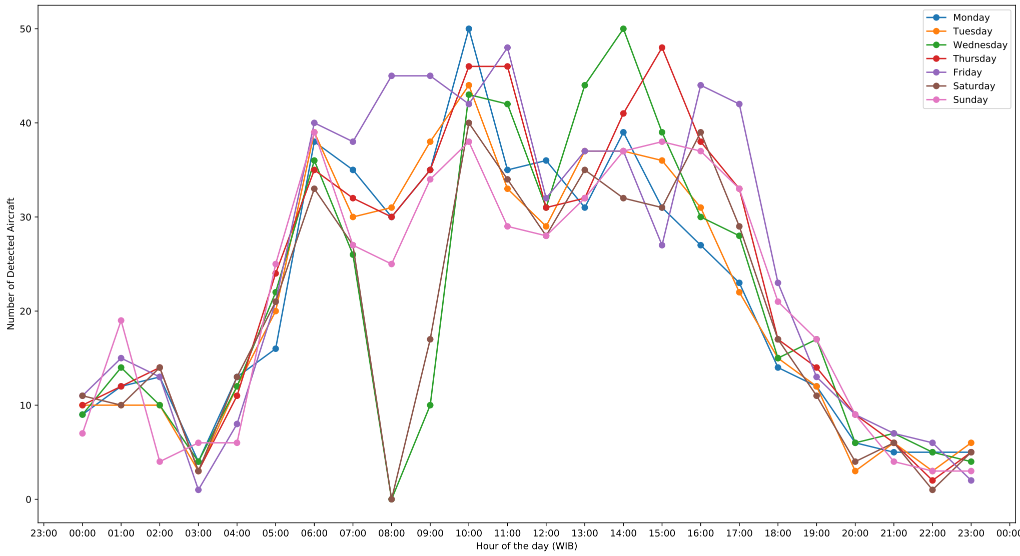

FIGURE 4.10: Number of detected aircraft per hour for week four

For figure ??, it represents the number of detected aircraft per hour in week four. Overall, the lowest points of air traffic falls at 03:00 and 22:00, Friday and Saturday, respectively. On the other hand, the highest points is at 10:00 on a Monday, and 14:00 on a Wednesday. At midnight, the number of deteted aircraft is around ten, and rose gradually upto 02:00 before sinking down at 03:00. Then, from 03:00 to 06:00, air traffic surged before fluctuating until 16:00. Do note that Wednesday and Saturday experienced an offline status between 07:00 and 08:00 before suddenly climbing in numbers of air traffic. After 16:00, all days experienced a slow slip back and then plummeted until 21:00, eventually leveling off up to 23:00.

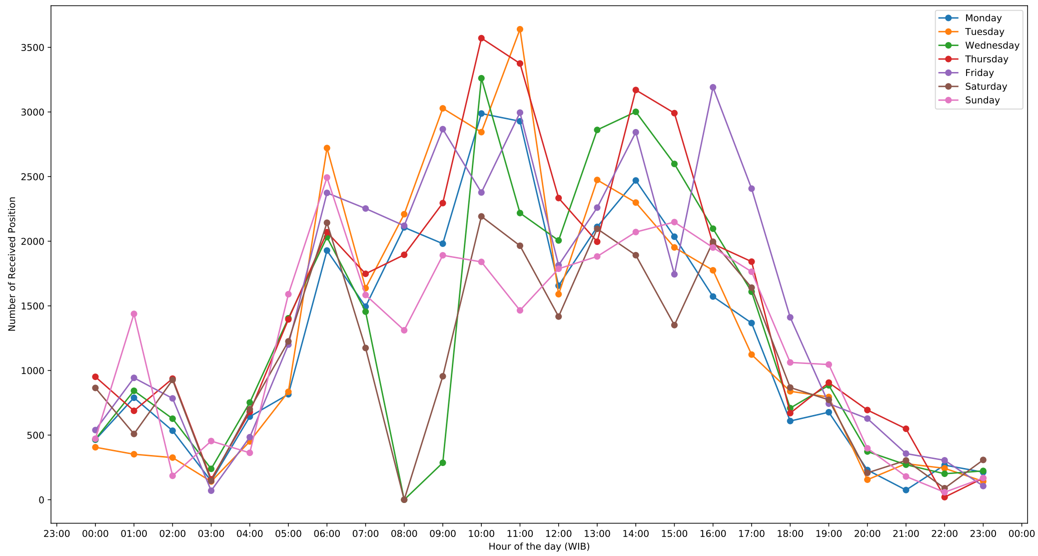

Figure 4.11: Number of received positions per hour for week four

Figure ?? represents the number of received positions per hour in week four. Overall, the lowest point of received positions is at 22:00 on a Thursday, followed by Friday at 3:00. On the contrary, the highest point of received position lies on a Tuesday at 11:00, followed by Thursday at 10:00. At midnight, the number of received positions varies. Some days starts below 500, and some above 500. However, all days experienced a drop at 03:00 except Sunday, where it rises in received position reports. Then, all days encountered a surge from 03:00 to 06:00 before fluctuating until 15:00. As previously mentioned, Wednesday and Saturday experienced an offline status between 07:00 and 08:00. Thus, the number of received positions is zero. From 15:00 to 21:00, position reports dropped significantly before leveling off until 23:00 at night.

4.3.5 Week Five

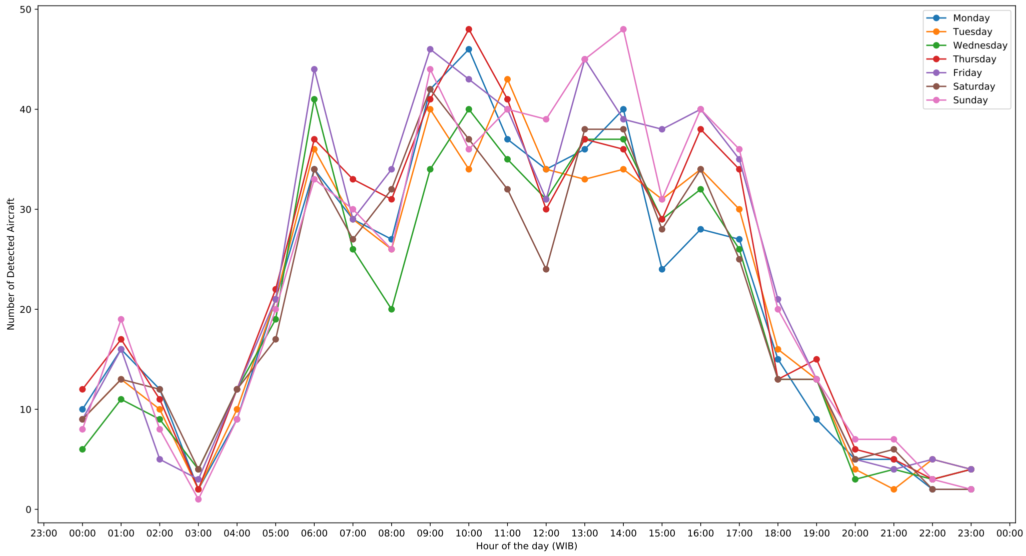

FIGURE 4.12: Number of detected aircraft per hour for week five

With figure **??**, it represents the number detected aircraft in week five. As can be seen on the graph, the lowest point of air traffic still lies 03:00 on a Sunday, followed by Tuesday at 21:00 and Saturday at 22:00. The highest number of detected aircraft is at 14:00 on a Sunday, followed by Thursday at 10:00. At midnight, several days started out below ten aircraft in air traffic, and some more than ten. However, all the days experienced a dive in air traffic at 03:00. After that, air traffic leaped until 06:00 before dropping moderately at 07:00 and 08:00. From then on, the number of aircraft for all days fluctuates until 16:00, where it then upto 20:00. Then, air traffic leveled off from 20:00 to 23:00.

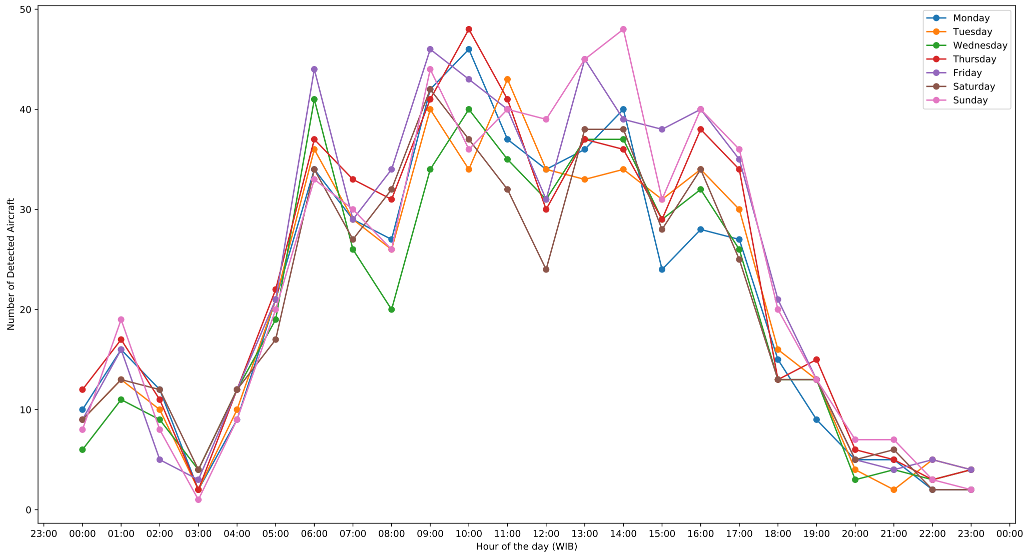

FIGURE 4.13: Number of received positions per hour for week five

As for figure ??, it illustrates the number of received positions per hour in week five. Overall, the lowest point lies at 03:00 on a Sunday and highest point at 13:00 on a Friday. At midnight, several days started out below 500 received positions such as Wednesday, Thursday, Friday, Saturday, and Sunday. For Monday and Tuesday, the number of received positions started out more than 500. However, at 03:00, position reports is very low for all days before soaring intul 06:00. After that, the data fluctuated from 06:00 until 16:00, where it then falls steeply upto 18:00. Then, for Wednesday, Thursday, and Saturday, the numbers climbed back up at 19:00 before dropping down again until 20:00. For the rest of the days, position report kept on decreasing until 20:00 before all of the days eventually leveled off untul 23:00.

4.4 Navigation Types Based on Positions Reported

From the total of five weeks of data collection, position reports were received. However, the source of these reports varies. The position reports would either come from ADS-B, MLAT, or other. Each week also has its own daily total of received position reports (Table **??**). Of the total positions received each week, the author divided the data results into two category; One describing the percentage of each navigation type per week, and the other describing how spread out the data is in terms of the percentage of reported positions on a daily basis. The total number of received position report for week one is 240,811. For week two, the total is 253,159. For week three, the total is 213,748. For week four, the total is 222,958. Lastly, the total for week five is 217,065.

Day	**Week 1**	**Week 2**	**Week 3**	**Week 4**	**Week 5**
Monday	27,148	43,031	32,203	30,013	29,519
Tuesday	25,762	37,559	31,292	33,389	31,371
Wednesday	34,951	36,740	29,565	30,932	26,922
Thursday	38,916	36,832	32,977	36,596	33,284
Friday	44,520	39,007	32,344	36,936	35,601
Saturday	27,886	33,060	26,547	26,224	28,435
Sunday	41,628	26,930	28,820	28,868	31,933
Total	240,811	253,159	213,748	222,958	217,065

Table 4.3: The daily total of all navigation types from each week

4.4.1 Percentage-Based

ADS-B

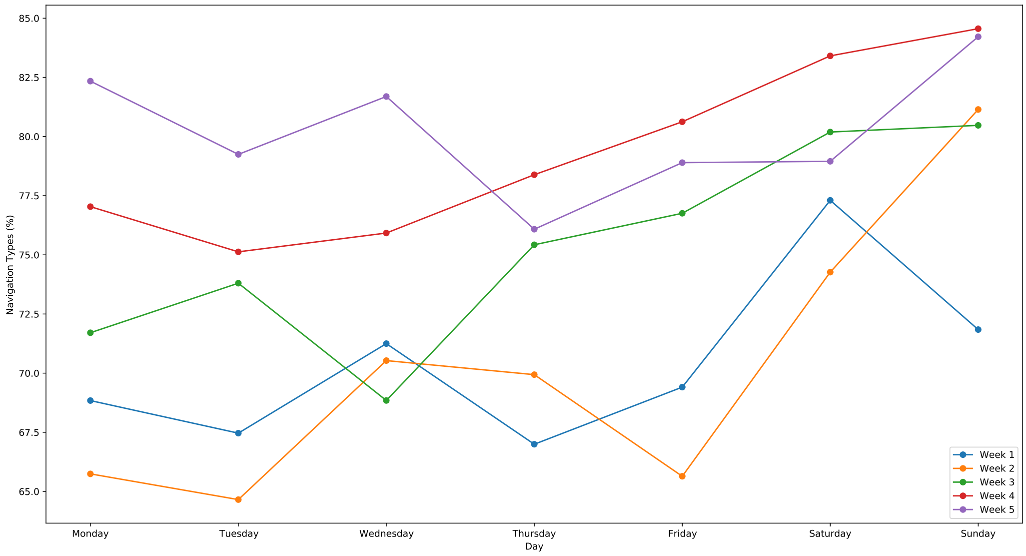

FIGURE 4.14: The percentage of ADS-B-based position reports per week

Day	Week 1 (%)	Week 2 (%)	Week 3 (%)	Week 4 (%)	Week 5 (%)
Monday	68.84	65.74	71.71	77.04	82.34
Tuesday	67.46	64.66	73.80	75.13	79.25
Wednesday	71.25	70.53	68.84	75.92	81.69
Thursday	67.00	69.94	75.43	78.39	76.08
Friday	69.41	65.64	76.76	80.62	78.90
Saturday	77.30	74.27	80.19	83.41	78.95
Sunday	71.84	81.14	80.47	84.56	84.22

TABLE 4.4: The daily percentage of ADS-B-based position report for all week.

The graph **??** illustrates just how much (in percentage) of ADS-B-based positions is emitted within each week. From a brief glance, it seems that of the total positions received,week four makes up almost 85% on Sunday as the highest percentage. Also, the lowest percentage is 64.66% at week two on Tuesday, still more than 50%.

For week one, it started out just below 70% on Monday and fluctuates until Thursday. Then, it gradually rises upto Saturday just a little above 77.5% before falling down on Sunday. For week two, it started a little above 65% on Monday and fell down slightly below 65% on Tuesday. Then, it rose significantly to more than 70% on Wednesday before falling down slightly on Thursday. After that, the percentage of ADS-B-based position report sinks on Friday before leaping on Saturday and Sunday, ending at more than 80%. As for week three, it started out just below 72.5% on Monday and increased gradually above 72.5% on Tuesday. Then, the percentage of position report dropped below 70% on Wednesday before climbing up above 75% on Thursday. After that, the percentage of ADS-B rose steadily until Saturday before leveling off on Sunday. For week four, it started out just a little below 77.5% on Monday and dipped slightly on Tuesday. Then on Wednesday through Sunday, the percentage of position report climbed almost constantly and ending at just below 85%. Lastly, for week five, it started out just below 82.5% on Monday and fluctuates until Thursday. Then, the percentage of position report climbed modestly on Friday before leveling off until Saturday at more than 77.5%. After that, it rose dramatically and ending at around 84% on Sunday.

MLAT

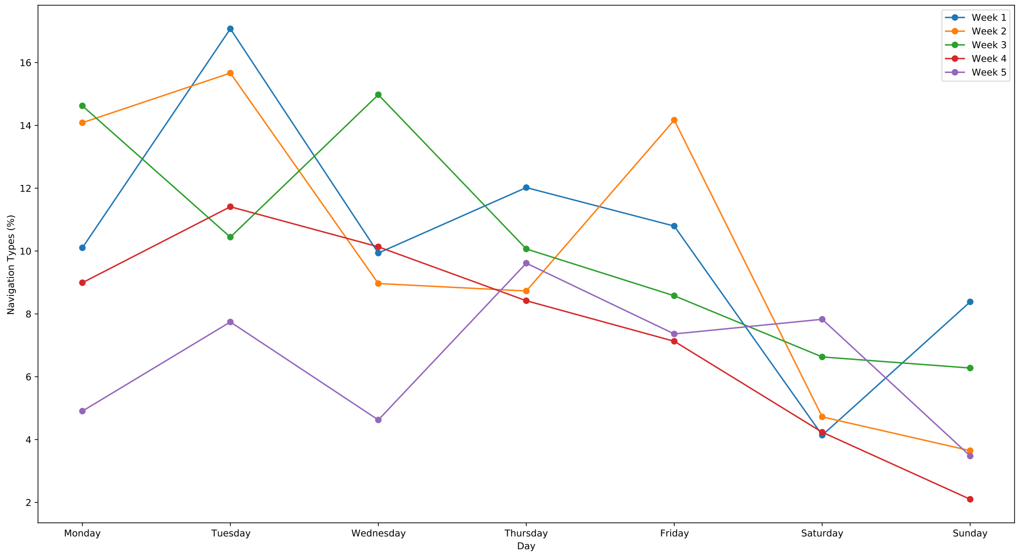

FIGURE 4.15: The percentage of MLAT-based position reports per week

Day	Week 1 (%)	Week 2 (%)	Week 3 (%)	Week 4 (%)	Week 5 (%)
Monday	10.10	14.09	14.62	8.99	4.91
Tuesday	17.08	15.67	10.44	11.41	7.74
Wednesday	9.94	8.97	14.98	10.14	4.62
Thursday	12.02	8.73	10.07	8.42	9.61
Friday	10.80	14.17	8.58	7.13	7.36
Saturday	4.14	4.72	6.63	4.23	7.83
Sunday	8.38	3.65	6.28	2.10	3.48

TABLE 4.5: The daily percentage of MLAT-based position report for all week.

As for figrue **??**, it describes the percentage of MLAT-based posistions that are emitted per week. Overall, it seems that MLAT-based position reports decreased gradually from Monday to Sunday. Additionally, of all the weeks, week one had the highest percentage in MLAT-based position report, which is about 17% on Tuesday. The lowest percentage belongs to week five, which is about 2% on Sunday.

For week one, it started out just above 10% on Monday and rose substantially on Tuesday before coming down steeply to below 10% on Wednesday. Then, it gradually rises upto Thursday to about 12% before falling down through Saturday. After that, it climbed to about 8% on Sunday. For week two, it started a about 14% on Monday and rises to about 15% on Tuesday. Then, it fell moderately to about 9% on Wednesday before slightly leveling off at around 8% on Thursday. After that, it soared to more than 14% on Friday before suddenly falling to less than 6% on Saturday. Then, the position report fell again, but a bit more calm at around 4% on Sunday. As for week three, it started out just above 14% on Monday and decreased gradually a little above 10% on Tuesday. Then, the percentage of MLAT-based position report rose and ended at more than 14% on Wednesday before falling down at about 10% on Thursday. After that, the percentage of MLAT-based reports decreased steadily until Saturday before leveling off on Sunday. For week four, it started out below 10% on Monday and rose modestly on Tuesday, ending at around 11%. Then on Wednesday through Sunday, the percentage of MLAT-based position report fell almost constantly and ending at just a little above 2%. Lastly, for week five, it started out just below 5% on Monday and fluctuates until Thursday. Then, the percentage of MLAT-based position report fell modestly on Friday before rising slightly until Saturday, ending at a little below 8%. After that, it rose sudddenly on Sunday, ending at around 3%.

Other

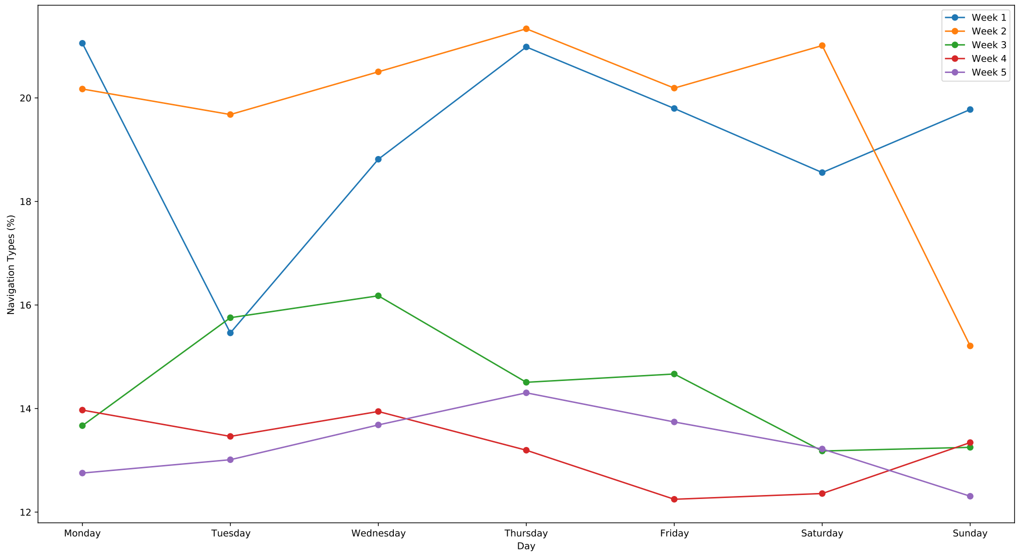

FIGURE 4.16: The percentage of other-based position reports per week

Day	Week 1 (%)	Week 2 (%)	Week 3 (%)	Week 4 (%)	Week 5 (%)
Monday	21.05	20.17	13.67	13.97	12.75
Tuesday	15.46	19.68	15.75	13.46	13.01
Wednesday	18.81	20.50	16.18	13.94	13.68
Thursday	20.98	21.33	14.51	13.20	14.30
Friday	19.80	20.19	14.67	12.25	13.74
Saturday	18.56	21.01	13.18	12.36	13.22
Sunday	19.78	15.21	13.25	13.34	12.31

TABLE 4.6: The daily percentage of other-based position reports for all week.

The graph **??** refers to the percentage of other-based navigation position reports from Monday through Sunday, for a total of five weeks. Overall, other-based navigations are relatively low in presence for week week three, four, and five. However, it is considerably higher in presence for week one and two. The highest presence of other-based navigation postion reports is 21.33% on Thursday, while the lowest is 12.31% on Sunday.

For week one, it started out about 21% on Monday and then plummeting to about 15% on Tuesday before climbing moderately to about 19% on Wednesday. Then, it kept rising to about 21% before decreasing moderately through Friday and Saturday, ending at about 19%. After that, it climbed until around 8% on Sunday. For week two, it started at about 20% on Monday and decreases slightly on Tuesday. Then, it rose constantly through Wednesday and Thursday, ending at around 21%. After that, it dropped in percentage on Friday and rises to about 21% before falling steeply on Sunday, ending at around 15%. For week three, it started at abot 14% on Monday and rises moderately to almost 16% on Tuesday. Then, it increased very subtle to around 16% before dropping to about 15%. After that it leveled off on Friday, dropped down to about 13% before leveling off again on Sunday at 13.25%. For week four, it started at about 14% on Monday and then slightly decreasing in percentage on Tuesday. Then, Wednesday, Thursday, and Friday has 13.94%, 13.20%, and 12.25%, respectively. After that, Saturday has 12.36% then rose on Sunday, ending at 13.34%. Lastly, week five started at around 13% and then climbed steadily through Tuesday, Wednesday, Thursday. After that, the percentage decreased steadily also through Friday and Saturday dropping a bit more steeply on Sunday at 12.31%.

Daily Box Plot

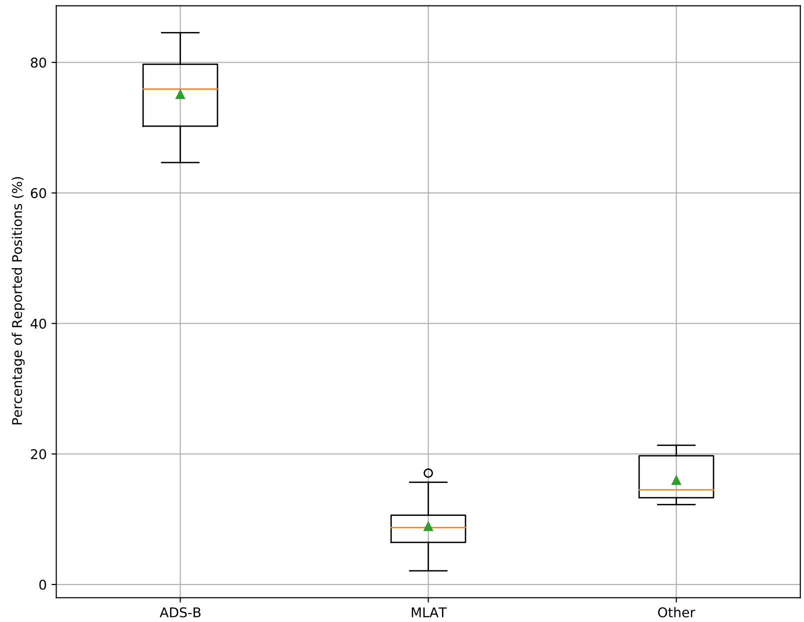

FIGURE 4.17: Box plot of daily percentage of reported positions

With figure ??, it illustrates just how much the data is spread out on a dialy basis. The data itself is the percentage of position report sources (ADS-B, MLAT, other) on a daily basis. For ADS-B, the 25th percentile of the data lies at around 70%, while the 75th percentile is just below 80%. The median is roughly about 76% denoted as the orange line. As for the minimum percentage of the reported position, it is 64.66% and the maximum is 84.56% with a daily average of 75.11%.

For MLAT, the 25th percentile of the data is at around 6% while the 75th percentile is around 11%. The median of the data is about 9% depicted as the orange line. As for the minimum percenteage of the reported position, it is 2.10% and the maximum is 17.08% with a daily average of 8.91%. Do note that there is an outlier present for MLAT just above the maximum percentage of the reported position.

Lastly, for other position report sources, the 25th percentile of the data lies around 13% while the 75th percentile is just below 20%. As for the median of the data, it is about 9%, also depicted as the orange line. The minimum percentage of the reported position data is 12.25%, whereas the maximum is 21.33%. The daily average is 15.98%.

4.5 Coverage Graph

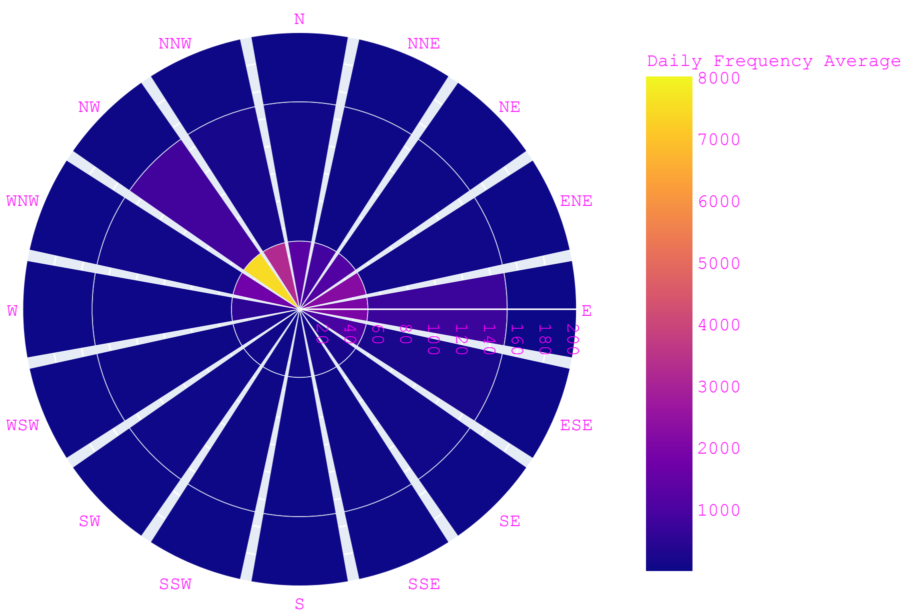

FIGURE 4.18: The daily average frequency of coverage.

The coverage graph data is retrieved from the FlightAware user's dashboard. In the dashboard, a compass-like graph gave the directions in cardinal, ordinal, and secondary inter-cardinal. In addition, it also gave the range from 0 to 200 miles. Figure **??** illustrated the correlation of data absorbed from the direction with the range. Overall, the highest daily frequency average of position reports recorded is from the northwest direction with a range of less than 50 miles.

For the range of less than 50 miles, all directions received at least one position reports. The northwest direction absorbed the most data, with about 7,457 daily average position reports. On the contrary, southsouthwest received the least amount of data, with only 28 position reports as the daily frequency average.

For the range of 51 to 100 miles, all directions received at least one position reports as the daily frequency average. Almost similar to range of less than 50 miles, the northwest direction received the most data, with 832 position reports as the daily frequency average. However, the south direction received the least amount of data, with only a daily average of 5 position reports.

For the range of 101 to 150 miles, not all directions received a position report. Here, the nothwest direction absorbed the most data, with a daily frequency average of 15 position reports. However, the least position reports received falls to eastnotheast, northeast, northnortheast, north, and eastsoutheast with 0 as their daily frequency average. Lastly, for the range 151 to 200 miles, the daily frequency average is 0. A pattern is present, where the bigger the range is, the lower the number of positions are reported.

4.6 Quality Indicators and ADS-B Version

As mentioned before, for this research the author focuses on three widely known ADS-B standards; They are DO-260, DO-260A, and DO-260B. After defining which rows are valid and further filtered the data, the author gets a new set of data. Before further filtering, the total data count was 3,242,130. After filtering based on ADS-B version, the new total data count is 3,004,178, which is 92.66% of the original data set. Furthermore, of the 3,004,178 data, 1,979,109 is ADS-B version 0, 63,236 is ADS-B version 1, and 961,833 is ADS-B version 2.

ADS-B Version	**Count**	**%**
0 (DO-260)	1,979,109	65.88
1 (DO-260A)	63,236	2.10
2 (DO-260B)	961,833	32.02
Total	3,004,178	100

Table 4.7: Total count of each ADS-B version.

For the message types, there are two kinds. One is ground-based message type and the other is airborne-based message types. The author distinguished these message types from the values of the barometric altimeter. The ground message type is 321 messages, making up 0.01% for all aircraft with a valid ADS-B version. As for the airborne messsage type, it is 3,003,857 messages, making up 99.99% for all aircraft with a valid ADS-B version.

Message Type	**Count**	**%**
Ground	321	0.01
Airborne	3,003,857	99.99
Total	3,004,178	100

Table 4.8: Total count of the message type.

4.6.1 Statistical Analysis of ADS-B Version 0

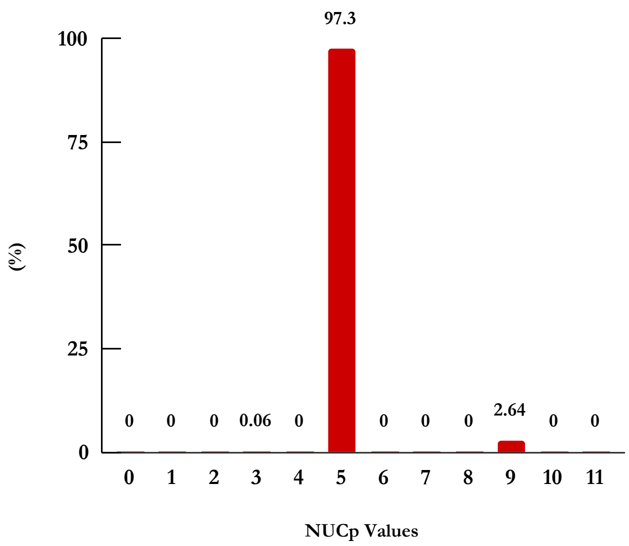

FIGURE 4.19: NUCp values for version 0

NUCp Value	Count	%
0	0	0
1	0	0
2	0	0
3	704	0.06
4	0	0
5	1,143,144	97.30
6	0	0
7	0	0
8	0	0
9	30,962	2.64
10	0	0
11	0	0

TABLE 4.9: The presence of NUCp for ADS-B version 0.

For NUCp, this quality indicator is only available in ADS-B version 0. NUCp is composed of HPL for integrity and Rc for accuracy. As seen on table **??**, the total presence of NUCp is 1,174,810. Of the total NUCp captured, there are some values that are not captured. However, value of 5 dominates all other values by 97.30%, followed by value 10 by 2.64%, and lastly value of 3 by 0.06%.

4.6.2 Statistical Analysis of ADS-B Version 1

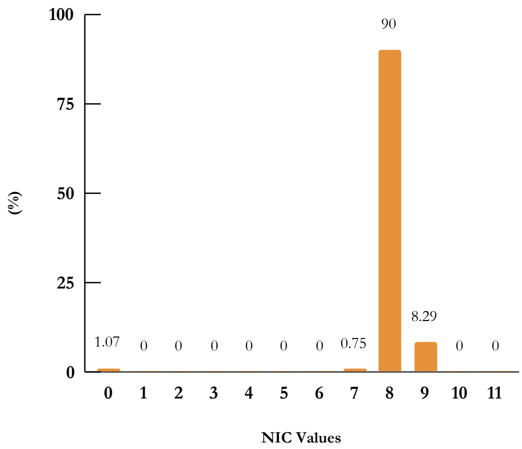

FIGURE 4.20: NIC values for version 1

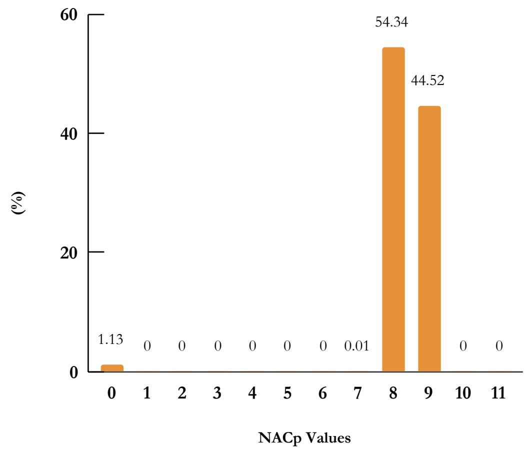

FIGURE 4.21: NACp values for version 1

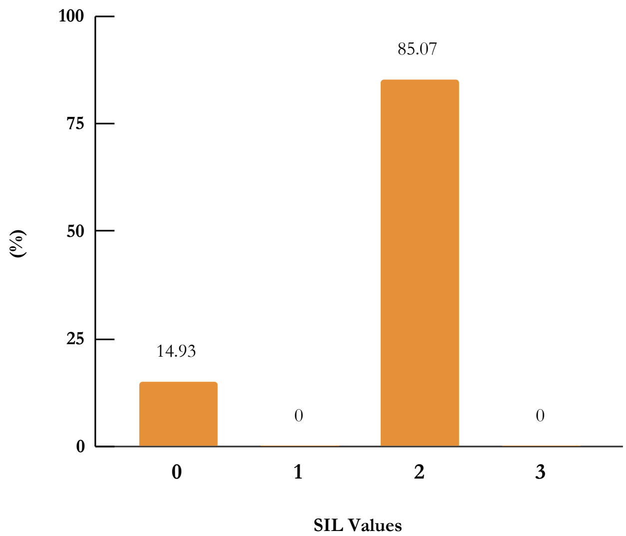

FIGURE 4.22: SIL values for version 1

NIC Value	Count	%
0	447	1.07
1	0	0
2	0	0
3	0	0
4	0	0
5	0	0
6	0	0
7	313	0.75
8	37,472	90
9	3,454	8.29
10	0	0
11	0	0

TABLE 4.10: The presence of NIC value for version 1.

NACp Value	Count	%
0	467	1.13
1	0	0
2	0	0
3	0	0
4	0	0
5	0	0
6	0	0
7	4	0.01
8	22,546	54.34
9	18,473	44.52
10	0	0
11	0	0

TABLE 4.11: The presence of NACp value for version 1.

SIL Value	Count	%
0	6,194	14.93
1	0	0
2	35,296	85.07
3	0	0

TABLE 4.12: The presence of SIL value for version 1.

For NIC version 1, this quality indicator indicates the integrity of the data being sent. As seen on table ??, the total presence of NIC in this version is 41,686. Of the total NIC captured, there are some values that are not captured. However, the value of 5 dominates all other values by 90%, followed by value 9 by 8.29%, then value of 1 by 1.07%, and lastly value of 7 by 0.75%.

For NACp, this quality indicator indicates the accuracy of the data being sent. As seen on table ??, the total presence of NIC in this version is 41,490. Of the total NACp captured, there are some values that are not captured. Nonetheless, there is a predominance of value 8 by 54.34%, followed by value 9 by 44.52%, then value 0 by 1.13%, and lastly value 7 by 0.01%.

For SIL version 1, this quality indicator indicates the probability of exceeding radius of containment, which is deifned by NIC, without any detection. As seen on table ??, the total presence of SIL in this version is 41,490. Of the total SIL captured, there are two SIL values that are not captured. Nonetheless, the value of 2 dominates all other values by 85.07%, followed by value of 0 with only 14.93%.

4.6.3 Statistical Analysis of ADS-B Version 2

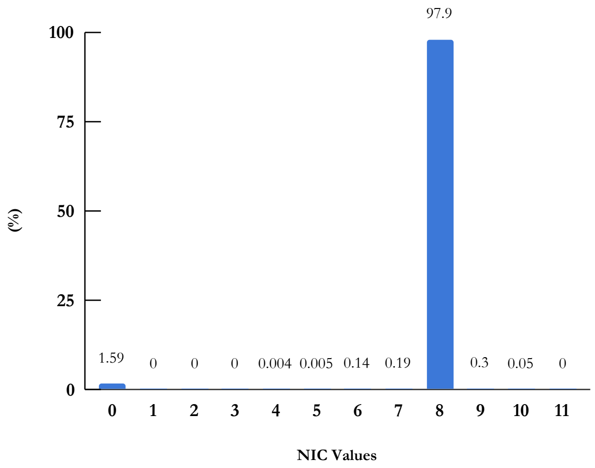

FIGURE 4.23: NIC values for version 2

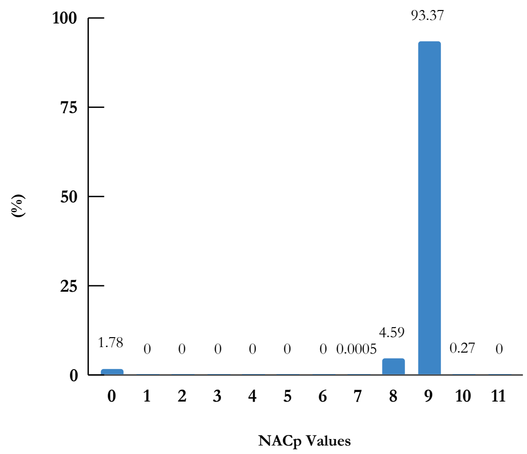

FIGURE 4.24: NACp values for version 2

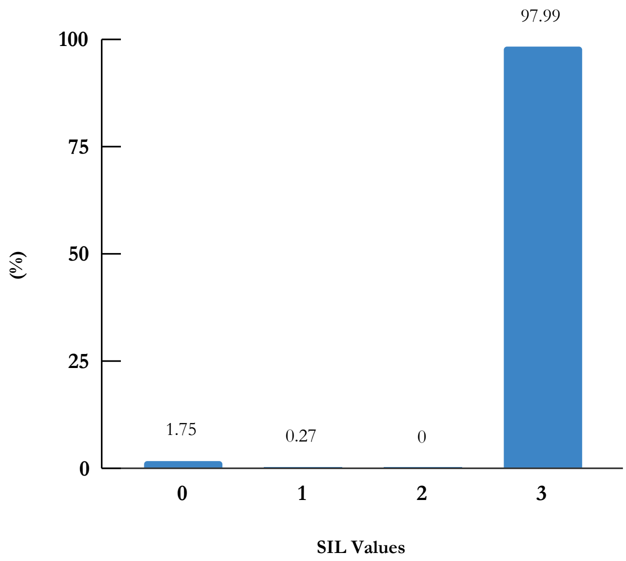

FIGURE 4.25: SIL values for version 2

NIC Value	Count	%
0	10,013	1.59
1	0	0
2	0	0
3	0	0
4	25	0.004
5	31	0.005
6	87	0.14
7	1,168	0.19
8	616,681	97.90
9	1,900	0.30
10	30	0.005
11	0	0

TABLE 4.13: The presence of NIC value for ADS-B version 2.

NACp Value	Count	%
0	11,146	1.78
1	0	0
2	0	0
3	0	0
4	0	0
5	0	0
6	0	0
7	3	0.0005
8	28,786	4.59
9	585,806	93.37
10	1,663	0.27
11	0	0

TABLE 4.14: The presence of NACp value for ADS-B version 2.

SIL Value	Count	%
0	10,967	1.75
1	1,673	0.27
2	0	0
3	614,764	97.99

TABLE 4.15: The presence of SIL value for ADS-B version 2.

For NIC version 2, as mentioned before, this quality indicator indicates the integrity of the data being sent. As seen on table **??**, the total presence of NIC in this version is 629,935. Of the total NIC captured, there are a few values that are not captured. However, the value of 8 dominates all other values by 97.90%, followed by value 0 by 1.59%, value of 9 by 0.30%, value of 7 by 0.19%, value of 6 by 0.14%, value of 5 by 0.005%, value of 10 by 0.005%, and lastly value of 4 by 0.004%.

For NACp, as mentioned before, this quality indicator indicates the accuracy of the data being sent. As seen on table **??**, the total presence of NIC in this version is 41,490. Of the total NACp captured, there are some values that are not captured. Nonetheless, there is a predominance of value 9 by 93.37%, followed by value 8 by 4.59%, value 0 by 1.78%, value of 10 by 0.27%, and lastly value 7 by only 0.0005%.

For SIL version 1, as mentioned before, this quality indicator indicates the probability of exceeding radius of containment, which is deifned by NIC, without any detection. As seen on table **??**, the total presence of SIL in this version is 627,404. Of the total SIL captured, there is one SIL values that is not captured. Nonetheless, the value of 3 dominates all other values by 97.99%, followed by value of 0 with 1.75%, and lastly value of 1 with only 0.27%.

4.6.4 Comparison with FAA regulation

Quality Indicator	**Minimum Requirements**
NACp	≥ 9
NIC	≥ 8
SIL	=3

TABLE 4.16: Minimum ADS-B Version 2 requirements for quality indicators by FAA.

As for comparison with FAA regulation, the author chose CFR section 91.227, where it specifies the equipment performance requirements for ADS-B OUT. In the regulation, the minimum ADS-B quality indicator value are also stated. The mentioned quality indicators are NACp, NACv, NIC, SDA, and SIL. The author focused on the minimum requirements for ADS-B version 2. Of the total known

NACp received, 93.635% has a value of greater than or equal to 9. For NIC with a value of greater than or equal to 8 is 98.598%. As for SIL with exactly 3 for the value is 97.985%.

CHAPTER 5
SUMMARY, CONCLUSION, RECOMMENDATION

5.1 Summary

In summary, the actvity of collecting ADS-B data, specifically its quality indicators is done. The receiver system consists of several hardwares such as Raspberry Pi 2 Model B, RTL-SDR dongle, 1090MHz ADS-B antenna, and others. Together along with supporting softwares, the author is able to collect data from November 9, 2020 00:00 until December 13, 2020 23:59 local time, a total of five weeks. The location of data collection is the author's own home, specifically 6° 21' 21.204" S, 106° 43' 10.776" E.

The way the data were collected was the author installed Raspberry Pi OS into the Raspberry Pi as well as installing PiAware and dump1090. After that, the author sets up the code to collect the data for every five seconds with Python, a programming language. Then, the author surveyed the rooftop and installed the ADS-B antenna. Once that was done, the author plugged every necessary cables and executed the right commands to start the data collection. The author checked the status of the data collection for every three hours to reduce the gap of offline status. However, some things are unavoidable such as power outages as mentioned in previous chapters. When the data collection was finished, the raw data was moved to a safe place in the computer for further processing. The total files that were collected was 568,374. With three empty files, the actual total files that was parsed is 568,371. The author then parsed and normalized the JSON files with Pandas. The results after parsing the files are saved into a CSV format. The total data (in rows) is 3,242,130 with a final file size of 622 megabyte.

5.2 Conclusion

The performance of the receiver system were satisfying. Air traffic was also present along with the data quality indicators of those traffic. The conclusions of the overall results of this research are the following:

1. The comparison between the author's site and all other sites were identical in numbers. This means that the receiver system is reliable.

2. Air traffic tends to plummet every Saturday within the five weeks of data collection. However, even with many fluctuations, air traffic increased ever so slightly from the start of data collection until the end. The daily average number of aircraft captured is 262.

3. The position reports sources can either be from ADS-B, MLAT, or other. On a daily basis, the average of ADS-B-based position reports was 75.11%, while MLAT was only 9.91%. For other sources, it was only 15.98% as the daily average.

4. Based on the number of aircraft reported, there is a daily and hourly pattern of air traffic.

5. With the antenna coverage, it was divided into distance and orientation. Northwest direction absorbed the most data while other direction is not as much. One of the cause could be the topography of the author's home.

Another is that there is a major airport approximately Northwest of the author's home.

6. Of the total of 3,004,178 messages, 321 are ground-based messages while 3,003,857 are airborne-based messages.

Message Type	**Count**	**%**
Ground	321	0.01
Airborne	3,003,857	99.99
Total	3,004,178	100

Table 5.1: Total count of the message type.

7. From the total of 3,004,178 messages that has a valid ADS-B version emitted, 65.88% of it is ADS-B version 0, 2.10% of it is ADS-B version 1, and 32.02% of it is ADS-B version 2. ADS-B version 0 dominates over the other ADS-B versions.

ADS-B Version	**Count**	**%**
0 (DO-260)	1,979,109	65.88
1 (DO-260A)	63,236	2.10
2 (DO-260B)	961,833	32.02
Total	3,004,178	100

Table 5.2: Total count of each ADS-B version.

8. ADS-B quality indicators were also received in this research.

   - For ADS-B version 0, it has NUCp as the quality indicator for position. 97.3% emmited NUCp value of 5, followed by NUCp value of 9 at 2.64%, and NUCp value of 3 with 0.06%.

- For ADS-B version 1, it has NIC, NACp, and SIL as the quality indicators. NIC has a predominance of value 8 with 90% of the total ADS-B version 1 data, followed by the value of 9 at 8.29%. NACp has 54.34% of value 8, followed by value of 9 at 44.52%. SIL value of 2 dominated by 85.07% and followed SIL value of 0 with 14.93%.
- For ADS-B version 2, it also has NIC, NACp, and SIL. NIC value of 8 dominated by 97.9% and followed by value of 0 at 1.59%. NACp has 93.37% of value 9, followed by value of 8 with 4.59%. SIL value of 3 dominated by 97.99%, followed by value of 0 with 1.75%, then value of 1 made up of only 0.27%.

9. The author used FAA regulation CFR section 91.227 for comparison. For NACp ADS-B version 2, 93.635% met the requirement. For NIC ADS-B version 2, 98.598% met the requirement. As for SIL ADS-B version 2, 97.985 % met the requirement stated by FAA. More than 50% of each quality indicator that was analyzed complied with the FAA regulation CFR section 91.227.

5.3 Recommendations

Based on the results, 65.88% of the messages received are still ADS-B version 0. For Indonesian aviation regulators, the author recommends to use DO-260A as the minimum standard reference for ADS-B performance, and DO-260B as the prefered ADS-B performance. This is because in DO-260A and B, it offers more capabilities and safety features than DO-260. It is also recommended that airline operators upgrade their fleet's avonics system to be compliant at the minimum of DO-260A, with DO-260B as highly desirable. By modernizing the avionics, it will improve the safety aspect of flying in a dense air traffic as well as reducing the workload of conventional radars.

As for future reasearch within this topic, the author recommends to use Raspberry Pi with more than 1GB of RAM. This is to avoid unresponsive pages and have the ability to open web browsers while collecting data. Parsing all of the aircraft.JSON files uses multiprocessing capability due to the big volume of data. Thus, the author recommends to use a powerful computer system. A much more clear field of view is preferred to achieve a greater range in tracking. Lastly, the author was only able to collect data for five weeks. As comparison with a paper by Simon Tesi (Tesi and Pleninger, 2020), the duration of his research was 6 months over the Czech Republic with an area of 78,866 KM^2. To fully represent ADS-B quality indicator over Indonesia, a scaled-up coverage as well as a longer duration of data collection is preferable.

Appendices

Appendix A: Python Codes

```
import pandas as pd
import matplotlib.pyplot as plt


# Load file as dataframe
FNAME = "Final_Daily_Reports.csv"

df = pd.read_csv(FNAME, skiprows=2)

df["Datetime"] = pd.to_datetime(df["Date"])  # Create colum day name

# Define time span
DT_INIT = "2020-11-09"
DT_FINAL = "2020-12-13"

df = df[(df["Datetime"] >= DT_INIT) & (df["Datetime"] <= DT_FINAL)]

# Create columns in percentage
df["ADS-B_p"] = (df["ADS-B"] / df["ALL_NAV"]) * 100
df["MLAT_p"] = (df["MLAT"] / df["ALL_NAV"]) * 100
df["Other_p"] = (df["Other"] / df["ALL_NAV"]) * 100

# Number of week to plot
NUM_WEEK = 5

# Plot daily number of positions
fig1, ax1 = plt.subplots(nrows=1, ncols=1, figsize=(20, 10))
for week in range(NUM_WEEK):
    day_start = 0 + 7 * week
    day_end = day_start + 7
    df_week = df.iloc[day_start:day_end]
    label = "Week " + str(week + 1)
    ax1.plot(
        df_week["Datetime"].dt.strftime("%A"), df_week["All Site"], "-o", label=label
    )
    ax1.plot(
        df_week["Datetime"].dt.strftime("%A"), df_week["Site 139042"], "-o", label=label
    )
ax1.set_xlabel("Day")
ax1.set_ylabel("Number of Aircraft")
ax1.legend()
```

```
# plt.savefig("Number_of_Aircraft.pdf", dpi=600)

# Plot daily number of Navigation Types
fig2, ax2 = plt.subplots(nrows=1, ncols=1, figsize=(20, 10))
for week in range(NUM_WEEK):
    day_start = 0 + 7 * week
    day_end = day_start + 7
    df_week = df.iloc[day_start:day_end]
    label = "Week " + str(week + 1)
    ax2.plot(
        df_week["Datetime"].dt.strftime("%A"), df_week["ALL_NAV"], "-o", label="All"
    )
    ax2.plot(
        df_week["Datetime"].dt.strftime("%A"), df_week["ADS-B"], "-o", label="ADS-B"
    )
    ax2.plot(df_week["Datetime"].dt.strftime("%A"), df_week["MLAT"], "-o", label="MLAT")
    ax2.plot(
        df_week["Datetime"].dt.strftime("%A"), df_week["Other"], "-o", label="Other"
    )
ax2.set_xlabel("Day")
ax2.set_ylabel("Number of Position Reports")
ax2.legend()


# Plot daily number of positions
fig3, ax3 = plt.subplots(nrows=1, ncols=1, figsize=(20, 10))
for week in range(NUM_WEEK):
    day_start = 0 + 7 * week
    day_end = day_start + 7
    df_week = df.iloc[day_start:day_end]
    label = "Week " + str(week + 1)
    ax3.plot(
        df_week["Datetime"].dt.strftime("%A"), df_week["ADS-B_p"], "-o", label=label
    )
    ax3.plot(
        df_week["Datetime"].dt.strftime("%A"), df_week["MLAT_p"], "-o", label=label
    )
    ax3.plot(
        df_week["Datetime"].dt.strftime("%A"), df_week["Other_p"], "-o", label=label
    )
ax3.set_xlabel("Day")
ax3.set_ylabel("Navigation Types (%) ")
ax3.legend()


# plt.savefig("Number_of_Aircraft.pdf", dpi=600)
plt.show()

import pandas as pd
import matplotlib.pyplot as plt
```

```
import matplotlib.dates as mdates

import matplotlib.ticker as tick

h_fmt = mdates.DateFormatter("%H:%M")

hours = mdates.YearLocator()


FNAME = "Final_Hourly_Reports.csv"

df = pd.read_csv(FNAME, parse_dates=["Datetime"])
df["Datetime"] = pd.to_datetime(df["Datetime"])  # Create colum day name

NUM_DAY = 7

# Select the week span
# Week 1
DT_INIT = "11/9/2020 0:00:00"
DT_FINAL = "11/16/2020 23:00:00"

# Week 2
DT_INIT = "11/16/2020 0:00:00"
DT_FINAL = "11/23/2020 23:00:00"

# Week 3
DT_INIT = "11/23/2020 0:00:00"
DT_FINAL = "11/30/2020 23:00:00"

# Week 4
DT_INIT = "11/30/2020 0:00:00"
DT_FINAL = "12/7/2020 23:00:00"

# # Week 5
DT_INIT = "12/7/2020 0:00:00"
DT_FINAL = "12/14/2020 23:00:00"


df = df[(df["Datetime"] >= DT_INIT) & (df["Datetime"] <= DT_FINAL)]


# Plot daily number of positions
fig1, ax1 = plt.subplots(nrows=1, ncols=1, figsize=(20, 10))
hours = mdates.HourLocator(interval=1)
for day in range(NUM_DAY):
    hour_start = 0 + 24 * day
    hour_end = hour_start + 24
    df_day = df.iloc[hour_start:hour_end]
    label = df_day["Datetime"].dt.strftime("%A").iloc[-1]
    hours = df["Datetime"][0:24]
```

```
    ax1.plot(hours, df_day["Number of Position"], "-o", label=label)
xticks = mdates.HourLocator(interval=1)
ax1.set_xlabel("Hour of the day (WIB)")
ax1.set_ylabel("Number of Received Position")
ax1.xaxis.set_major_locator(xticks)
ax1.xaxis.set_major_formatter(tick.FuncFormatter(h_fmt))
ax1.legend()


# Plot daily number of Aircraft
fig2, ax2 = plt.subplots(nrows=1, ncols=1, figsize=(20, 10))
hours = mdates.HourLocator(interval=1)
for day in range(NUM_DAY):
    hour_start = 0 + 24 * day
    hour_end = hour_start + 24
    df_day = df.iloc[hour_start:hour_end]
    label = df_day["Datetime"].dt.strftime("%A").iloc[-1]
    hours = df["Datetime"][0:24]
    ax2.plot(hours, df_day["Number of Aircraft"], "-o", label=label)
xticks = mdates.HourLocator(interval=1)
ax2.set_xlabel("Hour of the day (WIB)")
ax2.set_ylabel("Number of Detected Aircraft")
ax2.xaxis.set_major_locator(xticks)
ax2.xaxis.set_major_formatter(tick.FuncFormatter(h_fmt))
ax2.legend()

plt.xticks(rotation=0)
plt.show()

import os
import glob
import json
import itertools
import pandas as pd
from pandas.io.json import json_normalize


# List of all json files
data_pool = "aircraft_jsons/"
dirs = os.listdir(data_pool)
files = []
for dir in dirs:
    files_ = glob.glob(data_pool + dir + "/*.json")
    files.append(files_)
files = list(itertools.chain(*files))  # Flattening
files = [f for f in files if os.stat(f).st_size > 0]  # Remove empty files
nfiles = len(files)

# Parse all json file to dataframe
all_adsb_df = pd.DataFrame()
```

```
# Parse all the jsons to dataframe
for file in files:
    print("Processing: " + file)
    print("Number of files left: " + str(nfiles))
    f = open(file, "r")
    data = json.loads(f.read())
    df = pd.json_normalize(data, "aircraft", ["now", "messages"], record_prefix="ac_")
    all_adsb_df = all_adsb_df.append(df, sort=False)
    f.close()
    nfiles -= 1

all_adsb_df2 = all_adsb_df.copy()
all_adsb_df2 = all_adsb_df2.drop_duplicates()

# Postprocessing the dataframe
all_adsb_df["now"] = pd.to_datetime(
    all_adsb_df["now"], unit="s"
)  # convert unix time to datetime

# Move column "now" to the first column
col_name = "now"
col_value = all_adsb_df.pop(col_name)
all_adsb_df.insert(0, col_name, col_value)

# Save dataframe to CSV
all_adsb_df.to_csv("ADS-B_Piaware_Agha.csv")

import os
import shutil
import time
import datetime

src_dir = "/run/dump1090-fa"

now_unix = time.time()

dest_name = "/jsons_start_" + str(now_unix)
dest_dir = os.getcwd() + dest_name
os.mkdir(dest_dir)


def cp_ac_json():
    """
    Copy the aircraft.json produced by flightware,
    and name it with infix unix time.
    """
    fname_src = "aircraft.json"
    now_unix2 = time.time()
    fname_dest = "aircraft_" + str(now_unix2) + "_.json"
```

```
    src_file = os.path.join(src_dir, fname_src)
    dest_file = os.path.join(dest_dir, fname_dest)
    shutil.copy(src_file, dest_file)


# Copy the file every 5 seconds
starttime = time.time()
while True:
    cp_ac_json()
    print("Copied aircraft.json")
    print("Current Time: " + str(datetime.datetime.now()))
    time.sleep(5)
```

3

Turnitin Report

Statistical Analysis of ADS-B Quality Indicators of Data Obtained From a Low-Cost Receiver

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Curriculum Vitae

	Basic Information
Name	Aghadhia Firaz Uno Kusuma
Place of Birth	Surabaya
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Year	**Education**
2016 - Present	International University Liaison Indonesia
2013 - 2016	SMAN 2 Tangerang Selatan
Year	**Courses**
2020	Data Science Methodologies
2020	Google Analytics for Beginners
2019	Festo: Pneumatic and Hydraulic Training
Year	**Seminars & Workshops**
2019	Higher Education for Aviation Professions
2017	Elevator and Angle of Attack (AOA)
Year	**Work Experiences**
2017 - 2020	lesprivatable (Private Tutor)
2019 - 2020	Sriwijaya Air - OCC (Intern)
2019	EASA, IULI, European Union (VIP & VVIP Liaison Officer)
2018	Garuda Maintenance Facility (Intern)