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AIRCRAFT ADS-B OUT PERFORMANCE ANALYSIS: ACCURACY, INTEGRITY AND AVAILABILITY

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The undersigned certify that they have read, and recommended to the Institute of Engineering for acceptance, a project report entitled "Aircraft ADS-B out performance analysis: Accuracy, Integrity and Availability" submitted by Bijaya Mandal, Prasid Bhattarai and Rakesh Kumar Sah in partial fulfillment of the requirements for the degree of Bachelor of Aerospace Engineering.

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ABSTRACT

Automatic Dependent Surveillance - Broadcast (ADS-B) is an avionic in the aircraft that periodically broadcasts state vector estimates and additional information of the aircraft to the traffic control centers and other nearby airspace users. The sate vector estimates are based on the navigation system such as the GNSS and multitude of avionic sensors, which means that the quality of ADS-B broadcast is highly based on the quality of aircraft navigation and communication systems. This project aims to analyze the performances of relevant matrix such as the navigation accuracy, integrity, source integrity level and avionics system assurance level. Besides, the project also focuses on characterizing the quality and pattern in the ADSB data and identifying any errors or anomalies coming from potential failure modes. Statistical analysis is used to correlate the data with Required Navigation Performance (RNP) Specification, flight levels and flight phases. As the global uptake of the ADSB in the airspace is ever increasing, it is important to understand the quality and performance of the ADSB surveillance in various airspace where aircraft types and supporting ATM/CNS services are different. For this reason, the data retrieved by installing a low cost ADSB ground station in the Flight Information Region in Kathmandu, Nepal is compared against highly advanced airspace in Munich, Germany. Based on the mechanisms developed for ADSB data retrieval, monitoring, performance analysis and anomalies detection, the project envisages to develop a low-cost product prototype which offers the features to support aviation stakeholders in the decision-making process.

Key Words: ADS-B, accuracy, integrity, low-cost product

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LIST OF ABBREVIATIONS

ADS-B	Automatic Dependent Surveillance – Broadcast
ATS	Air Traffic Service
CAAN	Civil Aviation Authority of Nepal
CNS	Communication Navigation and Surveillance
EASA	European Aviation Safety Agency
ES	Extended Squitter
FIR	Flight Information Region
FL	Flight Level
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GVA	Geometric Vertical Accuracy
HFOM	Horizontal Figure of Merit (HFOM)
HPL	Horizontal Protection Level
ICAO	International Civil Aviation Authority
JSON	JavaScript Object Notation
MHZ	Megahertz
MOPS	Minimum Operational Performance Standards
MSL	Mean Sea Level
NACp	Navigation Accuracy Category
NIC	Navigation Integrity Category
NM	Nautical Mile
NUCp	Navigation Uncertainty Category
QNE	Question Nil Elevation
QNH	Query Nautical Height
RADAR	Radio Detection and Ranging
RVSM	Reduced Vertical Separation Minimum
UAT	Universal Access Transceiver
VFOM	Vertical Figure of Merit

CHAPTER 1 INTRODUCTION

1.1 Background

ADS-B stands for Automatic Dependent Surveillance Broadcast. The term "Automatic" means information is transmitted on a regular basis, with no pilot or operator involvement required. "Dependent" means position and velocity vectors are derived from the Global Positioning System (GPS) or another suitable Navigation System. Surveillance means it adapts technique for determining the three-dimensional position and identity of aircraft, vehicles, or other assets. "Broadcast" refers to it ability to transmit data is to anyone with the necessary receiving equipment. [1] This signal can be captured for surveillance purposes on the ground (ADS-B-out) or on-board other aircraft/vehicles (ADS-B-in). [2] In contrast to other types of Mode S surveillance, no interrogation is required. [3]

Aircraft position are obtained from the GNSS constellations. Similarly, other aircraft parameters are retrieved from on-board avionics. These parameters are transmitted to ground station and other aircraft using ADSB transponder.

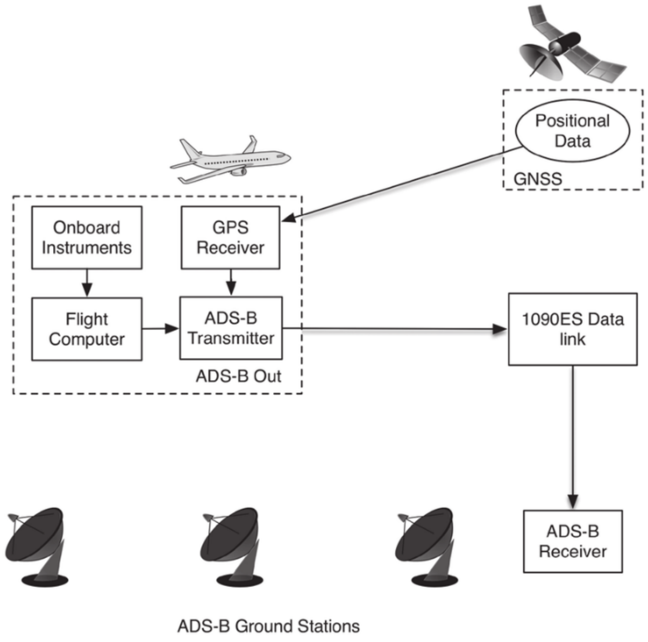


Figure 1.1: Mechanism of ADS-B [28]

1.2 Problem Statement

Most of the northern part of Nepal falls under uncontrolled region i.e., it doesn’t fall under any kind of surveillance region. In order to cover the areas of Nepal for better surveillance and communication, ADS-B can be a better option. It is comparatively easier and cheaper to set up an ADS-B station compared to other available CNS such as RADAR systems. [4] So, the proposed project can be important for the performance analysis in Kathmandu FIR.

1.3 Objectives

1.3.1 Main Objective

- To analyze the performance indicators of ADS-B system in terms of accuracy, integrity and availability.

1.3.2 Specific Objectives

- To use system engineering approach for installation and operation of ADS-B ground station.
- To continuously operate and collect data from ADS-B stations.
- To review aircraft ADS-B out interface document and implement the message decoder.
- To statistically analyze the quality indicators (NIC, NAC, SIL, SDA and GVA).
- To determine and correlate (with RNP) the horizontal position accuracy of ADS-B.
- To correlate difference of geometric and barometric altitude with Flight Level.
- To identify best and worst performing aircraft based on ADS-B data.
- To design fault detection and isolation mechanism.

1.4 Minimum Operational Performance Standards (MOPS) in ADS-B

MOPS is an acronym that stands for minimum operational performance standard. A MOPS provides guidelines for the creators, producers, installers, and users of specific pieces of equipment. MOPS provides the information needed to understand the justification for the given equipment requirements and features.

In the case of ADS-B, MOPS is a document that defines how the transponder must generate and transmit ADS-B messages. Extended squitter provides additional information based on the avionics system's Minimum Operational Performance Standards (MOPS):

- DO-260 (Version 0)
- DO-260A (Version 1)
- DO-260B (Version 2)
- DO-260C (Version 3), approved December 2020 [1]

1.5 Current State of Art

Since early 2004, Boeing has started installation of ATC transponder equipped with 1090ES ADS-B. Both Europe and the United States have made a decision to require transponders that adhere to the latest DO-260B standard published by the Radio Technical Commission for Aeronautics in 2009. The US intends to make ADS-B Out mandatory for all types of airplanes, including commercial air transport and general aviation, starting in January 2020. [5]

The first recorded requirement for ADS-B equipment is from November 2010 in Hudson Bay, Canada. This mandate will result in the reduction of separation distance from 80 nautical miles to 5 nautical miles while following. The following mandate for ADS-B will take place in December 2013 in Australia. Due to the lack of radar coverage in much of Australia's western airspace, the country has chosen to rapidly adopt ADS-B-based surveillance to avoid the expenses linked to the deployment and upkeep of costly radar systems. Europe has been mandated use of ADS-B Out on all airplanes entering European airspace by 2015. [5]

In case of Nepal, the implementation of ADS-B in the Kathmandu Flight Information Region (FIR) as a testing monitoring service began on November 28, 2020. [6] The ADS-B based surveillance service has utilized within the Class C airspace covered by ADS-B in the Kathmandu FIR, as specified below:

a) Kathmandu Terminal Control Area (From Flight Level 250 to the upper limit of the TMA)
b) Bhairahawa Control Zone
c) Air Traffic Service Airways (From Flight Level 250 to the upper limit of the Airway

The following plan has been established for the implementation of ADS-B within the airspace specified as

a) Beginning June 1, 2021, ADS-B shall be utilized for situational awareness.
b) December 1, 2021, ADS-B shall be used for Air Traffic Service (ATS) surveillance (as a backup for existing radar systems) within radar-covered airspace.
c) Beginning June 1, 2022, ADS-B will be fully utilized for ATS surveillance in conjunction with the existing radar service. [6]

Any civil aircraft flying within Kathmandu FIR should have ADS-B transmitting equipped with following standard.

a) EASA AMC 20-24, Certification Considerations for the Enhanced ATS in Non-Radar Areas using ADS-B Surveillance (ADS-BNRA) Application via 1090 MHZ Extended Squitter, or
b) EASA ED Decision 2013/031/R adopting Certification Specifications for Airborne Communications Navigation and Surveillance (CS ACNS), or

c) FAA AC 20-165B, Airworthiness Approval of Automatic Dependent Surveillance – Broadcast (ADS-B) Out Systems, or
d) The equipment configuration standards in Appendix XI of Civil Aviation Order 20.18 of the Civil Aviation Safety Authority of Australia.

If above requirements are not met by any ADS-B OUT equipage aircraft, the ADS-B equipage shall either be deactivated or allowed to transmit only a value of ‘zero ‘for NUCp, NIC and SIL.

1.6 Feasibility

1.6.1 Economic Feasibility:

The viability of implementing an ADS-B analyzing system would be influenced by various factors, such as the expenses involved in acquiring the necessary hardware, software, and personnel, as well as the possible return on investment. There may also be ongoing costs related to maintaining and updating the system to ensure it remains efficient.

Despite the costs, an ADS-B analyzing system has the potential to offer several advantages, such as enhancing aviation safety and efficiency. Through the analysis of ADS-B data, the system could identify potential conflicts and provide warnings to pilots and air traffic controllers, while also optimizing routing and reducing congestion, leading to cost savings and better operational efficiency.

In conclusion, the feasibility of an ADS-B analyzing system shows this is a low-cost product since the hardware and software required can be easily and cheaply accessible.

1.6.2 Operational Feasibility:

The historical trend study has proved ADS-B can have the following Stakeholders:

1. **Civil Aviation Authority of Nepal (CAAN):**

CAAN is the governing body of aviation industry in Nepal whose primary mission is to provide most efficient and the safest aerospace system. They establish the rules and regulations for operation of aircraft. PBN plan of CAAN have included ADS-B system installation and operation plan and is in testing phase.

2. **Air Route Traffic Control Centre (ARTCC):**
   The main goal of the Air Route Traffic Control Center (ARTCC) is to ensure safety and efficiency within a designated airspace at high altitudes. ARTCC personnel utilize radar screens to observe and guide aircraft safely in the upper atmosphere. The introduction of the ADS-B system will have a direct impact on the ARTCC, necessitating employee training in the operation of new equipment and system usage to optimize airspace utilization. [7]
3. **Airline Companies:**
   The primary aim of airline companies is to operate airplanes and securely convey passengers to their desired locations, while also generating sufficient profits to encourage the company's expansion. [7] To comply with CAAN PBN Plan, airline owners need to invest in ICAO-approved equipment like ADS-B for better efficiency.
4. **Crew and Pilots:**
   The airplane is controlled by the crew, particularly the pilots, who depend on the ADS-B system and the ARTCC for accurate information on the positioning of other aircraft and instructions on adjusting course.

These Stakeholders are the Primary member of aviation industry and the ADS-B Performance parameter analysis can be highly demanded by these Stakeholders.

1.7 Hardware Requirements

1.7.1 Antenna

In theory, any antenna that is designed to operate at the radio frequency of 1 GHz can be used to receive Mode S signals. However, it is possible to design own antenna as well. The carrier frequency of Mode S is 1090 MHz, which translates to a wavelength of 27.52 centimeters from the below relation.

$$\lambda = \frac{c}{f}$$

To create an antenna that is specifically tuned to this frequency, one can make use of a piece of conductor material (e.g., metal wire) and a coaxial feeder cable.

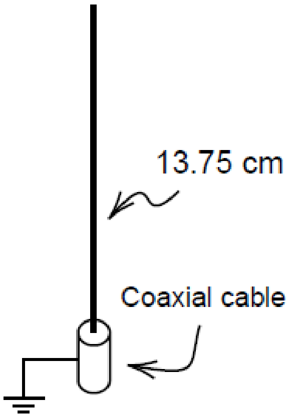


Figure 1.2: Monopole Antenna

Figure 1.3: Antenna installed on the rooftop of DMAE

1.7.2 Receiver

Today, a lot of Mode S receivers are constructed using software-defined radio technology. SDR is a type of radio where the functions of the physical layer, either fully or partially, are determined by software instead of hardware. To receive ADS-B signals

Figure 1.4: RTL-SDR (Receiver)

and other Mode S transmissions, the most commonly used low-cost receiver is RTL-SDR. RTL-SDR devices must be capable of handling the 2 million samples per second rate required for Mode S. In this scenario, we utilize the Radar Box (Flight stick) USB dongle receiver. This receiver boasts significant hardware upgrades such as an integrated filter, preamp, and ESD protection built-in.

1.7.3 Processor

The Raspberry Pi 4a is a fully operational computer in a compact and inexpensive design. Like many single-board computers, the Raspberry Pi is small in size, roughly the same as a credit card, but still boasts significant power. Despite its size, the Raspberry Pi is capable of performing the same tasks as larger and more power-intensive computers, though perhaps not at the same speed.

The Raspberry Pi, when integrated with the Radar Box as the receiver, forms a powerful and compact ADS-B monitoring system. The Raspberry Pi provides the computing power and versatility needed to process the data received from the RADAR Box, which serves as the receiver for ADS-B signals. The integration of these two devices allows for a cost-effective and customizable solution for monitoring air traffic data. The combination of the Raspberry Pi's open-source nature and the RADAR Box's advanced hardware features, such as the integrated filter, preamp, and ESD protection.

Figure 1.5: Raspberry Pi

1.8 Software Requirements

1.8.1 dump1090/readsb

Dump1090 is a simple Mode S decoder for RTL-SDR devices that allows you to receive and decode data transmitted by aircraft equipped with Mode S transponders. The software is open-source and can run on various platforms, including Raspberry Pi and Linux. The decoder takes in the raw RF signal from the RTL-SDR device, demodulates the signal, and decodes the data transmitted in the Mode S messages. The decoded data can then be displayed on a map or in other formats.

The decoder is also highly configurable, and supports several different output modes, including a simple console mode, a raw output mode for advanced users, and a web-based map mode that displays aircraft positions and flight data on a map.

1.8.2 MongoDB

MongoDB is a database that is designed to store and manage document-oriented data, represented as JSON documents. Unlike traditional relational databases that store data in tables with fixed columns and rows, MongoDB stores data in collections of documents, where each document can have a different structure and number of fields.

CHAPTER 2 LITERATURE REVIEW

2.1 GNSS Constellation

The term Global Navigation Satellite System (GNSS) refers to any satellite navigation system (for example, GPS, Glonass, Galileo, and Beidou) that provides continuous positioning around the world. Only GPS is certified to use in Aviation purpose.

There are three main segments of GNSS:

1. Space Segment:

The space segment's primary functions include generating and transmitting code and carrier phase signals, as well as storing and broadcasting the navigation message uploaded by the control segment. Onboard the satellites, highly stable atomic clocks control these transmissions. [8] GPS satellites orbit the Earth in six evenly spaced orbital planes, each with four slots occupied by baseline satellites. This 24-slot configuration ensures that at least four satellites can be seen from almost anywhere on the planet. [9]

2. Control Segment:

The control segment (also known as the ground segment) is in charge of ensuring that the GNSS functions properly. Its primary functions are: • controlling and maintaining the satellite constellation's status and configuration; • predicting ephemeris and satellite clock evolution; • maintaining the corresponding GNSS time scale (via atomic clocks); and • updating the navigation messages for all satellites. [8]

3. User Segment:

GNSS receivers make up the user segment. Their primary function is to receive GNSS signals, calculate pseudo ranges (and other observables), and solve navigation equations to obtain coordinates and provide an extremely accurate time.

A generic GNSS receiver consists of the following basic components: an antenna with preamplification, a radio frequency section, a microprocessor, an intermediate-precision oscillator, a feeding source, some memory for data storage, and a user interface. The calculated position is the antenna phase center. [10]

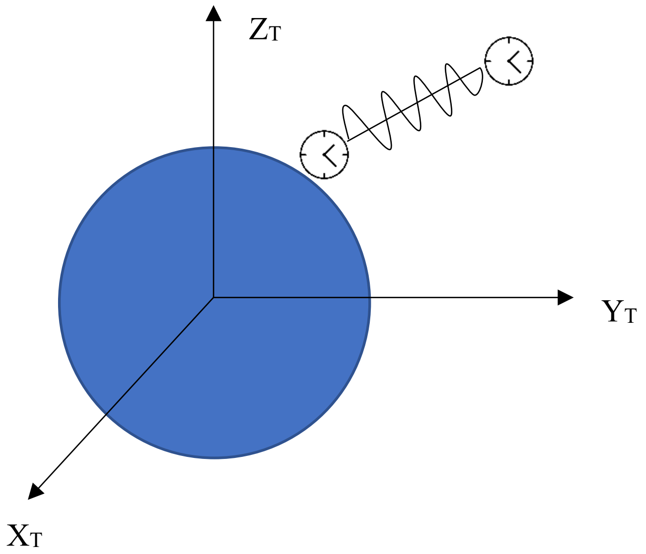


Figure 2.1: Working of GNSS

The signals which are transmitted from the satellite (Middle Earth Orbit, approximately 22,000 kilometers from the center of the Earth) and received by the user receiver travel at the speed of light. So, if we know the satellite transmit and receive times, we can calculate the distance between the satellite and the user receiver. The user receiver clock, on the other hand, is not precise, and the exact clock offset with respect to the reference time must be known. Satellite clocks are extremely accurate (atomic clocks). As a result, we don't know the precise distance between the satellite and the user receiver. We get the pseudo range instead.

Pseudo ranges equations in Navigations equation are given by the following equation:

$$\tau_c(t) = \{d_u^{(k)}/c + b_u - \delta B^{(k)}\} + \delta I_u^{(k)} + \delta T_{\underline{u}}^{(k)} + v_u \tag{1}$$

$$d_u^{(k)} = \{(x_u - x^{(k)})^2 + (y_u - y^{(k)})^2 + (z_u - z^{(k)})^2\}^{1/2} \tag{2}$$

Calculation of protection level:

In the precision approach, the horizontal and vertical protection levels are calculated using the equations below.

$$HPL = K_h * d_{major} \tag{4}$$

$$VPL = K_v * dU \tag{5}$$

Where $K_h = 6.00$ and $K_v = 5.33$

And,

$$d_{major} = \sqrt{\frac{d_{east}^2 + d_{north}^2}{2} + \sqrt{\frac{d_{east}^2 - d_{north}^2}{2} + d_{EN}^2}} \tag{6}$$

Where d_{east}, d_{north}, d_{EN}, d_U are the elements derived from D the variance/covariance matrix:

$$D = \begin{bmatrix} d_{east}^2 & d_{EN} & d_{EU} & d_{ET} \\ d_{EN} & d_{north}^2 & d_{NU} & d_{NT} \\ d_{EU} & d_{NU} & d_U^2 & d_{UT} \\ d_{ET} & d_{NT} & d_{UT} & d_i^2 \end{bmatrix} = (G^T W G)^{-1} \tag{7}$$

Here, the ith column of the geometry matrix G^T is defined as

$$G_i^T = \begin{bmatrix} \cos(El_i) \cdot \cos(Az_i) \\ \cos(El_i) \cdot \sin(Az_i) \\ \sin(El_i) \\ 1 \end{bmatrix} \tag{8}$$

Where El_i, Az_i are the elevation angle and azimuth of ith satellite. The W^{-1} weight matrix inverse is a diagonal matrix with the total variances of satellites.

$$W^{-1} = \begin{bmatrix} \sigma_1^2 & 0 & \dots & 0 \\ 0 & \sigma_2^2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \sigma_n^2 \end{bmatrix} \tag{9}$$

Where the ith variance has four components:

$$\sigma_i^2 = \sigma_{i,flt}^2 + \sigma_{i,UIRE}^2 + \sigma_{i,air}^2 + \sigma_{i,tropo}^2 \tag{10}$$

The concept of protection level was introduced in order to assign a numerical value to the reliability of navigation. If the protection level reaches the ICAO-defined alarm limit, satellite navigation may be regarded as failing to meet the required criteria. [10]

$$\text{Horizontal Position Error (HPE)} = d_{Major} * \text{UERE}$$

$$\text{Vertical Position Error (VPE)} = d_U * \text{UERE}$$

Here, UERE is the User Equivalent Range Error. This error consists of ranging error from the satellite and the avionics specific error.

NACp index are derived from the HPE error. The higher the HPE error, the bigger the Estimated position Uncertainty (EPU). Now, the NIC values are derived from EPU based on:

for NAC < 9:

$$Rc = 2 * EPU$$

for NAC >= 9:

$$Rc = 2.5 * EPU$$

And NIC gets values from 0-11 based on the corresponding Rc. [11]

2.2 Aircraft Altimeter (Barometer)

The aircraft altimeter is a barometer that measures pressure, rather than altitude directly. By measuring changes in atmospheric pressure, the pressure altimeter converts these changes into altitude through a set of assumptions and computer algorithms. This conversion process is based on standard atmospheric conditions, so any deviation from those conditions can lead to errors in determining the correct altitude. In essence, the pressure altimeter indirectly measures altitude by assuming a standard atmosphere and converting pressure changes into an altitude reading. [12]

Figure 2.2: Barometer [12]

When the temperature profile is colder than the standard atmosphere, the altimeter will display an altitude that is higher than the actual altitude of the aircraft. This discrepancy is particularly crucial in mountainous regions.

2.3 Geometric and Barometric Altitude

2.3.1 Barometric Altitude

In the field of civil aviation, barometric pressure-based altimeters installed on aircraft have traditionally been utilized to determine aircraft altitude from the mean sea level (MSL). These altimeters are configured to display pressure readings as altitude measurements in feet or meters, and their calibration is based on the presumption that pressure declines at a standard rate as altitude increases. They reference either the International Standard Atmosphere (ISA), which sets sea level pressure at 1013.25 hPa at 15°C, or the local sea level pressure provided by air traffic control (ATC), known as local QNH, depending on the aircraft's position relative to the transition altitude. [13]

Barometric altitude based on pressure difference is derived by using the following standard formula:

$$\mathrm{p} = \mathrm{p}_0 \left(1 - \alpha \frac{h}{t} \mathrm{t}_0\right)^{\frac{g_0}{\alpha \mathrm{R}}} \tag{11}$$

The above equation can be used to calculate the altitude 'h' from pressure difference as:

$$h = \frac{t_0}{\alpha}\{1 - \left(\frac{p}{p_0}\right)\frac{\alpha R}{g_0}\} \tag{12}$$

Where,

p = Pressure at altitude in hPa

p_0= Pressure at Mean Sea level i.e., 1013.25 hPa

α = Temperature gradient over the altitude (0.0065K/m)

t_0 = Temperature gradient at mean sea level

h = Altitude in meters

g_o = Acceleration due to gravity (9.81 m/s^2)

R = Gas Constant (287 J/KgK)

2.3.2 Geometric Altitude

The ADS-B's geometric altitude is determined using global navigation satellite systems, and in some cases, inertial navigation systems. These systems provide highly accurate altitude data that are updated frequently. The altitude is given in relation to the WGS84 reference ellipsoid. To be more precise, the altitude obtained from ADS-B is determined by measuring the distance between the aircraft and the WGS84 reference ellipsoid, rather than measuring the distance to the Earth's surface or sea level. The reason behind this approach is that the Earth's shape is not perfectly spherical, and by using a reference ellipsoid, it is possible to obtain altitude readings that are more accurate and reliable across various geographic regions. [13]

Although it is difficult to determine the exact level of accuracy of the geometric altitude obtained from ADS-B, studies suggest that it is roughly three times more accurate than the horizontal accuracy due to the positioning of satellites around the Earth. Specifically, research has demonstrated that the vertical error in the altitude measurement is less than 4.6 meters in 95% of the data collected. [14]

2.4 Performance Parameters

2.4.1 ADS-B Continuity

It is the probability that the system will operate as required without any unexpected breakdowns. The ADS-B system must deliver surveillance data at a rate of 1 Hz. The continuity of the ADS-B system is influenced by several elements including the uninterrupted flow of satellite information, the performance of onboard navigation systems and the constant communication of data links. [15]

2.4.2 ADS-B Uncertainty

The ADS-B Uncertainty signifies that at least 95% of the measurements are within the established uncertainty limits. Generally, a higher NUCp value implies greater confidence in the position measurement. The horizontal protection limit (HPL), the containment radius on horizontal position error (denoted as Rc/μ), and the containment radius on vertical position error (denoted as Rc/v) are utilized to quantify uncertainties when considering position error. All values are presented in a table. [3]

2.4.3 ADS-B Accuracy

The ADS-B Accuracy system is determined by comparing the aircraft's position as reported in the ADS-B message to its actual position. The quality of the position information can be assessed through the Navigation accuracy category position (NACp) value in the ADS-B message. This value indicates the accuracy of the horizontal position information (latitude and longitude) and vertical position information(altitude) transmitted from the aircraft's avionics. The NACp value is calculated by the ADS-B equipment based on the accuracy output from the position source, such as the Horizontal Figure of Merit (HFOM) from the GPS. The exact definitions for the Horizontal Figure of Merit (HFOM) and Vertical Figure of Merit (VFOM) are displayed in a table. [15]

Table 2.1: NACp Values [3]

NACp	HFOM	VFOM
11	< 3 m	< 4 m
10	< 10 m	< 15 m
9	< 30 m	< 45 m
8	< 0.05NM (93 m)	N/A
7	< 0.1 NM (185 m)	N/A
6	< 0.3 NM (556 m)	N/A
5	< 0.5 NM (926 m)	N/A
4	< 1.0 NM (1852 m)	N/A
3	< 2 NM (3704 m)	N/A
2	< 4 NM (7408 m)	N/A
1	< 10 NM (18520 m)	N/A
0	>10 NM or Unknown	N/A

The Navigation accuracy category - velocity (NACv) indicates that there is a 95% chance that the reported information regarding horizontal and vertical speeds is accurate. The definitions for Horizontal Figure of Merit for rate (HFOMr) and Vertical Figure of Merit for rate (VFOMr) are presented in the table below

Table 2.2: NACv Values [3]

NACv	HFOMr	VFOMr
0	N/A	N/A
1	< 10 m/s	< 15.2 m/s (50 fps)
3	< 3 m/s	< 4.5 m/s (15 fps)
3	< 1 m/s	< 1.5 m/s (5 fps)
4	< 0.3 m/s	< 0.46 m/s (1.5 fps)

2.4.4 ADS-B Integrity

The ADS-B integrity refers to the extent to which errors can be reliably detected. The NIC (Navigation Integrity Category) parameter defines a radius of position integrity containment. When using GPS as the position source, the NIC should be calculated based on the Horizontal Protection Limit (HPL) or Horizontal Integrity Limit (HIL). The relationship between NIC and Rc is as follows. [15]

Table 2.3: NIC and Containment Radius [3]

NIC	**Containment Radius**
0	Unknown
1	Rc < 20 NM (37.04 Km)
2	Rc < 8 NM (14.816 Km)
3	Rc < 4 NM (7.408 Km)
4	Rc < 2 NM (3.704 Km)
5	Rc < 1 NM (1852 m)
6	Rc < 0.3 NM (555.6 m)
7	Rc < 0.2 NM (370.4 m)
8	Rc < 0.1 NM (185.2 m)
9	Rc < 75 m
10	Rc < 25 m
11	Rc < 7.5 m

2.4.5 ADS-B SIL

The Surveillance Integrity Level (SIL) is used to indicate the likelihood of measurements exceeding the containment radius. Each SIL value corresponds to two probabilities, one for the horizontal component (P-RC) and one for the vertical component (P-VPL). [3] The definitions are in table below.

Table 2.4: Meaning of SIL Parameters [3]

SIL	P-RC	P-VPL
0	Unknown	Unknown
1	$< 1 * 10^{-3}$	$< 1 * 10^{-4}$
2	$< 1 * 10^{-5}$	$< 1 * 10^{-6}$
3	$< 1 * 10^{-7}$	$< 1 * 10^{-8}$

2.4.6 ADS-B SDA

The System Design Assurance (SDA) is a fixed value that is determined based on the System Safety Assessment and is dependent on the installation. System Safety Assessment is a structured and systematic process of identifying and analyzing hazards associated with the design, development, operation, and maintenance of a system. It represents the likelihood of an avionics malfunction resulting in the reported horizontal position exceeding the radius of containment defined by NIC, without triggering an alert.

Table 2.5: SDA Parameters [16]

SDA	Probability of Undetected Fault Causing transmission of False or Misleading Information
0	Unknown
1	$\leq 1*10^{-3}$ per flight
2	$\leq 1*10^{-5}$ per flight
3	$\leq 1*10^{-7}$ per flight

2.5 ADS-B Versions

Three implementations of ADS-B have been rolled out, with the aim of adding more information to the system. The first version, 0, was defined in the RTCA document DO-260. Version 1 was released around 2008 and was defined in DO-260A. Version 2 followed in 2012 and was defined in DO-260B. Currently, version 3 is under development. [17]

2.5.1 Version 0

The standardization of ADS-B messages was established by DO-260, which initially relied on Navigation Uncertainty Category for Position (NUCp) as the sole method of indicating the accuracy or integrity of the horizontal position data utilized by the ADS-B system. [18]

2.5.2 Version 1

DO-260A acknowledged the restrictions of relying solely on NUCp, which prompted modifications to the formats and protocols. It became possible to report accuracy and integrity independently using Navigation Accuracy Category for Position (NACp), Navigation Integrity Category (NIC), and Surveillance Integrity Level (SIL). [18]

2.5.3 Version 2

Version 2 of ADS-B, which builds upon 206B, incorporates lessons learned from operational use of ADS-B data. Significant modifications include expanded levels of NIC to enhance support for airborne and surface applications, elimination of the vertical component in calculating NIC and NAC parameters, and redefinition of the format and content of TC=28 and TC=31 messages. [18]

Table 2.6: Version of ADS-B and related parameters [3]

Indicator	**Acronym**	**Version**	**Values**
Navigation uncertainty category-Position	NUCp	0	0-9
Navigation uncertainty category-rate (velocity)	NUCr	0	0-4
Navigation accuracy category-position	NACp	1,2	0-11
Navigation accuracy category-velocity	NACv	1,2	0-4
Navigation integrity category	NIC	1,2	0-11
Surveillance integrity level	SIL	1,2	0-3

2.6 Anomalies in ADS-B message

2.6.1 Dropout

Dropout refers to an interruption in updates that occur within one second. While ADS-B is designed to update information at a rate of 1Hz, it's common to find that the update rate is longer than one second. Multiple dropouts have occurred during flight, and they've varied in duration. During enroute, the time between updates must not exceed three seconds. If the interval between two consecutive updates equals or exceeds three seconds, it's considered a dropout. [15]

2.6.2 Missing Payload

Missing payload refers to two distinct issues. In some instances, both basic and long messages are completely omitted, while in other cases, certain message fields are absent from the payload. [15]

2.6.3 Data Jump

Data jump refers to a situation where a data point deviates greatly from its preceding and subsequent samples. This anomaly is most commonly seen in latitude and longitude data and involves a deviation from the regular set of data, appearing as a jump when graphed. The cause of this is most likely due to encoding issues in either the GPS system or the generation of ADS-B messages. This phenomenon is also known as "ghost traffic" to air traffic controllers, where an aircraft is detected in an area but in reality, there is no actual traffic present. [15]

2.6.4 Altitude Discrepancy

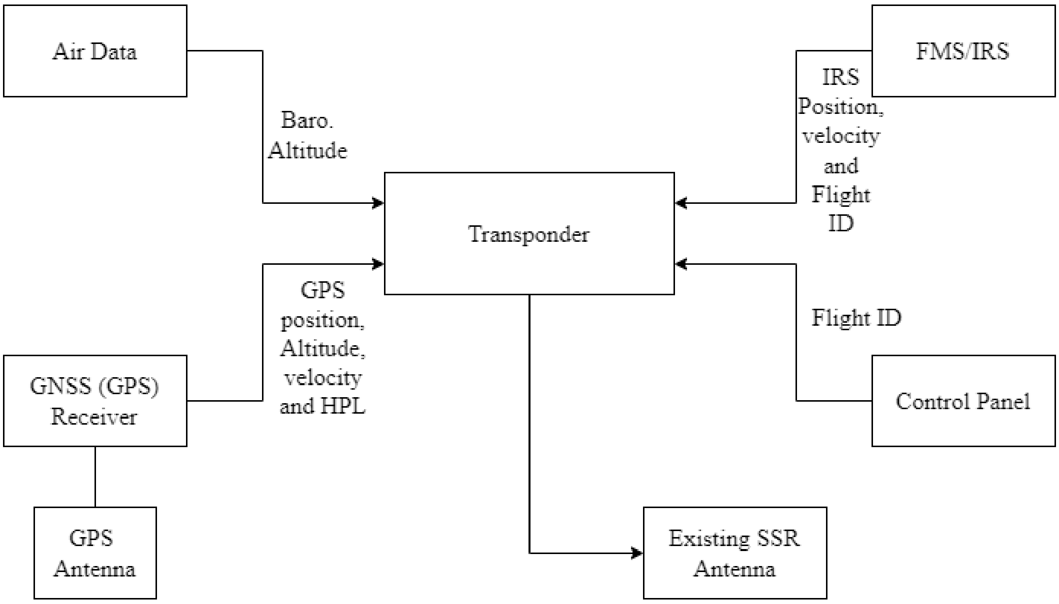
The data provides two separate altitudes, one from a pressure sensor and the other from GPS. The aviation industry has long relied on barometric altitude for measuring altitude and maintaining separation. The examination of the long report reveals discrepancies between barometric and GPS-based altitude. [15]

2.6.5 Low Confidential Data

Expectations are that the ADS-B position report should have an NIC value higher than 8 and an NACp value higher than 7. Nevertheless, the ADS-B system sometimes reports positions with values lower than these expectations. When the NIC is greater than 8 or the NACp is greater than 7, this data is referred to as precision condition data [15]

2.7 Existing ADS-B avionics and errors

The ADS-B Out avionics system on an aircraft obtains input from several sources to create and transmit ADS-B messages. The system receives information such as time, horizontal and vertical position, and speed from an onboard GNSS receiver, as well as barometric pressure altitude from an altitude encoder installed onboard. Additionally, the system incorporates pilot-entered aircraft identification details, including beacon code and call sign. Subsequently, the avionics compiles this information into a digital ADS-B message and broadcasts it via the aircraft's installed antenna.



Typically, any given aircraft will have at least one of the ADS-B out data link: [19]

Figure 2.3:ADS-B Out System [22]

2.7.1 Universal Access Transceiver (UAT)

UAT is an ADS-B Out avionics that uses a frequency of 978 MHz to broadcast aircraft position data to other aircraft and ground stations. UAT is primarily used in general aviation and provides weather and traffic information to pilots.

2.7.2 Extended Squitter (ES)

ES is another type of ADS-B Out avionics that uses a frequency of 1090 MHz to broadcast aircraft position data to other aircraft and ground stations. ES is primarily used in commercial aviation and is required for aircraft flying in certain airspace.

2.7.3 Mode S Transponder with ADS-B Out

Mode S transponders are already installed in most aircraft and can be upgraded with an ADS-B Out capability. Mode S transponders with ADS-B Out use a frequency of 1090 MHz to broadcast aircraft position data to other aircraft and ground stations.

2.7.4 GPS receiver with ADS-B Out

A GPS receiver with ADS-B Out is a standalone device that receives GPS signals and broadcasts aircraft position data to other aircraft and ground stations using either 978 MHz or 1090 MHz frequencies.

2.7.5 Integrated ADS-B Out System

An integrated ADS-B Out system is a complete avionics suite that includes both the transponder and GPS receiver with ADS-B Out capabilities. Integrated systems are commonly used in new aircraft and offer enhanced functionality and ease of use.

Some of the ADS-B out avionics manufacturer are:

1. Rockwell Collins

2. Honeywell
3. Garmin
4. ACSS

Table 2.7: ADS-B Out Avionics [17], [20], [21], [22]

Manufacturer	**Model**	**Aircraft**
Rockwell Collins	TPR 901-201	B747
	ISS 2100	B787
	TPR 901-021	Most of the Airbus aircrafts
Honeywell	TRA 100B	B737/B767/B777 /Embraer 170
Garmin	GPS 3000 and GTX 3000	ATR-42/ATR-72
ACSS	XS-950	A320/A330

Table 2.8: Known ADS-B Out Avionics Problems [17]

Manufacturer	**Model**	**Problems**
Rockwell Collins	TPR901	Track jump problem
		Missing and improper message elements
		Software problem interfacing with flight Id source
		Rely on INS-derived location for ADS-B reports while taxiing and switch to GNSS only when approaching the runway
	TDR94	Position error with good NIC and NUC
	TSS-4100	The pattern of erroneous positional data
		Track extrapolation issue
Honeywell	TRA 100	Geometric altitude reporting as barometric altitude
		Missing or improper message elements link NACv
		Track jump
		Software flaw that causes an erroneous NACV=0 reporting condition
	Primus II RCZ	Filling flight plans as ADS-B equipped, but not transmitting ADS-B
		Radio Management Unit (RMU) fail to notify the flight crew that ADS-B Out functionality is disabled.
Garmin	N/A	Flight ID problem
ACSS	N/A	Reports NUC based on HFOM

2.8 ADS-B Performance Monitoring System

As per the ICAO standard [23], the parameters to be considered for the monitoring of ADS-B system are:

1. Integrity Reports in Percentage of aircraft (NIC Value)
2. Horizontal Position accuracy of ADS-B system (NACp Value)
3. Geometric and Barometric Height Deviation
4. Number of Position Monitoring.
5. Message Interval rate.

CHAPTER 3 METHODLOGY

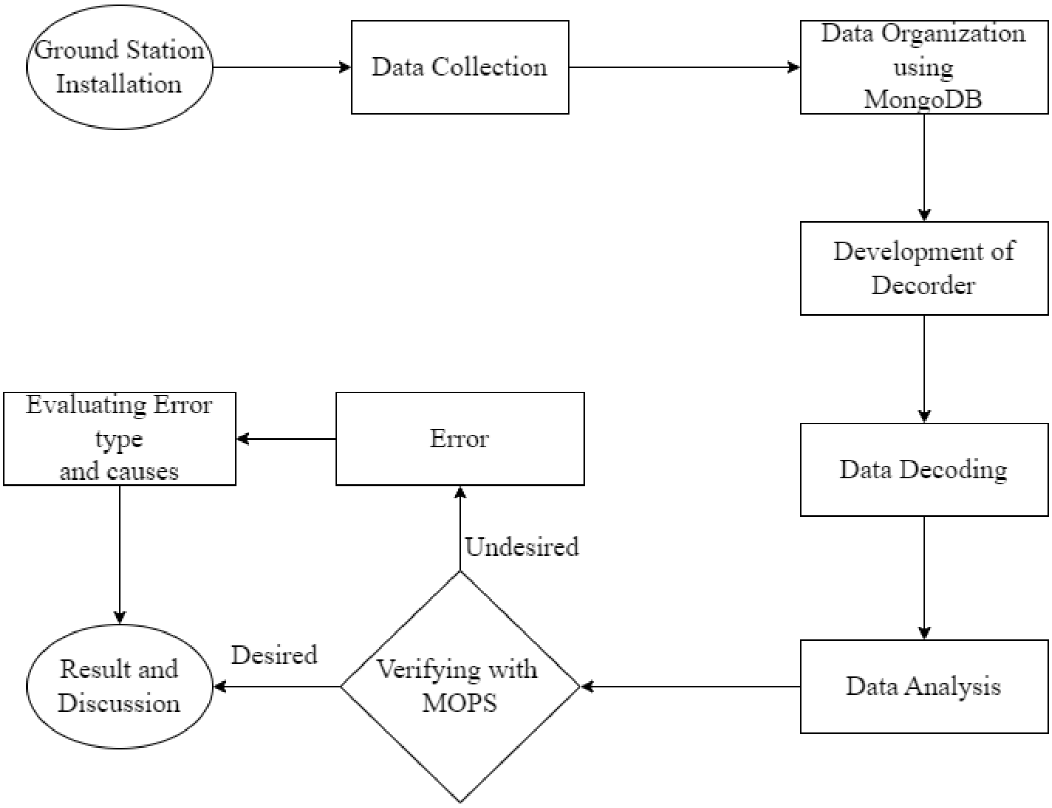


Figure 3.1: Methodology

3.1 Ground Station Installation

To analyze the performance of ADS-B Out from aircraft, an ADS-B ground station has been installed on the roof of the Department of Mechanical and Aerospace at Pulchowk Campus as well as in Munich, Germany. The ADS-B ground station is able to receive signals broadcasted by the Mode S transponder.

The following components are used:

a) Raspberry Pi
b) Antenna 1090 MHz
c) Radar Box (as a receiver)
d) Cooling fan.

3.2 Data Collection

The ground station has been installed and the Raspberry Pi has been configured to receive Mode S signals through the use of dump 1090 (readsb). The signals are transmitted as a hexadecimal string. A Python script was used to gather the data. Although data collection began in December, there were few outages due to storage issue and electricity outage which prevented consistent data collection.

3.3 Data Organization using MongoDB

Since the update rate of ADS-B messages is 1 second, a large number of JSON files have been collected. Proper organization of these JSON files is necessary for the analysis of ADS-B parameters, which is achieved by using MongoDB. The JSON files can be organized according to specific requirements, such as:

a) By a specific flight
b) By aircraft type
c) By flight phases

3.4 ADS-B Message Decoder

The Python-based decoder is used to extract information such as position, velocity, and identification from the Mode S Extended Squitter transmission. By decoding the received hexadecimal string, we obtain an ADS-B frame composed of 112 bits, which is divided into five main segments as illustrated below:

DF (5)	CA (3)	ICAO (24)	ME (56)	PI (24)

The ADS-B message for civil aircraft begins with the Downlink Format 17, which is represented by the binary value 10001 in the first 5 bits. The transponder's capability is indicated by bits 6-8, followed by the 24-bit transponder code, also referred to as the ICAO code. The last two sections of the message are the 56-bit payload and the 24-bit parity. The table provided below summarizes the essential details of an ADS-B message.

Table 3.1: Structure of ADS-B Message [3]

Bits	No. Bits	Abbreviation	Information
1-5	5	DF	Downlink Format
6-8	3	CA	Transponder capability
9-32	24	ICAO	aircraft ICAO address
33-38 (33-37)	56 (5)	ME (TC)	Message, extended squitter (Type code)
89-112	24	PI	Parity /Interrogator ID

The ICAO address, which acts as a unique identifier for each aircraft, is located within the binary representation of the message between bits 9 and 32 (or between positions 3 and 8 in hexadecimal). Each Mode S transponder is assigned a unique ICAO address.

In order to determine the contents of an ADS-B message, it is necessary to examine the Type Code of the message, which can be found in the first five bits of the ME segment (bits 33-37). Table 3.2 outlines the various Type Codes and the corresponding information contained within the ME segment.

Table 3.2: ADS-B Message Type Code [3]

Type Code	Data frame content
1-4	Aircraft identification
5-8	Surface position
9-18	Airborne position (Barometric Altitude)
19	Airborne velocities
20-22	Airborne position (GNSS)
23-27	Reserved
28	Aircraft status
29	Target state and status information
31	Aircraft operational status

3.4.1 Aircraft Identification

The Type Code of this particular message range from 1 to 4. The ME field, which is 56 bits in length, is comprised of 10 components and is organized in the following manner:

<table>
<tr><td>TC, 5</td><td>CA, 3</td><td>C1, 6</td><td>C2, 6</td><td>C3, 6</td><td>C4, 6</td><td>C5, 6</td><td>C6, 6</td><td>C7, 6</td><td>C8, 6</td></tr>
<tr><td colspan="7" rowspan="3"></td><td colspan="3">TC: Type code</td></tr>
<tr><td colspan="3">CA: Aircraft category</td></tr>
<tr><td colspan="3">C: Character</td></tr>
</table>

The message includes the aircraft's callsign as its identification. The last eight sections of the previously shown structure diagram correspond to the characters of the callsign.

3.4.2 Airborne position

The aircraft airborne position message is utilized to transmit the altitude and position of the aircraft. This message is identified by Type Code 9-18 and 20-22. If the Type Code is between 9 and 18, the encoded altitude specifies the barometric altitude of the aircraft. On the other hand, if the Type Code is between 20 and 22, the encoded altitude denotes the GNSS altitude of the aircraft. The composition of the ME field of the ADS-B airborne position message is illustrated below:

TC, 5	SS, 2	SAF, 1	ALT, 12	T, 1	F, 1	LAT-CPR, 17	LON-CPR, 17

The message contains eight fields, and the information for all essential fields is presented in the table below:

Table 3.3: Airborne Position Message Structure [3]

Field	**Abbreviation**	**MSG**
Type code 9-18: barometric altitude 20-22: GNSS altitude	TC	33-37
Encoded altitude	ALT	41-52
Encoded latitude	LAT-CPR	55-71
Encoded longitude	LON-CPR	72-88

3.4.3 Surface Position

A distinct type of message is utilized to transmit the position information of an aircraft when it is on the ground. In contrast to the airborne position message, the surface position message also provides the speed of the aircraft. The surface position message is identified by Type Code 5-8, and the structure of the ME field for the surface position message is as follows:

TC, 5	MOV, 7	S, 1	TRK, 7	T, 1	F, 1	LAT-CPR, 17	LON-CPR, 17

The message contains eight fields, and the information for all essential fields is presented in the table below:

Table 3.4: Surface Position Message Structure [3]

Field	Abbreviation	MSG
Type code	TC	33-37
Movement (ground speed)	ALT	38-44
Ground track (with respect to true north)	TRK	46-52
Encoded latitude	LAT-CPR	55-71
Encoded longitude	LON-CPR	72-88

3.4.4 Airborne Velocities

Type Code 19 (TC=19) is used to transmit airborne velocities. The table below demonstrates the overall structure of this message:

Table 3.5: Airborne Velocities Message Structure [3]

Field		**MSG**
Type code (TC=19)	TC	33-37
Sub-type	ST	38-40
Navigation uncertainty category for velocity ADS-B version 0 ADS-B version 1-2	NUCr NACv	43-45
Sub-type specific fields	-	46-67
Source bit for vertical rate (0: GNSS, 1: Barometer)	V_rS_{rc}	68
Sign bit for vertical rate (0: Up, 1: Down)	S_{vr}	69
Vertical rate	V_rS_{rc}	70-78
Others	-	79-88

3.4.5 Aircraft Operational Status

The aircraft operational status message is intended to provide diverse information about an aircraft and is transmitted using Type Code 31 (TC=31). However, the structures of this message type vary greatly across different versions of ADS-B.

Table 3.6: Aircraft Operational Status Message Structure for Version 2

FIELD		**MSG**
Type code (TC=31)	TC	33-37
ADS-B version	Ver	73-75
NIC supplement-A	NICa	76
Navigation accuracy category-position	NACp	77-80
Geometric vertical accuracy	GVA	81-82
Source Integrity level	SIL	83-84

3.5 Data Decoding

The hexadecimal string was decoded using the opensource python library pyModeS (https://github.com/junzis/pyModeS). Different messages contain different types of information. Few of them are listed below:

3.5.1 Aircraft Identification

```
"Message": "8D406AE82350F374E03820000000",

"ICAO address": "406AE8",

"Downlink Format": "17",

"Protocol": "Mode-S Extended Squitter (ADS-B)",

"Type": "Identification and category"
```

3.5.2 Aircraft Position

```
"Message": "8D4064BB58BF0039108C75000000",

"ICAO address": "4064BB",

"Downlink Format": "17",

"Protocol": "Mode-S Extended Squitter (ADS-B)",

"Type": "Airborne position (with barometric altitude)",

"CPR format": "Even",

"CPR Latitude": "0.05572509765625",

"CPR Longitude": "0.27433013916015625",

"Altitude": "37000 feet"
```

3.5.3 Surface Position

```
"Message": "8D4064BB990956A7780437000000",
"ICAO address": "4064BB",
"Downlink Format": "17",
"Protocol": "Mode-S Extended Squitter (ADS-B)",
"Type": "Ground position",
"Speed": "463 knots",
"Track": "132.64 degrees"
```

3.5.4 Airborne Velocities

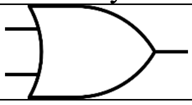
```
"Message": "8D4BB285990DB30B380437000000",
"ICAO address": "4BB285",
"Downlink Format": "17",
"Protocol": "Mode-S Extended Squitter (ADS-B)",
"Type": "Ground speed",
"Speed": "442 knots",
"Track": "281.46 degrees",
"Vertical rate": "0 feet/minute"
```

3.6 Data Analysis

Data analysis of ADS-B out performance parameters involves the examination and interpretation of the data contained in these files to gain insights and draw conclusions about the performance of the ADS-B system. The message from ADS-B Out transponders is grouped daily and weekly and different parameters like barometric altitude, geometric altitude, NIC, NACp, SIL, SDA, etc. are extracted.

3.7 Fault Tree Analysis: Anomaly Detection & Identification

The Fault Tree Analysis (FTA) method is an approach to identify the underlying reasons for failures or potential failures by starting from the top and working downwards. It utilizes Boolean logic to merge various lower-level events.

Name of Gate Used	Classic FTA Symbol	Description
OR Gate		Any one of the events triggers the output.

Anomaly in ADS-B can be categorized under two main sub divisions, namely:

3.7.1 Error in Avionics

There can be several factors leading to the error in avionics side. Inadequate functioning of Barometer to read the barometric altitude can result from either of Incorrect QNH reading. Pilot can also make mistake in reading QNH value due to heavy workload. Barometer efficiency also depends upon the flight level. Its efficiency decreases with increase in altitude due to atmospheric pressure change. Barometer needs to be properly calibrated to avoid such error.

Incorrect parameter retrieval leads to avionics error. Avionics partially functionality can lead to data jump like track jumping, Longitude and latitude jump, etc. Wrong ICAO address results from installation error leading to incorrect parameter retrieval. Wrong 24-bit code also can lead to such issues.

GNSS efficiency depends upon geometry of satellite and atmospheric activities. Geometry refers to Dilution of Precision (DOP). Lower the DOP, better the GNSS performance. Ionospheric activities also should be minimum. GNSS failure ultimately leads to position error. RF Jamming also should be avoided as it can cause error in position.

There can be blockage in the static port of pitot static tube leading to error in reading of velocity.

3.7.2 Error in Ground Station

Ground station plays an important role in this System. Error in the system can degrade the performance of entire system leading to failures from minute failure to critical failure mode.

The data can be corrupted in the ground station when the data receiver is inaccurate or there might be problem in the data processing procedure in the ground station. Failure in operation procedure can arise due to communication error. Inadequate training to the operation can also lead to errors. There can be reduction in the ADS-B integrity. Ground station equipment can be out of service due to lack of maintenance or environment condition like rain, storm, etc.

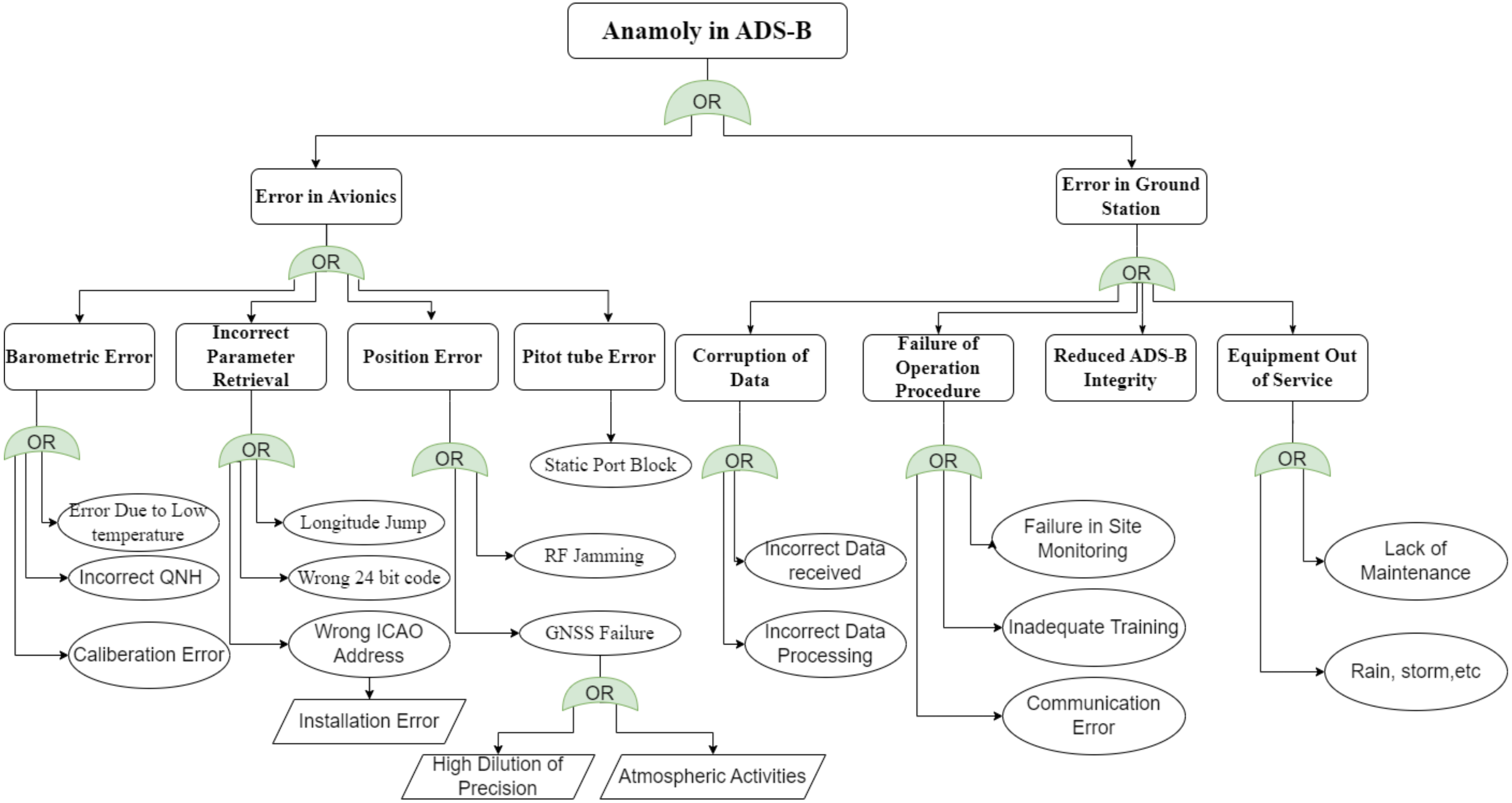


Figure 3.2: Fault Tree Diagram

3.8 Verifying with MOPS

Minimum Operational Performance Standards (MOPS) are used as a reference to verify the performance of ADS-B parameters. For example, the MOPS requirement for the Enroute data update rate is that it must not exceed 3 seconds. If the performance parameters do not meet the MOPS standards, they are categorized as errors.

3.8.1 Evaluating Error type and causes

Errors detected during MOPS verification are further evaluated to determine the type of error among the different types such as dropout, missing payload, data jump, altitude discrepancy, or low-confidence data. After identifying the error type, further investigation is conducted to understand the cause of the error. The reasons for errors could be attributed to aircraft avionics, altitude, range, heading, or position.

3.9 System Level Architecture

The system level architecture interrelates different interfaces and modules in a system. In our ADS-B monitoring system, there are various blocks which are divided into three different groups: input gateway, ADS-B processor and service platform. The Ground Station is the main input gateway for the data required for our monitoring system.

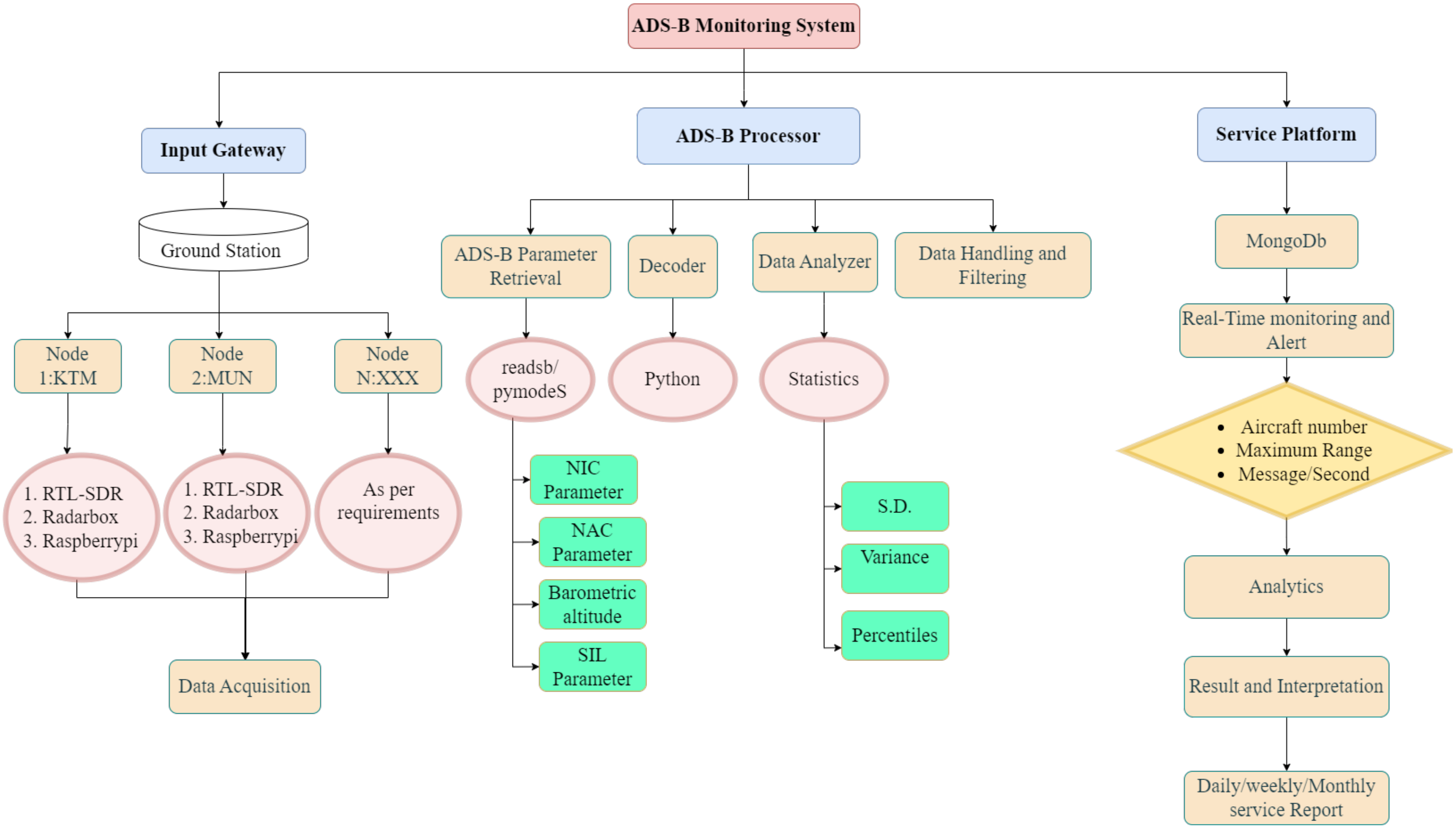


Figure 3.3: System Level Architecture

3.10 System Requirements

Table 3.7: System Requirement

Type	ID	Requirement Description
Functional	FR1	The ADSB data analytics shall compute the periodic or cyclic statistical distribution based on, avionics transponder (ADS-B or Mode-S), particular aircraft type, phases of flight and versions of ADS-B message.
	FR2	The ADSB monitoring visualization shall provide ADS-B parameters like latitude and longitude, Baro-Alt as well as Geo-Alt, NIC, NAC, SIL and version type.
	FR3	The core processing shall characterize the behavior of flights based on the flight levels approach, descent and departing.
	FR4	The core processing shall characterize the aircraft and compare with the database (where aircraft model can be looked upon and check its characteristics)
	FR5	The system shall detect anomalies in the ADSB avionics messages
	FR6	The system shall identify anomalies in the ADSB avionics messages
	FR7	The system shall locate the root source of anomalies in the ADSB avionics
Operational	OR1	The data logging shall be repeated after within two seconds.
	OR2	The operator shall have access to software that supports ports like VNC viewer and SSH.
	OR3	The operator shall have backup for the power outage issue.
	OR4	The operator shall be familiarized with the knowledge of ADS-B parameter and Surveillance System.
Design	DR1	The receiver antenna shall be vertically polarized tuned to 1090Mhz.
	DR2	The antenna location shall not be obstructed by any kind of obstacles while receiving the signal from the aircraft.
	DR3	Adding low noise amplifier (LNA) shall improve the performance of the system.
	DR4	The power supply shall be continuous with sufficient storage capacity.
	DR5	Raspberry pi temperature shall be regulated around the operating temperature range. Integration of cooling fan is recommended.
User	UR1	The product shall provide correlation between geometric and barometric altitude.
	UR2	The product shall provide ADS-B performance statistical report by daily, weekly and monthly.
	UR3	The product shall provide real time visualization as well as region of anomalies.
	UR4	The product shall provide ADS-B avionics quality.
	UR5	The product shall provide open interface to third party.

CHAPTER 4 RESULT AND DISCUSSION

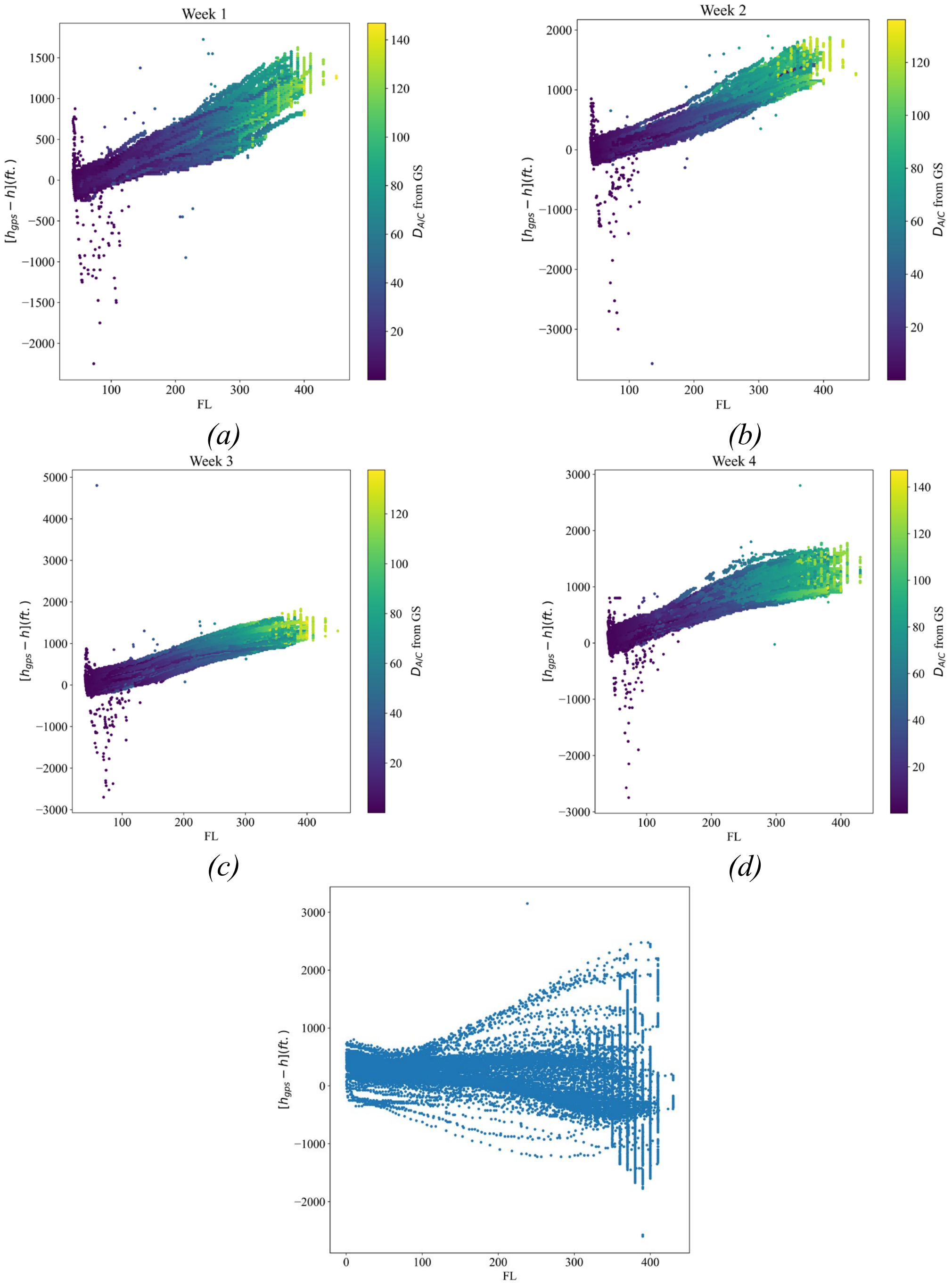
For the performance analysis, following assumptions and considerations have been made:

1. The barometric altitude of all range is expressed in terms of FL but as per the recommended practices, altitude above transition altitude is only expressed in FL. The altimetry system used in the Kathmandu Flight Information Region (FIR), includes a designated layer to distinguish between aircraft using QNH and those using a standard pressure of 1013.2 hPa. This layer, known as the transition layer, is applicable for altitudes ranging between a transition altitude of 13,500 feet and a transition level of Flight Level (FL) 150. [24]
2. $D_{A/C}$ from Ground Station (GS) refers to the distance of aircraft tracked from the installed ground station at Pulchowk Campus in Nautical Miles.
3. The difference of geometric and barometric altitude is denoted by [h_{gps} - h] (ft). The difference is expressed in term of feet.

$$\Delta altitude = h_{gps} - h$$

4. Data obtained from ground installation were divided into 4 weeks. Week 1 contains the data collected from Jan 11, 2023 to Jan 17, 2023. Week 2 contains the data collected from Feb 4, 2023 to Feb 10, 2023. Similarly, Week 3 refers to Feb 11, 2023 to Feb 17, 2023 and Week 4 refers to Feb 18, 2023 to Feb 24, 2023.
5. Data in Munich airspace were collected from ADS-B exchange for the aircraft flying in Munich for one day.

4.1 Correlation of Aircraft Barometric Altitude and Geometric Altitude



(a) *(b)* *(c)* *(d)* *(e)*

Figure 4.1: Altitude Difference vs FL

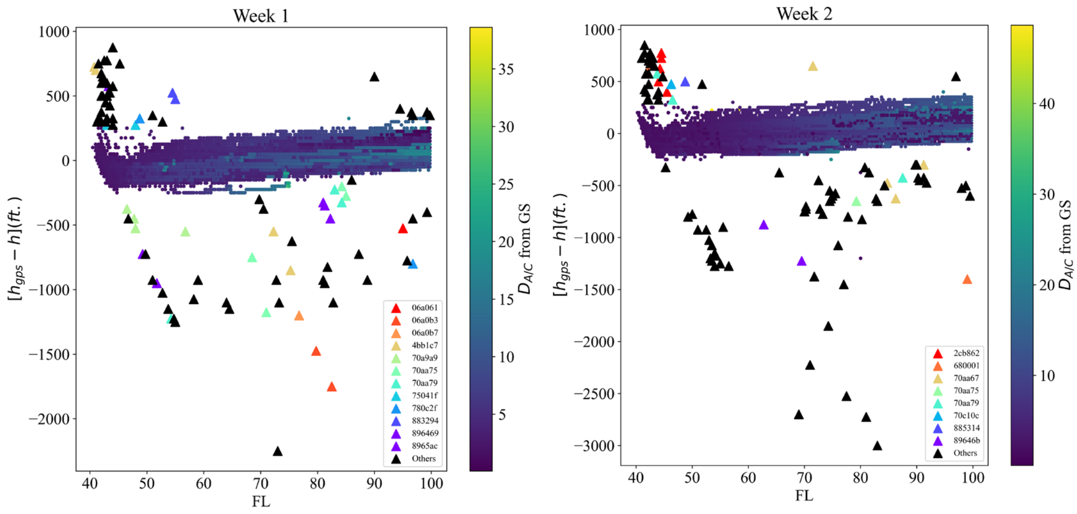
for (a) week 1 (b) week 2 (c) week 3 (d) week 4 of KTM FIR and (e) Munich Airspace

In fig 4.1(a)-(d), [h_{gps} - h] keeps on increasing with the increase in FL. This is due to the variation of barometric altitude with increase in pressure on increasing the altitude. From equation 11 and 12, barometric altitude decreases with decrease in temperature and pressure. Therefore, the variation in [h_{gps} - h] increases with increase in altitude.

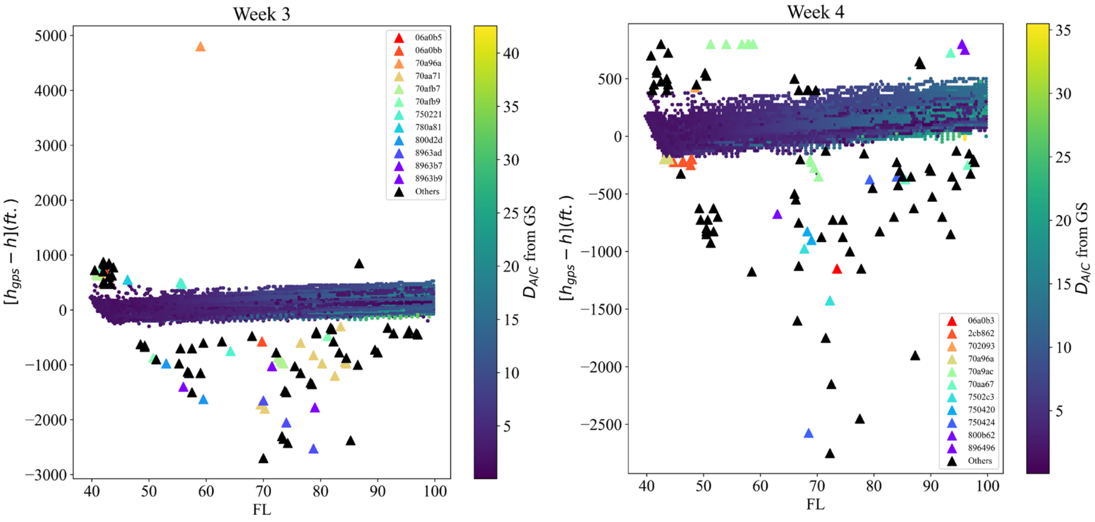
Table 4.1: Correlation Coefficients

SN	WEEK	Correlation Coefficients
1	Week 1	0.968
2	Week 2	0.975
3	Week 3	0.967
4	Week 4	0.956

The maximum distant aircraft tracked by ground station was around 125 NM in the southern region and maximum altitude was around 450 FL. In fig. 4.1 (a) – (d), large number of outliers were detected with maximum outliers being in the FL below 100. This can be seen in the graph below where the FL is grouped as 0-100, 100-200, 200-300 and greater than 300:



(a) *(b)*



(c) *(d)*

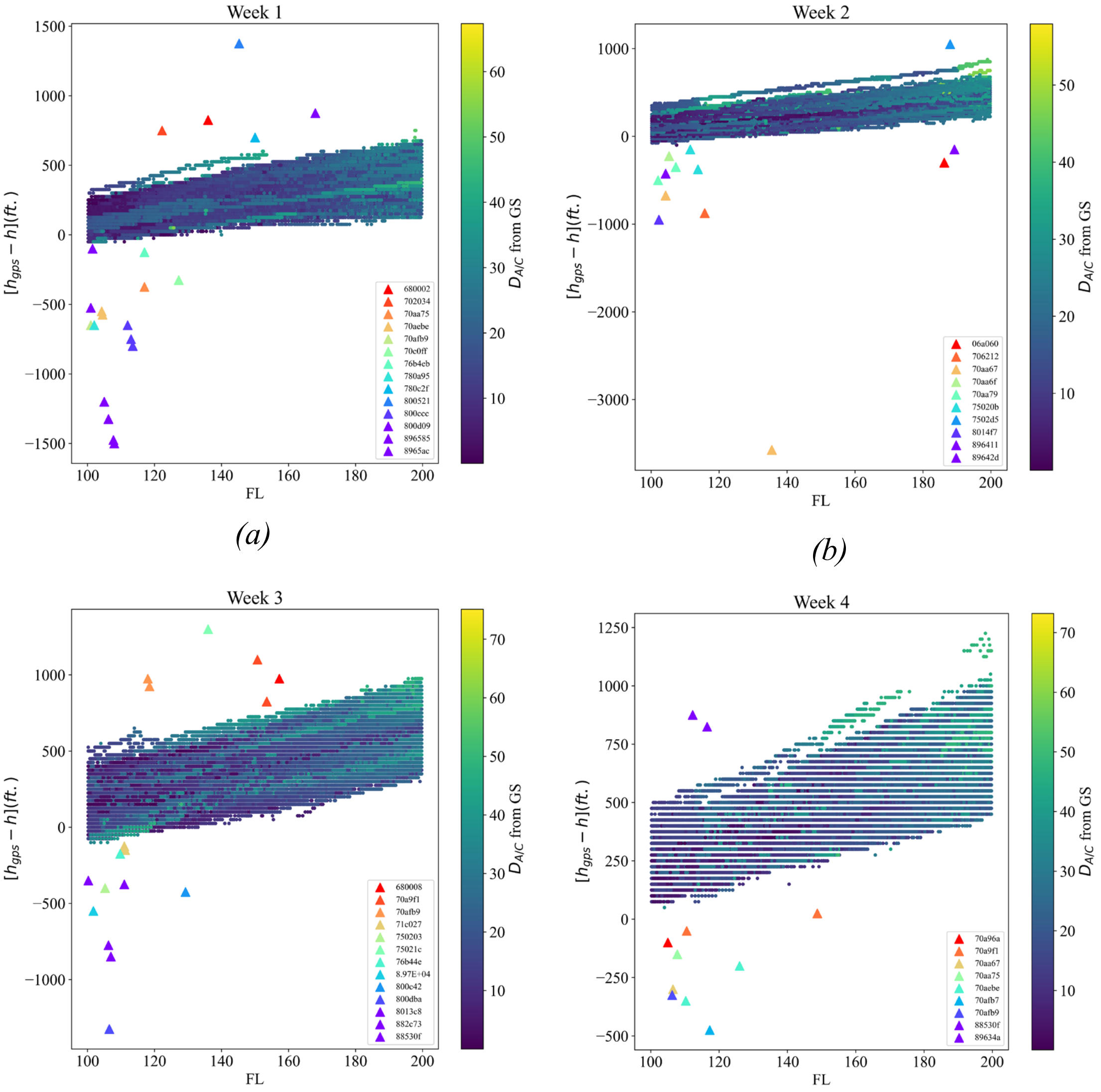
Figure 4.2: Altitude difference vs FL (0-100)

for (a) week 1 (b) week 2 (c) week 3 (d) week 4

The gradient in this range of FL was linear and lower and it goes on increasing in 100-200 FL,200-300 FL, and greater than300 FL. The number of outliers also decreases with increase in FL. Most of the outliers were obtained in 0-100 FL. The outliers are represented by triangle in the plots. The [h_{gps} - h] was in the range of -300 to 300 ft in 0-100 FL. This altitude is the terminal airspace. Since the air traffic is high in this altitude range, the error should be as minimum as possible. Hence, ADS-B data obtained cannot be used for navigation purpose solely. However, ATC can apply data fusion with other surveillance system data.

Table 4.2: Outliers in 0-100 FL

SN	Week	Number of Outliers in 0-100 FL
1	Week 1	624
2	Week 2	556
3	Week 3	475
4	Week 4	636



(a) *(b)*

(c) *(d)*

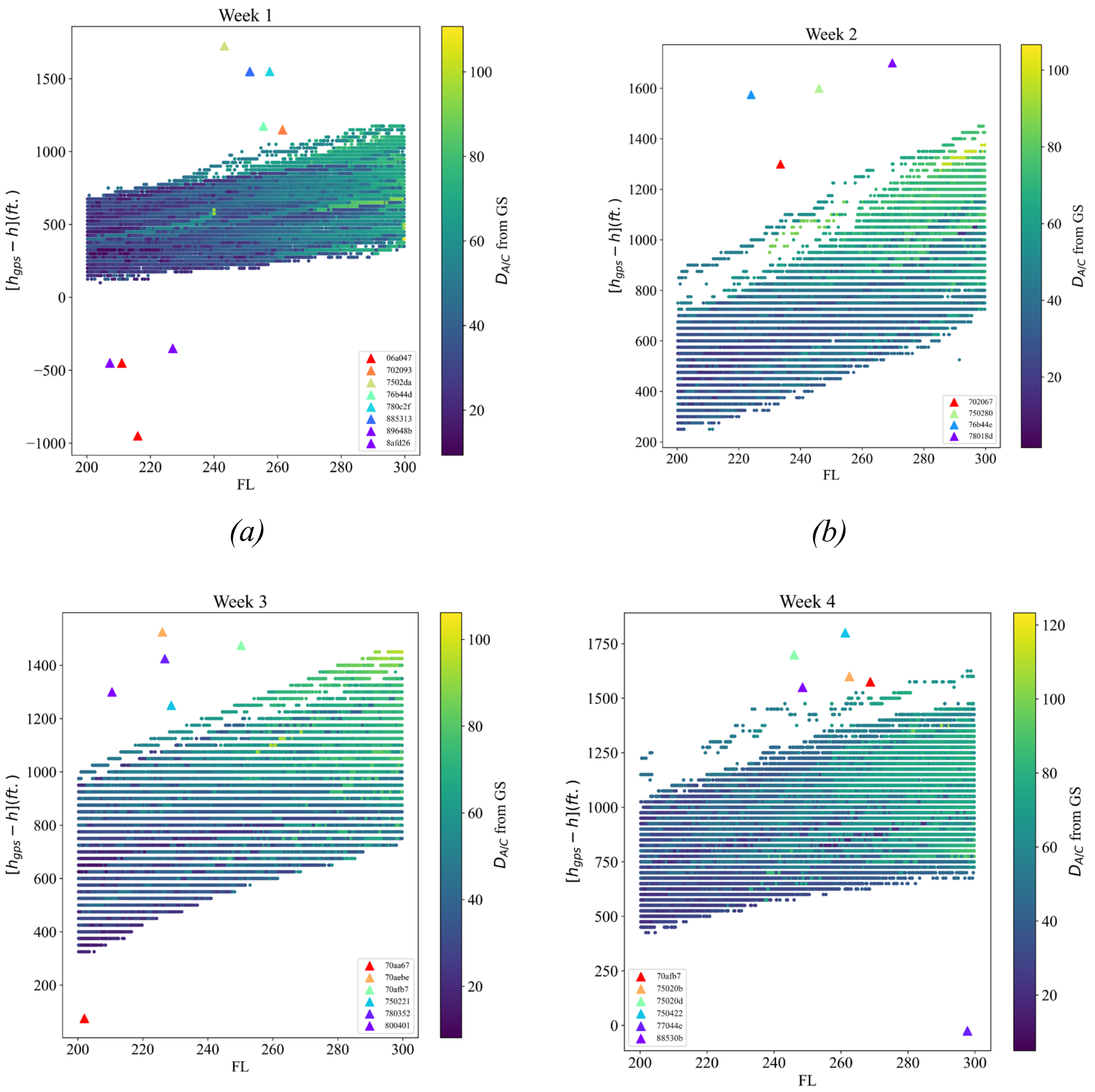
Figure 4.3: Altitude difference vs FL (100-200)

(a) for week 1 (b) for week 2 (c) for week 3 (d) for week 4

The number of outliers decreased in 100-200 FL than in 0-100 FL. The transition altitude falls under this range of FL. Transition altitude is defined between 13500 feet and 150FL as described earlier. Above transition altitude the standard QNA value is given and below transitions altitude Local QNH value is given to determine the barometric altitude. In case of above the transition altitude QNE value is same so it helps to reduce the separation criteria since both the aircraft operation have same QNE value.

Table 4.3: Outliers in 100-200 FL

SN	Week	Number of Outliers in 100-200FL
1	Week 1	91
2	Week 2	78
3	Week 3	69
4	Week 4	78



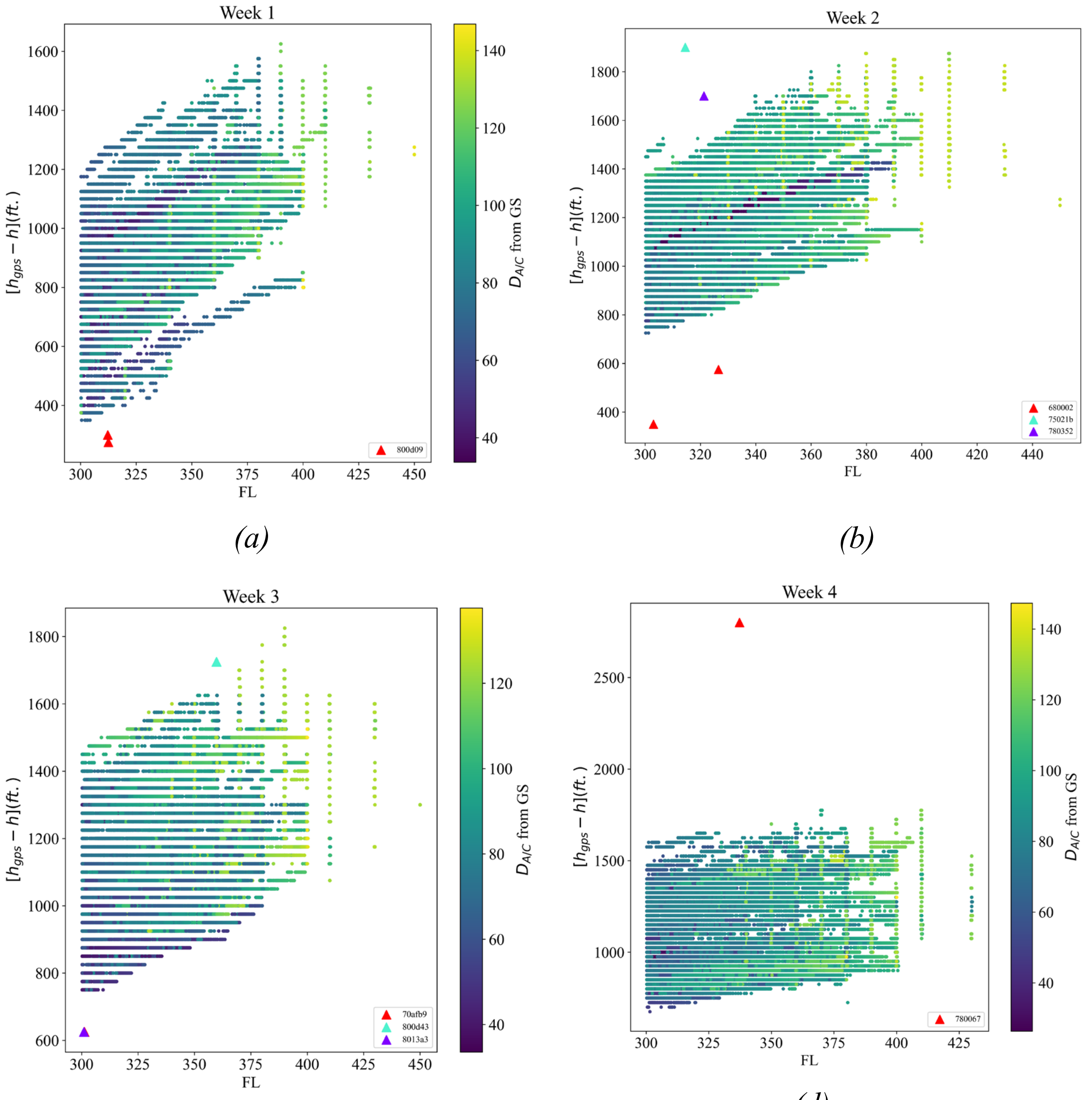
(a) *(b)*

(c) *(d)*

Figure 4.4: Altitude difference vs FL (200-300)

(a) for week 1 (b) for week 2 (c) for week 3 (d) for week 4

This number of Outlier drastically decreased in 200-300 FL. The gradient increases due to higher altitude. This can be also validated from the correlation of pressure with altitude as shown in appendix. This is the region of Reduced Vertical Separation Minima (RVSM). The altitude above 290 FL up to 410 FL is the RVSM where the vertical separation should be less than 1000 ft. [25] The vertical error should be less than 245 ft to fly in this airspace. From the plot, the aircraft altitude difference ranges around 1200 ft. Therefore, aircraft flying under this region cannot use RVSM procedure.



(a) (b) (c) (d)

Figure 4.5: Altitude difference vs FL (>300)

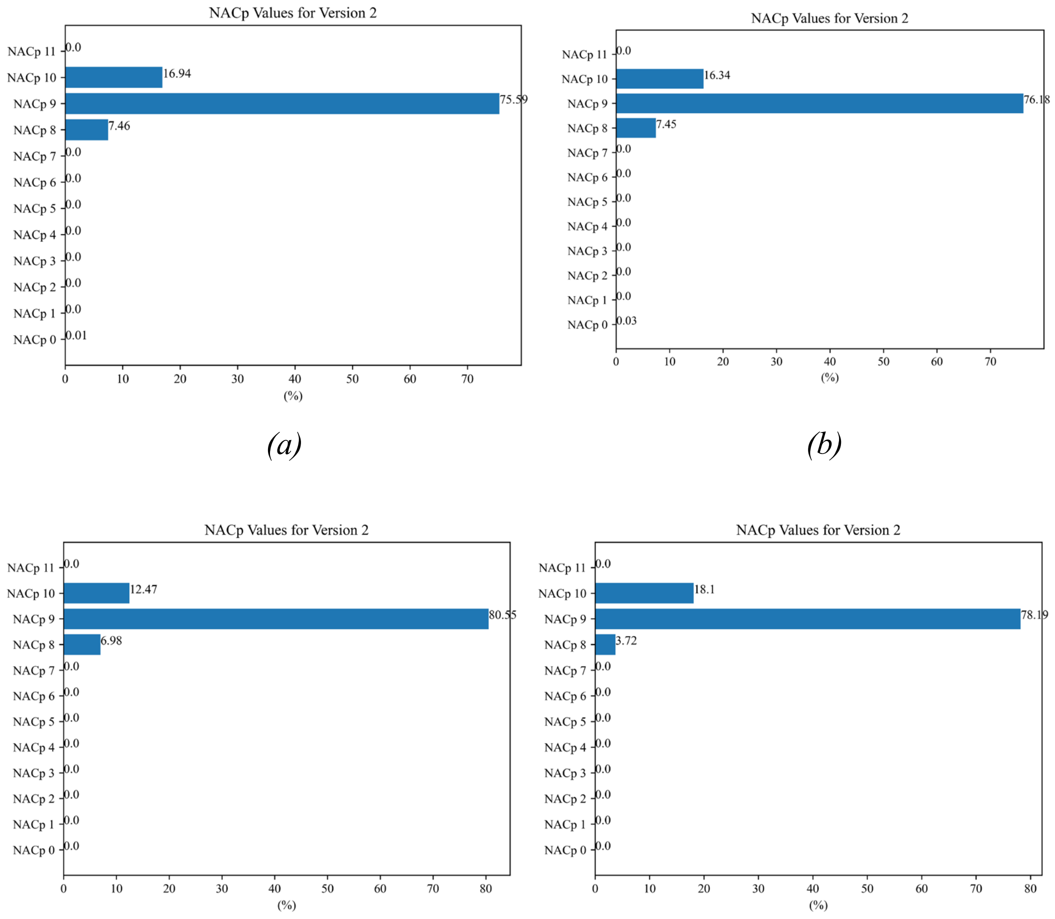
(a) for week 1 (b) for week 2 (c) for week 3 (d) for week 4

Outliers are further reduced in the airspace above altitude of 300 FL. The number of aircraft flying in this altitude are also very less. On analyzing the distance from this ground station, it was found that the aircraft flying at the altitude above 300 FL were in Indian Airspace.

Table 4.4: Outliers in FL>300

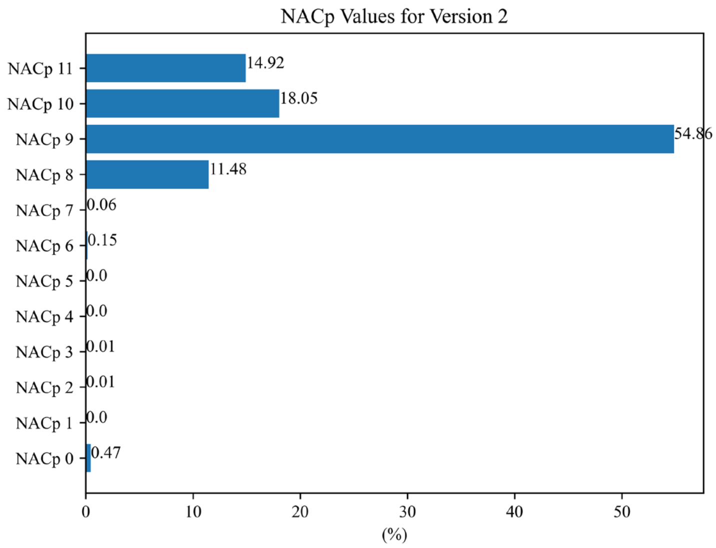
SN	Week	Number of Outliers in FL>300
1	Week 1	0
2	Week 2	11
3	Week 3	73
4	Week 4	13

4.2 Accuracy and Integrity Performances



(a) *(b)*

(c) *(d)*



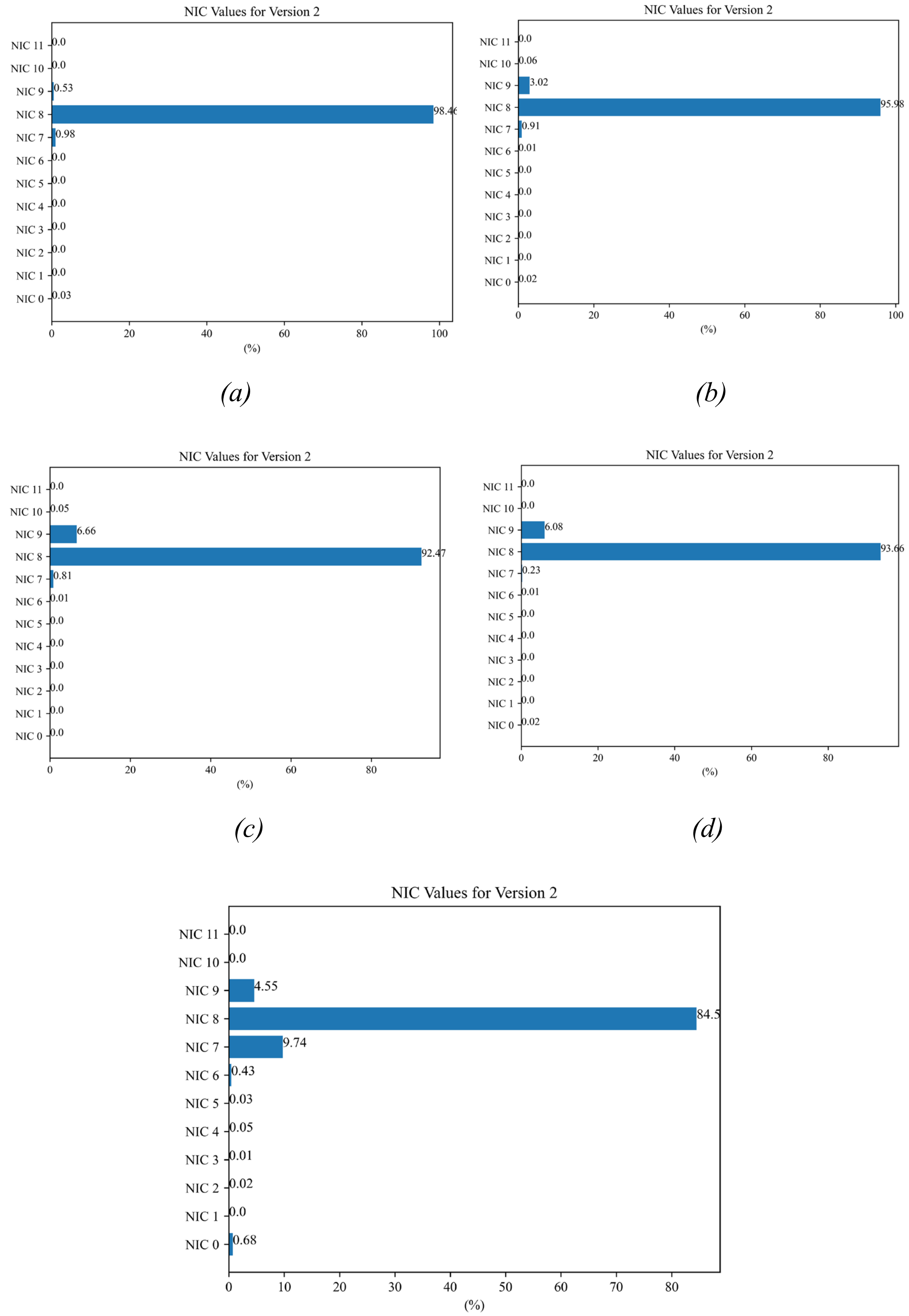
(e)

Figure 4.6: NACp Values

for (a) week 1 (b) week 2 (c) week 3 (d) week 4 of KTM FIR and (e) Munich Airspace

The NACp parameter is used to indicate the level of uncertainty in an aircraft's horizontal position. It is determined by measuring the errors generated by the aircraft's avionics and other sensors and data sources. Upon examining the plots, it is evident that NACp is consistently 9 for over 75% of the data points. Referring to the table 2.1, we can determine that NACp value 9 corresponds to an uncertainty level of less than 30 meters. This implies that the reported position of the aircraft may be off by up to 30 meters.

In addition, NACp values of 10 can also be observed, indicating a higher level of accuracy in the aircraft's position, with an uncertainty level of less than 10 meters. Achieving an NACp of 10 requires the use of highly accurate avionics and precise sensors and data sources. In fig. 4.6 (e), there are 14.92% of data sets with NACp value 11 which indicates that the aircrafts were flying with uncertainty level less than 3 meters. A higher NACp value is always preferred during the approach and landing phases of a flight, particularly in congested airspace. In countries where ADS-B has been implemented, there is a requirement for aircraft to maintain a minimum NACp of 8 and the NACp values < 8 are flagged red. [26]



(a) *(b)*

(c) *(d)*

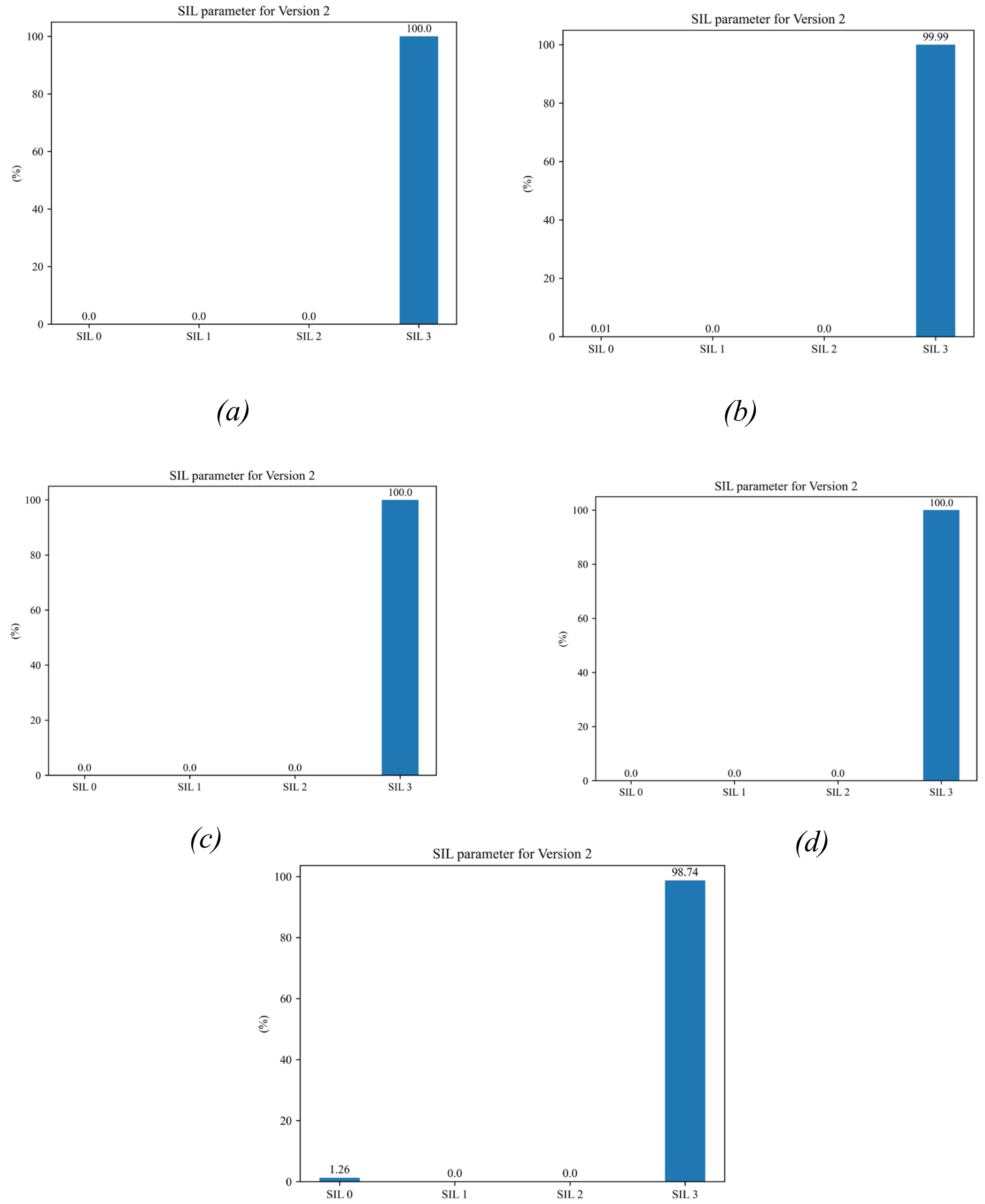
(e)

Figure 4.7: NIC Parameters

for (a) week 1 (b) week 2 (c) week 3 (d) week 4 of KTM FIR and (e) Munich Airspace

The NIC values of version 2 aircrafts were plotted as shown in figure 4.7. The NIC value was 8 for maximum time which indicates that the radius of containment is less than 185 m.

4.3 Surveillance Integrity Level (SIL)



(a) *(b)*

(c) *(d)*

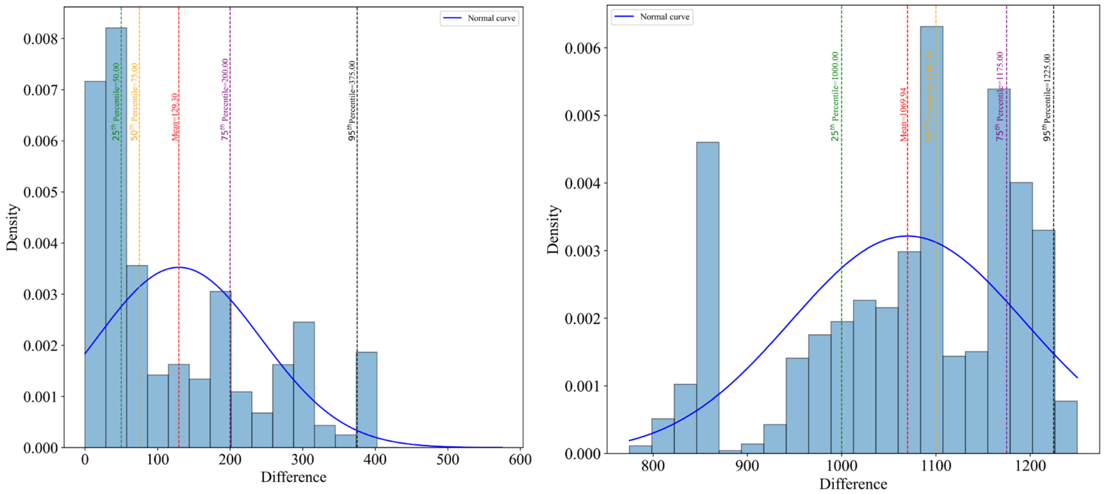
(e)

Figure 4.8: SIL Parameters

for (a) week 1 (b) week 2 (c) week 3 (d) week 4 of KTM FIR and (e) Munich Airspace

The SIL parameter indicates the likelihood of exceeding the measured containment radius. During weeks 1, 3, and 4, the SIL value is consistently 3, indicating that the probability of exceeding the measured containment radius is less than 10^{-7}. This means that for aircraft with a NIC value of 9 and SIL value of 3, the probability of exceeding the corresponding containment radius (less than 185.2m for NIC 9) is 10^{-7} in the horizontal plane. In week 2, there are some SIL values of 0, which may be due to the NIC value being 0.

4.4 Performance Categorization

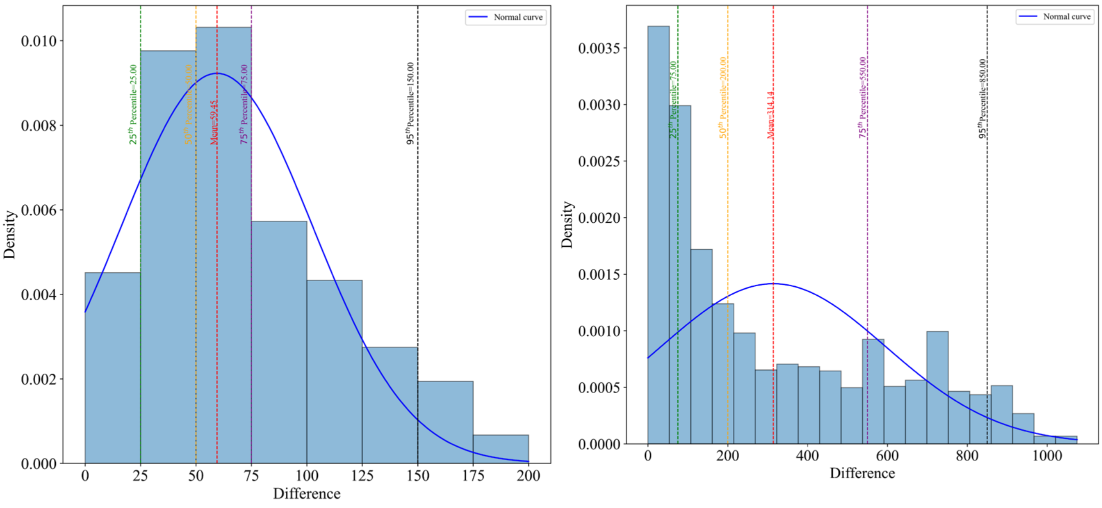


(a) *(b)*

Figure 4.9: Histogram of difference in altitude of (a) ATR 72-500 (70a9f1) and (b) Airbus A330-243(70aa71) above cruising altitude

From fig. 4.9 (a), it can be observed that the mean difference between the geometric and barometric measurements is 129.30 feet. Interestingly, the mean difference below cruise altitude is only 59.45 feet, indicating that the mean difference above cruise altitude is more than twice that below cruise altitude. The increase in altitude results in the variation of environmental conditions such as temperature and pressure, which causes the mean difference to increase. Additionally, the presence of outliers may also contribute to this increase.

Fig. 4.9 (b) represents data collected from Nepal Airlines' Airbus model A330-243 above cruising altitude. The figure displays a mean difference of 1069.94 feet, along with a 95th percentile value of 1225 feet. This indicates that 95% of the data show the geometric altitude to be higher than the barometric altitude by up to 1225 feet.



(a) *(b)*

Figure 4.10: Histogram of difference in altitude

of (a) ATR 72-500 (70a9f1) and (b) Airbus A330-243(70aa71) below cruising altitude

The figure above displays a mean deviation of 59.45 feet between the geometric and barometric measurements based on data collected from January 11 to 17. Additionally, the 95th percentile of the data is 150 feet, indicating that the altitude differences remain within 150 feet for 95% of the time.

Fig 4.10 (b) represents data obtained from Nepal Airlines Airbus model A330-243. The figure above shows that the mean deviation between the geometric and barometric measurements is 314.14 feet, while the 95th percentile of the data is 850 feet, indicating that altitude differences remain within 850 feet for 95% of the time. Furthermore, the probability of having an altitude difference less than 75 feet is less than 0.25.

Based on the data collected from January 11 to 17, it is observed that the mean difference and 95th percentile for the ATR 72-500 is lower than that of the Airbus model A330-243, as well as other models. Therefore, it can be concluded that the ATR

72-500 is the best performing aircraft for that week. In contrast, the Airbus A330-243 model from Nepal Airlines is the least performing aircraft. This conclusion is drawn from the histogram of the data.

4.5 Correlation of RNP Procedures and ADS-B Performances

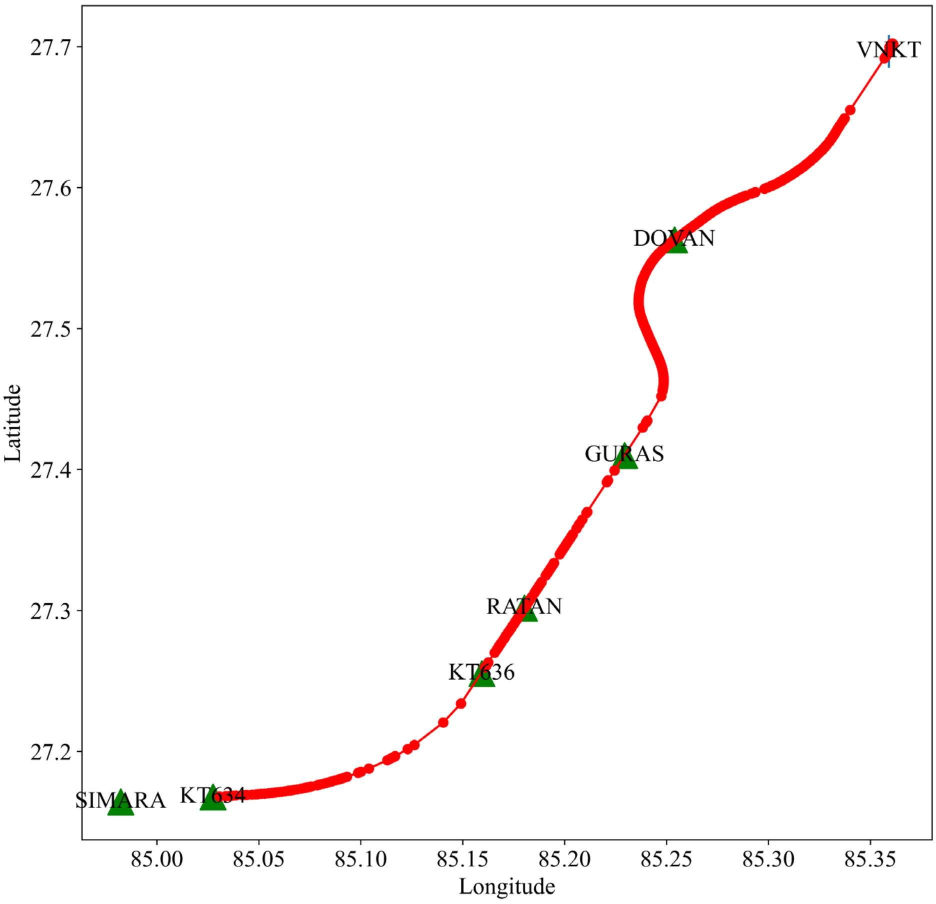


Figure 4.11: ADS-B Data Correlation with RNP Procedure

In figure 4.11, the latitude longitude values of Airbus A330-300 (Turkish Airlines) from January 16 are plotted. It can be seen that the position values from ADS-B data indicate that the aircraft has followed RNP approach as defined in the published AIP chart.

CHAPTER 5 CONCLUSION AND FUTURE ENHANCEMENT

5.1 Conclusion

In this project, system engineering approach was used for installation and operation of ADS-B ground station was applied. Data for 1.5 month was collected. The statistical analysis of NIC, NAC, SIL and GVA was performed.

On analyzing the [h_{gps} - h] VS FL graph, the [h_{gps} - h] value keeps on increasing with increase in altitude. There were number of outliers in lower FL and the numbers keep on decreasing with increase in FL. ADS-B system cannot be used for terminal airspace as a navigation aid however, by applying data fusion technique with other surveillance system data, the system can be used. The [h_{gps} - h] value is greater than 245 ft in 290-410 FL implying RVSM procedure are not applicable with ADS-B system as a surveillance technique.

From the Performance Parameter for Version 2, the following conclusion were made: In Kathmandu FIR, NACp value was 9 for 77.63% of time, 8 for 6.41 % of time and 10 for 15.96 % of time which means the uncertainty position were < 30 m for 77.63 % of time, <186.2m for 6.41% of time and <10m for 15.6% of time. NACp 10 was mostly obtained from the aircraft of Nepal Airlines with hexadecimal code ‘70a96a’. This aircraft can be termed as best performing aircraft in terms of accuracy. In Munich Airspace, NACp value were 8 for 11.488% of time, 9 for 54.86% of time, 10 for 18.05% of time, 11 for 14.92% of time and less than 8 for remaining. NACp value 11 indicates the uncertainty position was <3m. We can conclude that Munich airspace allowed the high precision-based procedure for flying. On further investigating NACp = 11, we could find the existence of VNAV and LNAV procedure being used.

NIC values were obtained 0 for 0.02% (RC>20NM) of time,7 for 0.56% (RC< 0.2NM) of time,8 for 95.13% (RC<185m) of time,9 for 4.07%(RC<75m) of time and 10 for 0.22% (RC<25) of time. From the correlation of NIC and NACp parameter, it was found that NIC parameter have bounded the NACp values. The presence of 0 in NIC means there were the instances when the information obtained were not trust worthy. The presence of SIL value 0 have validated the presence of NIC value 0 for 0.02% of time.

The mean values of difference in altitude of the best performing (ATR 72-500) and worst performing (Airbus A330-234) were found to be 59.45 ft and 314.14 ft for below cruising altitude and 129.3 ft and 1069.94 ft above cruising altitude respectively.

5.2 Future Enhancement

The preliminary analysis of the aircraft model containing the outliers was done. The possible cause for the detection of such outliner were identified. In order to valid those possible cause, the detail analysis of these aircraft model can be done in the future. The root cause for such scenario can be identified in future. Real time monitoring and alert system can be developed by retrieving the data collected from the ground station. Graphana can be used as an important tool for this purpose. Data handling is a prime factor to be considered for the better outcome as the project. As size of data set goes on increasing with time, it is highly recommended to use Cloud server as database to handle such large size data in future.

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APPENDICES

Figure 1: Physical Setup of ADS-B Ground Station

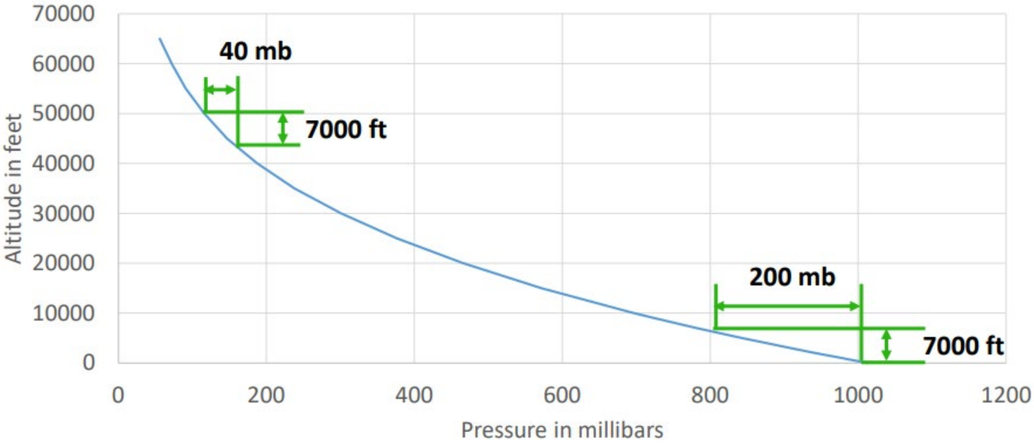
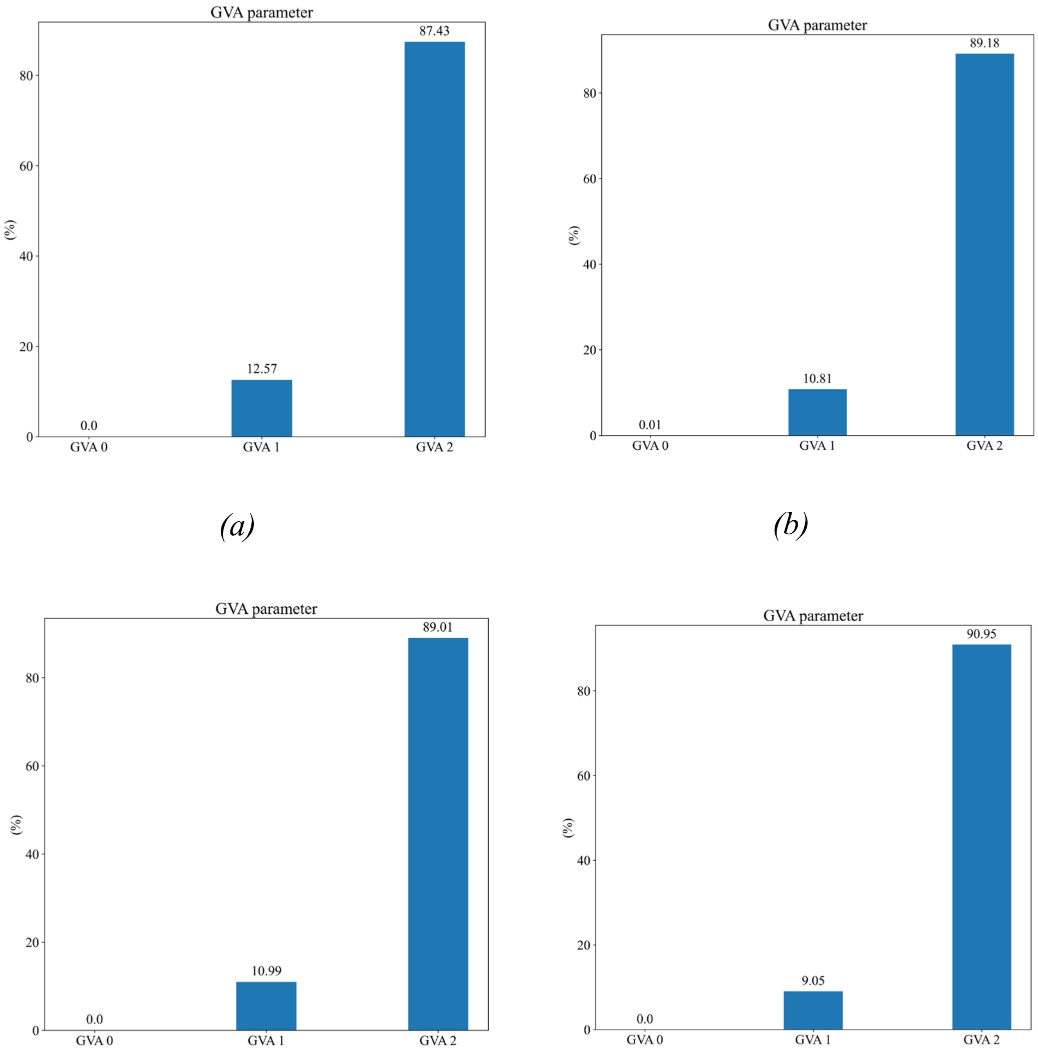


Figure 2: Standard altitude vs Pressure



(a) *(b)*

(c) *(d)*

Figure 3: GVA Parameters

for (a) week 1 (b) week 2 (c) week 3 (d) week 4

Table 1: Possible Causes for large number of outliers

S.N.	Aircraft Model	Number of Outliers	Possible Cause
1	Airbus A320-200	307	Instrument error or Incorrect calibration might have occurred; however, it requires further investigation for confirmation
2	Airbus A320-214(WL)	222	The number of errors obtained were similar per week. So, there may be some avionics error like incorrect parameter retrieval
3	Boeing 737 MAX 8	186	Since Angle of attack sensor have already been identified as a problem in this model there can be problem in the transponder too.
4	ATR 72-500 (72-212A)	149	Since this model have Garmin transponder, there is a history of Flight ID Problem and can be the same case here.
5	Boeing 787-8 Dreamliner	136	Data jump are likely to have occurred.
6	Boeing 737-8KN(WL)	98	Here, most of the error were obtained during the winter days and were reduced as in the sunny days. So, barometric error due to low temperature may be the possible cause however it requires further investigation.
7	Airbus A330-243	96	Reduced ADS-B equipment integrity can be the possible cause.
8	Boeing 737-800	78	Occurrence of the event are small but frequently. There might be possible cases of data jump.
9	Airbus A320neo	75	Since it has Updated Calibration from A320-200 there may be other possible cause. Another Avionics error could have occurred.
10	Airbus A319-100	56	Position error can be the possible cause
11	Airbus A330-300	38	Environment and Human factor can be the possible cause

Table 2: NIC Parameters and their Values (Version 2) [3]

TC	NICa	NICb	NICc	NIC	Rc
5	0	N/A	0	11	< 7.5 m
6	0	N/A	0	10	< 25 m
7	1	N/A	0	9	< 75 m
	0	N/A	0	8	< 0.1 NM (185 m)
8	1	N/A	1	7	< 0.2 NM (370 m)
	1	N/A	0	6	< 0.3 NM (556 m)
	0	N/A	1		< 0.6 NM (1111 m)
	0	N/A	0	0	> 0.6 NM or unknown
9	0	0	N/A	11	< 7.5 m
10	0	0	N/A	10	< 25 m
11	1	1	N/A	9	< 75 m
	0	0	N/A	8	< 0.1 NM (185 m)
12	0	0	N/A	7	< 0.2 NM (370 m)
13	0	1	N/A	6	< 0.3 NM (556 m)
	0	0	N/A		< 0.5 NM (926 m)
	1	1	N/A		< 0.6 NM (1111 m)
14	0	0	N/A	5	< 1.0 NM (1852 m)
15	0	0	N/A	4	< 2 NM (3702 m)
16	1	1	N/A	3	< 4 NM (7408 m)
	0	0	N/A	2	< 8 NM (14.8 km)
17	0	0	N/A	1	< 20 NM (37.0 km)
18	0	0	N/A	0	> 20 NM or unknown
20	N/A	N/A	N/A	11	< 7.5 m
21	N/A	N/A	N/A	10	<2 5 m
22	N/A	N/A	N/A	0	> 25 m