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PERFORMANCE ANALYSIS OF AUTOMATIC DEPENDENT SURVEILLANCE-BROADCAST (ADS-B) AND BREAKDOWN OF ANOMALIES

by

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Bachelor of Science in Aeronautical Engineering
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Submitted to the Graduate Faculty

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for the degree of

Master of Science

Grand Forks, North Dakota

December
2017

This thesis, submitted by Asma Tabassum in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

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Committee Member

This thesis is being submitted by the appointed advisory committee as having met all of the requirements of the School of Graduate Studies at the University of North Dakota and is hereby approved.

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Dean of the School of Graduate Studies

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Department	Mechanical Engineering
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Asma Tabassum
December 2017

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ABSTRACT

This thesis work analyzes the performance of Automatic Dependent Surveillance-Broadcast (ADS-B) data received from Grand Forks International Airport, detects anomalies in the data and quantifies the associated potential risk. This work also assesses severity associated anomalous data in Detect and Avoid (DAA) for Unmanned Aircraft System (UAS). The received data were raw and archived in GDL-90 format. A python module is developed to parse the raw data into readable data in a .csv file. The anomaly detection algorithm is based on Federal Aviation Administration's (FAA) ADS-B performance assessment report. An extensive study is carried out on two main types of anomalies, namely dropouts and altitude deviations. A dropout is considered when the update rate exceeds three seconds. Dropouts are of different durations and have a different level of risk depending on how much time ADS-B is unavailable as the surveillance system. Altitude deviation refers to the deviation between barometric and geometric altitude. Deviation ranges from 25 feet to 600 feet have been observed. As of now, barometric altitude has been used for separation and surveillance while geometric altitude can be used in cases where barometric altitude is not available. Many UAS might not have both sensors installed on board due to size and weight constrains. There might be a chance of misinterpretation of vertical separation specially while flying in National Airspace (NAS) if the ownship UAS and intruder manned aircraft use two different altitude sources for separation standard. The characteristics and agreement between two different altitudes is investigated with a regression based approach. Multiple risk matrices are established based on the severity of the DAA well clear. ADS-B is called the Backbone of FAA Next Generation Air Transportation System, NextGen. NextGen is the series of inter-linked programs, systems, and policies that implement advanced technologies and capabilities. ADS-B utilizes the Satellite based Global Positioning System (GPS) technology to provide the pilot and the Air Traffic Control (ATC) with more information which enables an efficient navigation of aircraft in increasingly congested airspace. FAA mandated all aircraft, both manned and unmanned, be equipped with ADS-B out by the year 2020 to fly within most controlled airspace. As a fundamental component of NextGen it is crucial to understand the behavior and potential risk with ADS-B Systems.

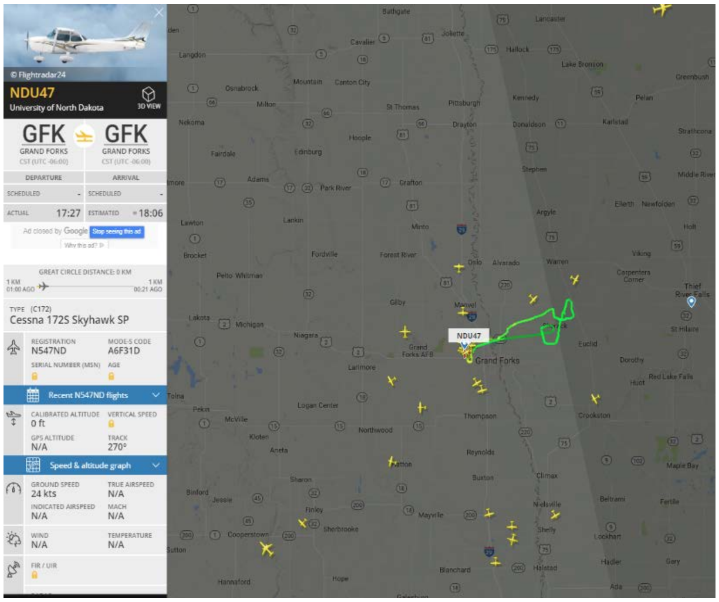
CHAPTER I

INTRODUCTION

An analysis of the performance of Automatic Dependent Surveillance-Broadcast (ADS-B) data received from Grand Forks International Airport was carried out to understand its' vulnerabilities and recognize the effects on present and future Air Traffic Control (ATC) operation. At present unmanned aircraft systems (UAS) and autonomous air traffic control (ATC) towers being integrated into the aviation industry[1]. As a fundamental component of future surveillance system, the anomalies and vulnerabilities of ADS-B system need to be identified for a fully utilized airspace with enhanced situational awareness. This work is partially funded by ASSURE [2], an alliance of universities across the United States by the Federal Aviation Administration for System Safety of UAS. The initial findings fed into the Surveillance Critically Research group and the expanded work is presented in this study.

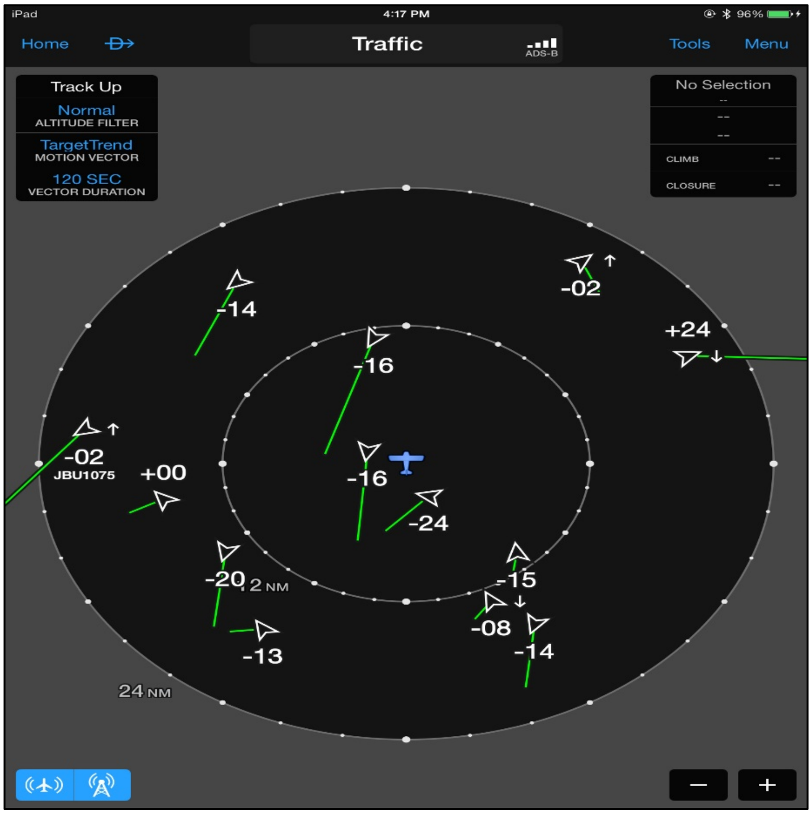
1.1 Motivation

In order to meet increasing air travel demand, airspace capacity must be increased, which in turn depends to a large extent on the ATC technology, the capability of ATC and associated functions to manage the airspace. One way of increasing airspace capacity is to reduce the required separation minima between aircraft, which demands very high performance (accuracy, integrity, continuity, and availability) of the navigation and associated functions of communications and surveillance. Reducing the separation between aircraft to increase airspace capacity, without considering the constraints will cause an increase in the risk of collision. To overcome the limitations and to meet the future air travel demand, the International Civil Aviation Organization (ICAO) [3] established a special committee on Future Air Navigation Systems (FANS) to develop a plan and program for future air traffic [4]. As a result, a new surveillance technology referred to as Automatic Dependent Surveillance-Broadcast (ADS-B) was proposed by the ICAO and is envisioned to fill the gaps in the current surveillance systems. Figure 1 provides a visual interpretation how air traffic is tracked in real time using ADS-B data and Figure 2 provides onboard ADS-B traffic display. Air traffic around Grand Forks are shown in real time on map in Figure 1. Upon clicking on aircraft sign, the flight information as well as the trajectory can be seen.



NDU47
University of North Dakota
GFK GRAND FORKS CST (UTC -06:00)
GFK GRAND FORKS CST (UTC -06:00)
DEPARTURE SCHEDULED -
ACTUAL 17:27
ARRIVAL SCHEDULED -
ESTIMATED 18:06
GREAT CIRCLE DISTANCE: 0 KM
1 KM 01:00 AGO
1 KM 00:21 AGO
TYPE (C172) Cessna 172S Skyhawk SP
REGISTRATION N547ND
MODE-S CODE A6F31D
CALIBRATED ALTITUDE 0 ft
GPS ALTITUDE N/A
TRACK 270°
GROUND SPEED 24 kts
TRUE AIRSPEED N/A
INDICATED AIRSPEED N/A
MACH N/A
WIND N/A
TEMPERATURE N/A

Figure 1: Real Time Flight Tracking with ADS-B Data. In curtesy of FlightRdara24[5].



Track Up
Normal ALTITUDE FILTER
TargetTrend MOTION VECTOR
120 SEC VECTOR DURATION

Figure 2:GARMIN Onboard ADS-B Traffic Display [6]

However, the display onboard is different in the sense that it can identify the potential threat and provides more clear traffic scenario. In Figure 2, the blue aircraft sign indicating the ownship, the traffics are shown with two different range. From the Figure three aircraft are found within 2 NM. The number indicates the flight level, for example -16 means the aircraft is flying 16000 feet below the ownship.

In line with this, the FAA’s Next Generation Air Transportation System (NextGen) [1] and EUROCONTROL’s Single European Sky (SES) and its ATM Research (SESAR) program [7] recognize ADS-B as key to the respective goals to modernize the ATC operations and address the limitations in the current surveillance systems. ICAO envisages that the ADS-B system should resolve the problems faced in the current surveillance systems. Hence, ADS-B is critical to the requirements to accommodate the increase in air travel demand in the future. The UAS in the NAS, is expected to be integrated without reducing existing capacity, decreasing safety, negatively impacting current operators. NextGen envisioned to contribute capabilities designed to reduce technical barriers related to safety and operational challenges associated with enabling routine UAS access to the NAS. One of the main focus of UAS in NAS project is to assess how planned NextGen separation assurance systems, with different functional allocations, perform for UAS in mixed operations with manned aircraft and the applicability to UAS and the performance of NASA NextGen separation assurance systems in flight tests with realistic latencies and uncertain trajectories [8]. Figure 3 represents a conceptual architecture of side by side operation UAS and manned aircraft in the NAS.

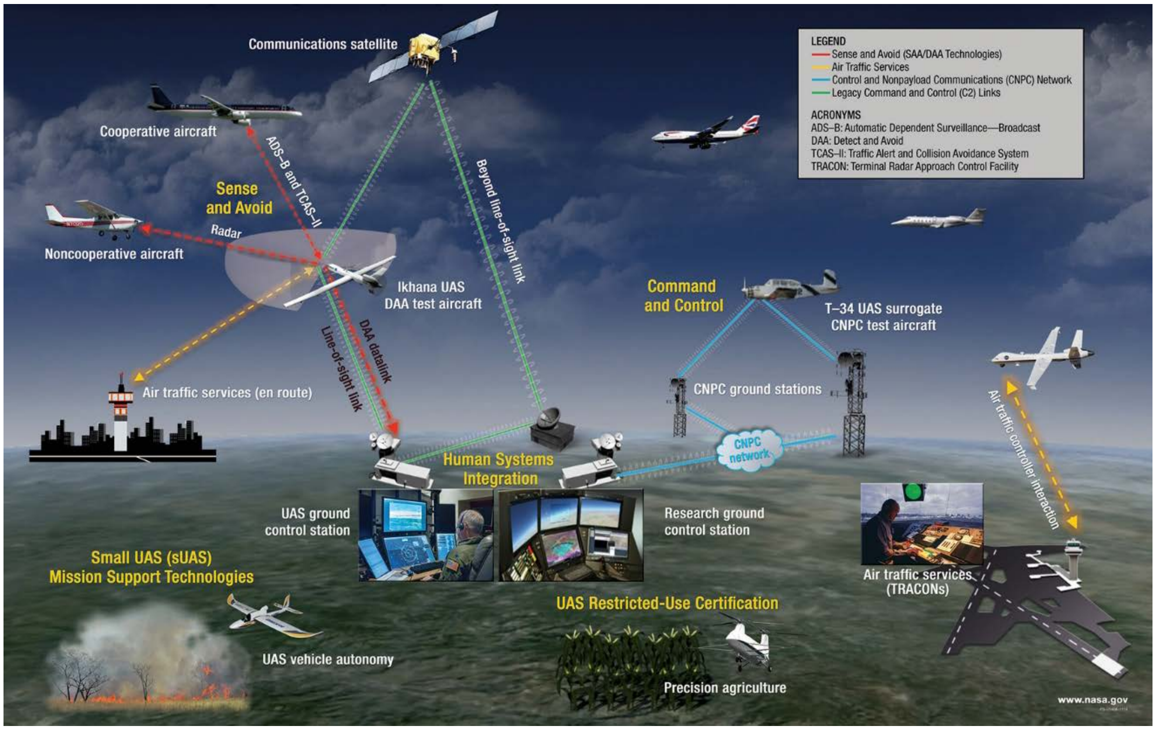


Figure 3: Operation of UAS in line with Manned Aircraft in same airspace.[8]

It should be noted that only in the United States ADS-B works in two distinct frequencies one is 1090ES, and another is 978 MHz. Among them 1090ES is of international standard and aircraft must be equipped with 1090ES transponder in order to fly above the transition altitude. On the other hand, 978MHz datalink is used by General Aviation only in United States Airspace except Class A. According to Minimal Operational Performance Standard for UAS [9], UAS needs to be equipped with UAT ADS-B to fly within NAS. Though a lot study has found on the 1090ES ADS-B system, however, UAT ADS-B lacks addressing the important questions regarding limitations, failure modes including their characterization, modeling, and assessment of impacts. This is probably because UAT is newer comparative to 1090ES and only used in USA. Therefore, an in-detail study mentioning and recognizing the anomalies and its effect on safe operation especially when UAS will engulf NAS is needed to ensure uninterrupted operation in any operational environment to support the ATC surveillance.

1.2 Structure of the Thesis

Given, the motivation above the aim of this thesis is to assess the vulnerabilities of UAT ADS-B messages, discuss and identify the failure mode and quantify the risk in UAS operation. The structure of the thesis is as follows:

Chapter 2 discusses ATC operation in the past, present and future. It introduces surveillance sensors and systems used in ATC, their performances, limitations, and applications. It also contains a broad overview of ADS-B system and its potential of serving ATC in the near future.

Chapter 3 provides ADS-B message definition from RTCA DO-282B, data extraction, and sorting methods. This chapter discusses message inspection steps, definitions of anomalies. The anomalies observed are introduced in this chapter.

Chapter 4 contains an in-depth analysis of two principle type of anomalies namely dropout and altitude discrepancy. These two anomalies are observed more frequently and considered more severe as they have direct and immediate impacts on the airspace safety.

Chapter 5 presents some hypothetical geometric encounter between UAS and Manned aircraft to understand the severity and hazard associated with ADS-B data anomalies on UAS. The encounters are designed to bring out the highest possible hazard and risk that could take place in the presence of anomalies.

Chapter 6 connects the anomalies to potential reasons with a system level assessment that leads to the anomaly. The system level assessment follows a top-down architecture starts from the main event and goes all the down to all subsystems that individually or collectively responsible for the failure. This chapter also incorporates barometric and geometric altitude to a measurement system comparison model with a weighted deming regression model, in order to assess if these two-system data can be modeled mathematically.

Chapter 7 consists the concluding remarks and the overall scenario in a broader sense.

CHAPTER II

BACKGROUND AND OVERVIEW OF ADS-B

This chapter provides a background of the air traffic control surveillance systems. It describes the ATC operations, systems used for the surveillance, their performance, and limitations. It highlights slow shifting of ATC towards cooperative surveillance systems and the evolution of NextGen. Also, this chapter contains a detailed overview of the ADS-B system architecture and past studied and contemporaray researches on this field.

2.1 Background of ATC Surveillance System

The world of air traffic is slowly shifting towards the cooperative surveillance system from the non-cooperative system. Surveillance plays an important role in ATC to accurately and reliably determine the location of aircraft, which has a direct influence on the separation distances required between aircraft and therefore on how efficiently a given airspace may be utilized. The demand of increased flexibility for airspace users by reducing restrictions associated with flying along fixed routes requires improved navigation capability onboard the aircraft. Equally, accurate surveillance is required to assist in the detection and resolution of any potential conflicts associated with the flexible use of the airspace which is likely to result in a more dynamic environment [10]. International Civil Aviation organization listed some parameters in order to characterize any surveillance system. The chararacteriscts is as follow[10] :

i. Coverage volume – the volume of airspace in which the system operates to specifications
ii. Accuracy – a measure of the difference between the estimated and true position of an aircraft.
iii. Integrity – an indication that the aircraft's estimated position is within a stated containment volume of its true position. Integrity includes the concept of an alarm will be generated if this ceases to be the case, within a defined time to alarm. Integrity can be used to indicate whether the system is operating normally.
iv. Update rate – the rate at which the aircraft's position is updated to users.
v. Reliability – the probability that the system will continue operating to specification within a defined period. Sometimes this is called continuity.
vi. Availability – the percentage of the total operating time during which the system is performing to specification.

Also, ICAO stated some other issues which need to be considered when designing a surveillance system for ATC. According to ICAO surveillance system guidance materials [10] they are:

i. The ability to uniquely identify targets.
ii. The impact of the loss of surveillance of individual aircraft both in the short (few seconds) and long-term.
iii. The impact of the loss of surveillance over an extended area.
iv. Backup or emergency procedures to be applied in the event of aircraft or ground system failure.

v. The ability to operate to specification with the expected traffic density.

vi. The ability to operate in harmony with other systems such as the Traffic Collision Avoidance Systems (TCAS) and Airborne Separation Assistance Systems (ASAS).

vii. The ability to obtain Aircraft Derived Data (ADD).

viii. The interaction between communication, navigation, and surveillance functions.

Today's surveillance systems can be classified into two broad categories. One is Ground-based, and another is airborne. The ground-based surveillance system is mostly consisting of different RADAR and beacon. ADS-B is an airborne surveillance system which make use of satellite navigation such as GPS for generating surveillance information. Table 1 illustrates the application of two different systems in ATC.

Table 1:Surveillance Application Categories [4]

Surveillance System	Applications
Ground-Based System	a) ATC surveillance in airspace with radar coverage b) ATC surveillance in airspace without radar coverage c) Airport surface surveillance d) Aircraft derived data for ground-based ATM tools.
Airborne System	a) Situational awareness Enhanced traffic situational awareness on the airport surface Enhanced traffic situational awareness during flight operations Enhanced successive visual approaches b) Airborne spacing and separation Enhanced sequencing and merging operations

2.1.1 RADAR

Radar provides the air traffic control with an accurate and trustworthy on-screen plan view of the aircraft position in real-time [10]. The required separation between aircraft for safe operation can be greatly reduced in comparison to the procedural separation. There are two main kinds of radar: one is Primary Surveillance Radar, and another is Secondary Surveillance Radar. Primary Surveillance Radar (PSR) transmits a high-power signal which is reflected by the aircraft back to the radar. The radar determines the aircraft's position in the form of range calculating the elapsed time between transmission and reception of the reflected signal. The direction of the aircraft is the direction in which the narrow beam radar antenna is facing. Primary radar does not provide the identity or the altitude of the aircraft. Also, it does not require any specific equipment on the aircraft. Secondary Surveillance Radar (SSR) systems consist of two main elements, a ground-based interrogator/receiver, and an aircraft transponder. The aircraft's transponder responds to interrogations from the ground station, enabling the aircraft's range and bearing from the ground station to be determined. The development of Secondary Surveillance Radar evolved from military Identification Friend or Foe (IFF) systems which allowed the use of the Mode A/C service for civil aviation. Since then it has been significantly developed to include the Mode S service. SSR frequencies of 1030 and 1090 MHz remain shared with the military. In many cases, SSR is co-located with the primary radar, usually with the SSR mounted on the top of the primary radar antenna. Mode A/C transponders provide identification (Mode A code) and altitude (Mode C) data with 100 feet resolution information in reply to interrogations.

2.1.2 Mode S Transponder

Mode S is an improved version of Mode A/C. It contains all the functions of Mode A/C and allows selective addressing of targets by the use of unique 24-bit aircraft addresses, and a two-way data link between the ground station and aircraft for the exchange of information. It also provides the transponder capability to report altitude data with 25 feet resolution although accuracy and resolution also depend on the altitude sensor systems on board the aircraft. A Mode S transponder is backward compatible with a conventional SSR Mode A/C radar, and the detection and processing of Mode A/C transponder replies are essentially identical. To achieve Mode S benefits, the aircraft transponders must be a Mode S capable transponder.

2.1.3 ADS-B

ADS-B is a system that uses transmissions from aircraft to provide geographical position, pressure altitude data, positional integrity measures, flight identity, 24-bit aircraft address, velocity and other data which have been determined by airborne sensors. Typically, the airborne position sensor is a GPS receiver or the GPS output. This sensor must provide integrity data that indicates the positional errors containment bound. The altitude sensor is typically the same barometric source/air data computer source used for secondary radar. There are two different ADS-B systems: ADS-B Out and ADS-B In. ADS-B Out in aircraft collects its state information including 3D position, velocity, and altitude and then broadcasts this information to the ground stations and other aircrafts via a data link. There are two different data links available; 1090ES which utilize Mode-S transponder, and another is 978 MHz Universal Access Transceiver (UAT) channel. Any aircraft equipped with ADS-B In will receive the ADS-B message sent out by other aircraft as well as ground stations. Table 2 summarizes the performance parameters for different ATC surveillance system.

Table 2: Surveillance System Performance Comparison [10]

Surveillance System	Coverage	Accuracy	Integrity
Primary Radar	S-band 60-80 NM L-band 160-220 NM	In range: 0.1 NM RMS or 0.2 NM 2 σ In azimuth: 0.15 degrees RMS or 0.3 degrees 2 σ	No integrity report provided.
Secondary Surveillance Radar	200 NM-250 NM	In range: 0.03 NM RMS In azimuth: 0.07 degrees RMS or 0.14 degrees 2 σ for random errors.	No integrity report provided.
Mode S	200 NM-250 NM	Same as SSR	No integrity the report provided.
ADS-B	200 NM-250 NM	Determined by the aircraft avionics and independent of range from the sensor.	Integrity value is downlinked in the ADS-B message.

The same performance parameters are used to assess different surveillance technologies. However, when applied to different technologies, the definition of the parameters may change slightly. While ground-based surveillance systems are old, insufficient and slow for today's fastest moving air traffic, airborne surveillance systems are named as a solution to provide an increased level of safety, faster route, and fewer traffic delays.

2.2 NEXTGEN and ADS-B Overview

Over the past several years, airspace has become congested by increasing number of flights. The introduction of Unmanned Aircraft Systems (UAS) in the National Airspace (NAS) has further increased the congestion. According to FAA, the use of small unmanned aircraft systems (SUAS) for commercial operations has greatly increased in recent years. Not only for commercial purpose, hobbyists are also using this platform for various recreational activities. Figure 4 provides a statistic of using UAS for commercial purpose as per FAA.

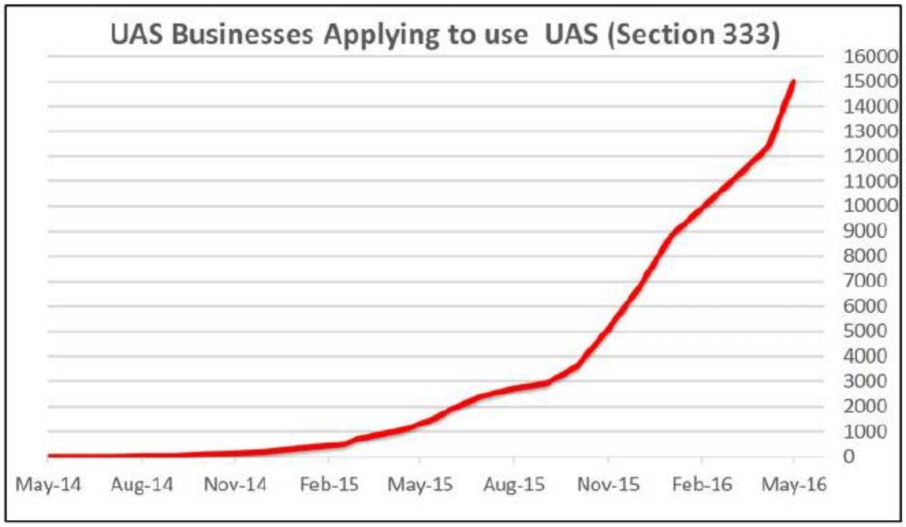


Figure 4: Number of Applications for SUAS Business Use Under Section 333

FAA also states that more than 6,800 airspace waiver requests were submitted for operations in controlled airspace by the end of December 2016. While almost half of them were for operations in class D airspace (i.e., smaller airports with control towers), other classes were also requested and regularly flown. Figure 5 is the pie chart showing the waiver request submitted to FAA till December 2016.

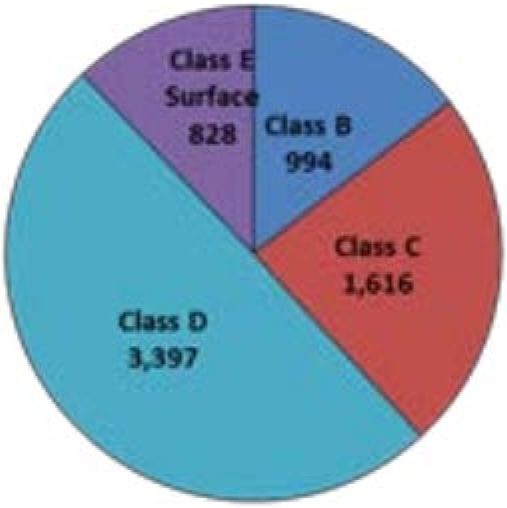


Figure 5: Aerospace Waiver Request

These statistics of UAS integration in NAS indicate towards a unified airspace for both manned and unmanned aircraft. It is a matter of assessment if introducing NextGen can provide required safety and reliability for the co-existence of manned and unmanned aircraft. Next Generation Air Transportation System in short NextGen is series of inter-linked programs, systems, and policies that implement advanced technologies and capabilities [1]. ADS-B is the backbone of this NextGen program, which utilizes the Satellite-based Global Positioning System (GPS) technology to provide the pilot and Air Traffic Control (ATC) with more information which enables an efficient navigation of aircraft in the increasingly congested airspace. FAA mandated all aircraft should be equipped with ADS-B out by the year 2020 to fly within the most controlled airspace. The General Aviation ADS-B Rebate Program [11] is introduced by the FAA to encourage and help owners to equip aircraft with the required avionics for NextGen. The step by step initiatives taken by FAA [1] for NextGen are:

i. Delivering Nationwide Infrastructure: The foundational infrastructure for NextGen includes ADS-B that will replace radars as the primary means by which air traffic controllers track and manage aircraft [1].
ii. Delivering Improved Air Traffic Control: En-Route Automation Modernization (ERAM) is helping to advance the transition of air traffic control to air traffic management by using flying more precise, satellite-based procedures than traditional ground-based procedures.
iii. Delivering Performance Based Navigation: New Performance Based Navigation (PBN) procedures use satellite-based precision to fly more direct routes, saving fuel and time, increasing traffic flow, and resulting in fewer carbon emissions.
iv. Delivering Improved Multiple Runway Operations: New separation standards to avoid the hazards of wake turbulence are improving the efficiency of aircraft arrivals and departures, reducing taxi times, and saving fuel.

Thus, the satellite-based surveillance system, ADS-B is the core of the NextGen. The next section will provide a broad description of the overall ADS-B system.

2.3 Overview of ADS-B

This section introduces the overall ADS-B system and highlights some of the contemporary works with ADS-B.

2.3.1 ADS-B infrastructure

RTCA defines [4] ADS-B as a function on an aircraft or a surface vehicle operating within the surface movement area that periodically broadcasts its position and other information without knowing the recipients and without expecting acknowledgments. The system is automatic in the sense that it does not require external intervention to transmit the information. It is characterized as a dependent due to its dependence on aircraft navigation avionics to obtain the surveillance information. ADS-B is a cooperative system because it requires common equipage for aircraft, or vehicles on the airport surface to exchange information. It also provides aircraft state information such as horizontal position, altitude, vector, velocity and trajectory intent information. A complete ADS-B system architecture represented in Figure 6 includes ADS-Out, Ground Stations, ADS-B In, and dual-band data links. ADS-B Out uses onboard GPS sensors to calculate position information and velocity. Primary altitude information comes from an onboard barometric altimeter. The Air Data Computer passes this altitude and altitude rate. A secondary altitude is also available from the onboard GPS. The ADS-B message generator then creates the message according to the standard. ADS-B has two different well-defined message format as described in RTCA DO-260B for 1090ES and RTCA DO-282B for UAT [12]. A ground station includes a receiver which relays the message to ATC and sends out some additional report such flight information, traffic information to the sender aircraft. Also, it provides a service called Automatic Dependent Surveillance-Rebroadcast (ADS-R) and Traffic Information Service-Broadcast (TIS-B). The ADS-R system monitors if there are proximate aircraft with differing ADS-B links and then rebroadcast surveillance information received on one link frequency to aircraft on the other link frequency. ADS-B In refers to appropriate avionics equipage that can receive, process and display information[13] transmitted via ADS-B Out as well as from ground stations. ADS-B In provides the pilot with extended situation awareness and self-separation. ADS-B In avionics are capable of receiving and decoding ADS-B, ADS-R, and TIS-B messages. The surveillance data processing system processes ownship and nearby traffic data. A Cockpit Display of Traffic Information (CDTI) provides pilots with surveillance information of traffic along with some application-specific information, such as traffic indications, alerts, and spacing guidance [13].

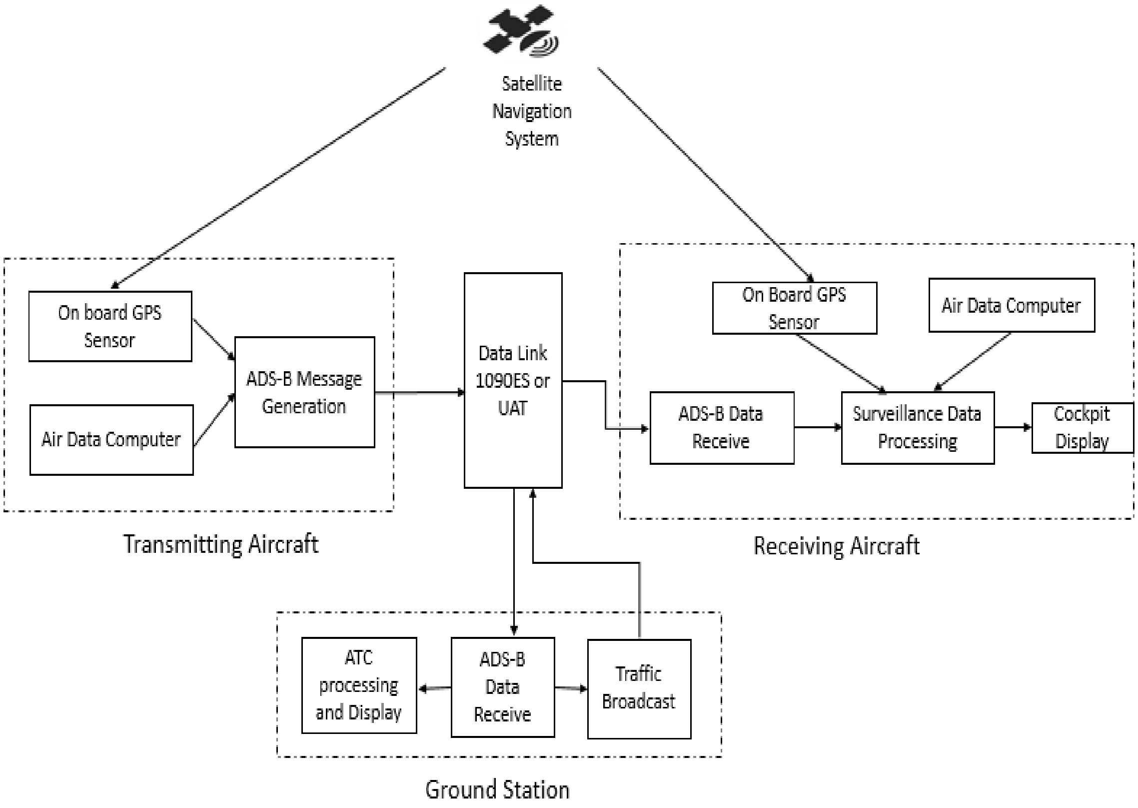


Figure 6: A Complete System Architecture including all the Component, ADS-B Out, ADS-B In, Datalink and Ground Station

As mentioned earlier, ADS-B makes use of two different datalinks; 1090ES and 978MHz. Transmissions at 1090ES are supported by secondary surveillance radars (SSRs). The existing Mode S signal used for SSR was modified to support ADS-B [13]. The UAT is a 978MHz data link intend to serve not only ADS-B but also Flight Information Service (FIS-B), Traffic Information Service (TIS-B), and Automatic Dependent Surveillance Rebroadcast (ADS-R). One of the main differences between these two frequencies is that 1090 ES is a wideband link and is of international standard, where UAT has narrow bandwidth and operated mainly in the-United States' (US) airspace, except for class A. But in terms of data transmission, 978MHz has higher data bandwidth than 1090MHz ES, because of less interference and congestion [14].

2.3.2 Related work

As one of the fundamental components of NextGen, a lot of research was done and is still going on different aspects of ADS-B. This includes but not limited to security and verification of messages [15]–[19], experimental attack analysis [20]–[24], data quality analysis [25]–[29], safety assessment [4], [30], flight testing [25], [31], [32] etc. ADS-B security protocol have been a topic of lot of studies since the system evolution. Having an open and known data format, which is broadcast on known frequencies makes the protocol highly susceptible to radio frequency (RF) attacks. Attacks can be either passive or active and can be initiated from within or outside of the ATC system (e.g. an unauthorized ADS-B transceiver). Passive attacks include eavesdropping, where the attacker try to listens in on periodic ADS-B messages to obtain unique identifiers or position trajectory of communicating aircraft without necessarily disrupting the system [17]. Experimental attacks were generated and infused to ADS-B messages in order to visualize the severity and find a solution to the potential attacks. Matthias et al. [20] assesses the practicability of different threats and quantify the main factors that impact the success of such attacks. The results revealed that attacks on ADS-B can be inexpensive and highly successful. Various technique was discussed to adopt while verifying original ADS-B messages. These include traditional Kalman filtering, Group Validation [17], cryptography [15], Identity-Based Signature with Batch Verification [33]. Each of the solutions is yet to be implemented in the real-time ADS-B network. A handful amount of study was found on 1090ES ADS-B data assessment describing the data integrity, accuracy, error detected and potential risk. Busyairah evaluates ADS-B messages collected from London Terminal Area Ground Receiver and describes an assessment framework [4]. This framework provides an outline for evaluating 1090ES ADS-B data performance. This involves comparing onboard GPS data collected from British Airways with received ADS-B data from ground station [29]. As this framework needs both the recorded flight data and ADS-B data for the assessment, it is not possible to use this if only ADS-B data is available. Findings of this study revealed that often ADS-B failed to assign correct Navigation Integrity Category (NIC) and Navigation Accuracy Category for position (NACp) value. Nur et al. [28] analyzes 29 aircraft ADS-B data and address deviation between barometric and geometric altitude. The deviation was in the range of 25 feet to 1450 feet. This work focused on how specific onboard avionics affect the deviation. Zhang [25] conducted a flight test to analyze integrity and accuracy of ADS-B data in China. A probabilistic analysis was carried out to quantify the risk of different ADS-B failure mode [30]. Several flight tests were conducted to check the conformity of the transmitted ADS-B messages with the performance standard. Flight inspection report of I90 TRACON/HOUSTON flight test [31], conducted by FAA, relates the lower integrity and accuracy of position information with the lower coverage of Satellite Availability and Signal loss. Also, it evaluated the use of the dual data link. The CRISTAL-ITP [32] Project by EUROCONTROL, tested to confirm the quality of the ADS-B Out information from the reference aircraft regarding update interval and accuracy. Although many data evaluation works have been done on 1090ES ADS-B data, no study has been found till writing this review on UAT data evaluation available to public. One of the reason can be UAT ADS-B is new comparative to 1090ES and only used by general aviation aircraft in United States' airspace. This work is carried out on a large scale in comparison to other, which ensures improvement of the result statistically. The other studies carried out mostly consider small dataset (one day or few hours) except for Zhang et al. [25] which consider one month of data. However, that study was centered on two pieces of integrity information from ADS-B data. The work carried out in this thesis is novel in a sense that this is the first kind of work that analysis a large volume (one month) of UAT ADS-B data taking account for all major information available in the data frame.

CHAPTER III

ANOMALY DETECTION IN ADS-B MESSAGE

This chapter describes step-by-step ADS-B message extraction and identify the performance parameters of the ADS-B system. It also provides a structural framework for the anomaly detection algorithm and introduces the anomalies that detected through inspection. This chapter is the backbone of the study and feeds into analysis conducted in chapters four and five.

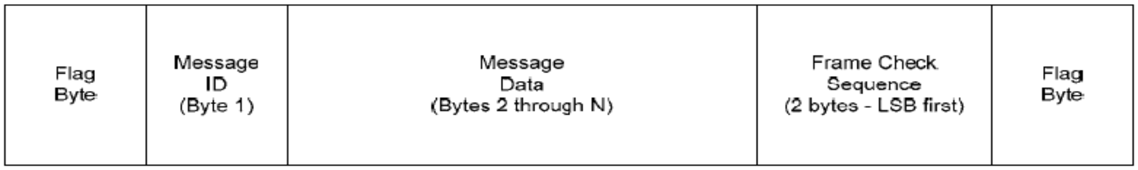
3.1 GDL-90 UAT Data

The test data received from UND Aerospace was in GDL-90 format. This is the format of the data interface to the serial communication and control panel ports of the Garmin AT UAT Data Link Sensor, model GDL 90 [34]. The ground receiver at the Grand Forks International Airport is a GDL 90 ADS-B system which is aviation's first certified ADS-B datalink transceiver [6]. It is designed to transmit, receive and decode ADS-B messages received via 978 MHz datalinks. This system works in two different interfaces, one is "Traffic interface", and another is "Pass-through interface." Traffic interface when enabled by the GDL 90 configuration, provides conflict alerts for proximate traffic that are projected to enter the protected zone surrounding the ownship position. On the other hand, Pass-through interface does not provide conflict alerts. The output reports under this interface consists of the message payloads that are recived over the UAT data link, without modification. Due to constraints on the interface bandwidth, received UAT messages are filtered by range from ownship [34]. This study made use of the archived pass-through data. There are two Pass-through report messages; one for the Basic UAT message and one for the Long UAT message. The difference between basic and long message is that long message contains some additional state information. The message structure for basic and long UAT is defined in RTCA DO-282B [12]. A python module was developed to decode the messages. Section 3.1.1 provides detail description of the message definition and development of the extraction algorithm.

3.1.1. Message Definition

The generic format of GDL-90 datalink message structure is based on "Async HDLC," as described in RTCA DO-267 [34]. Figure 7 represents the message structure in data frame. The message structure is as follows:

i. A Flag Byte character (0x7E).
ii. A one-byte Message-ID which specifies the type of message being transmitted.
iii. The Message Data, which can be of variable lengths.
iv. A message Frame Check Sequence (FCS). The FCS is a 16-bit CRC with the least significant byte first.
v. Another Flag Byte character (0x7E).



Flag Byte	Message ID (Byte 1)	Message Data (Bytes 2 through N)	Frame Check Sequence (2 bytes - LSB first)	Flag Byte

Figure 7: GDL-90 Message Structure

“Byte-stuffing” technique is used to provide the binary transparency. To include a data byte that coincides with either a Flag Byte (0x7E) or Control-Escape character (0x7D) within a message, each is converted into a unique two-byte sequence. On reception, any Control-Escape characters found are discarded, and the following byte is included in the message after being converted to its original form by XOR’ing with the value 0x20 [34]. The Frame check sequence (FCS) is then calculated on the clear messages. If the calculated FCS matched with FCS in messages, the message is authenticated and ready for use. The message ID for basic UAT is 30_{10} and long UAT is 31_{10}. The format of UAT message in GDL 90 interface is shown in Table 3.

Table 3:Message Information and Size

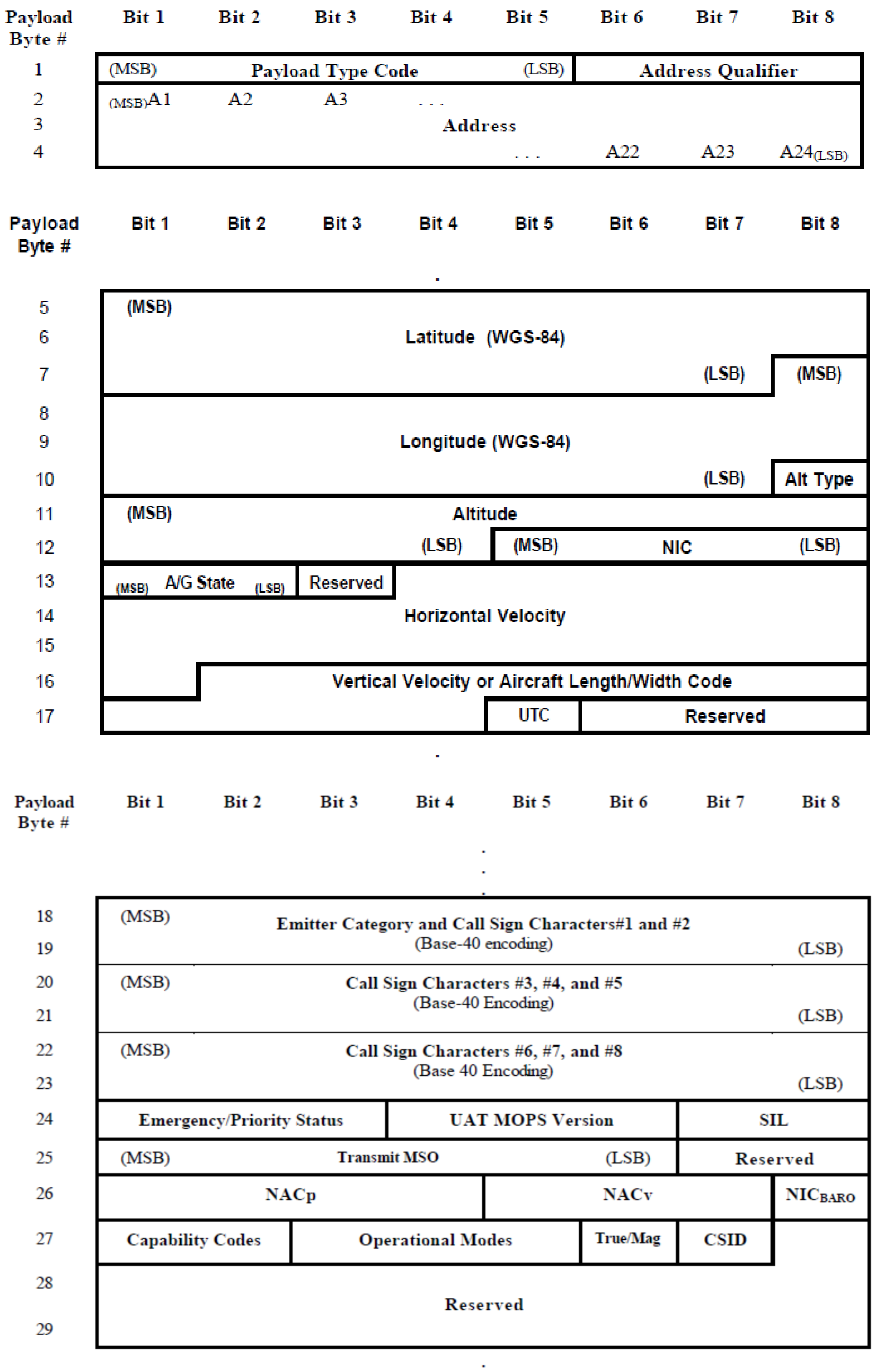
Basic UAT message			Long UAT message		
Byte #	Name	Size	Byte #	Name	Size
1	Message ID	1	1	Message ID	1
2-4	Time of Reception	3	2-4	Time of Reception	3
5-22	Basic Payload	18	5-38	Long Payload	34
	Total Length	22		Total Length	38

It should be noted time is not broadcasted with the UAT message. It is found from the heartbeat message generated by GDL 90 sensor itself. The message ID for the heartbeat is 0_{10}. This message outputs UAT Time Stamp, in seconds elapsed since UTC midnight (0000Z). So, the time stamp for the messages is assigned from the preceded heartbeat message. Each basic and long UAT message frame is known as the Payload. The information encoded in the frame is called payload element. Each transmitted ADS-B message contains a payload that the receiver first identifies by the “Payload Type Code” encoded in the first 5 bits of the payload [12]. “Payload Type Code” for basic and long messages are 0 and 1 respectively. The composition of ADS-B payload is presented in Table 4.

Table 4: Payload Composition

Type Code	ADS-B Message Payload Byte Number			
	1-4	5-17	18-29	30-34
0	Header, HDR	State Vector, SV	Not present in Basic message	
1	Header, HDR	State Vector, SV	Mode Status, MS	Auxiliary State Vector, AUX SV

There are four basic payloads in ADS-B message: Header, State vector, Mode Status and Auxiliary State vector. All UAT message incorporates a Header which provides a means to correlate different message received from a given aircraft. The header includes Payload Type Code, Address Qualifier, and Aircraft Address fields. State vector contains position information, i.e., latitude, longitude, primary altitude, horizontal and vertical velocity. It also contains the air or ground status of the aircraft and the type of primary altitude. Mode status elements are aircraft intent data that specify various parameters of the onboard avionics including call sign, quality indicators of the position data both in horizontal and vertical directions, a quality indicator for velocity data, source integrity level and capability modes. Furthermore, the auxiliary payloads include the information about secondary altitude. A conceptual illustration of the payloads elements in data frame is provided in Figure 8.



Payload Byte #	Bit 1	Bit 2	Bit 3	Bit 4	Bit 5	Bit 6	Bit 7	Bit 8
1	(MSB) Payload Type Code (LSB)					Address Qualifier		
2	(MSB)A1	A2	A3	. . .				
3	Address							
4					. . .	A22	A23	A24(LSB)

Payload Byte #	Bit 1	Bit 2	Bit 3	Bit 4	Bit 5	Bit 6	Bit 7	Bit 8
5	(MSB) Latitude (WGS-84)							
6								
7							(LSB)	(MSB) Longitude (WGS-84)
8								
9								
10							(LSB)	Alt Type
11	(MSB) Altitude							
12				(LSB)	(MSB) NIC (LSB)			
13	(MSB) A/G State (LSB)		Reserved	Horizontal Velocity				
14								
15								
16		Vertical Velocity or Aircraft Length/Width Code						
17					UTC	Reserved		

Payload Byte #	Bit 1	Bit 2	Bit 3	Bit 4	Bit 5	Bit 6	Bit 7	Bit 8
18	(MSB) Emitter Category and Call Sign Characters#1 and #2 (Base-40 encoding)							
19								(LSB)
20	(MSB) Call Sign Characters #3, #4, and #5 (Base-40 Encoding)							
21								(LSB)
22	(MSB) Call Sign Characters #6, #7, and #8 (Base 40 Encoding)							
23								(LSB)
24	Emergency/Priority Status			UAT MOPS Version			SIL	
25	(MSB) Transmit MSO (LSB)						Reserved	
26	NACp				NACv			NIC_{BARO}
27	Capability Codes		Operational Modes			True/Mag	CSID	Reserved
28								
29								

Figure 8: Message Fields in Different Payload Elements [8]

3.1.2. Message Decode

A python module is developed to decode the data as defined as RTCA DO 282B. The module read the archived binary data from a text file. Authenticate messages and then decode in consonance with the byte-to-byte definition. Figure 9 shows the algorithm adopted to decode the archived raw data stream.

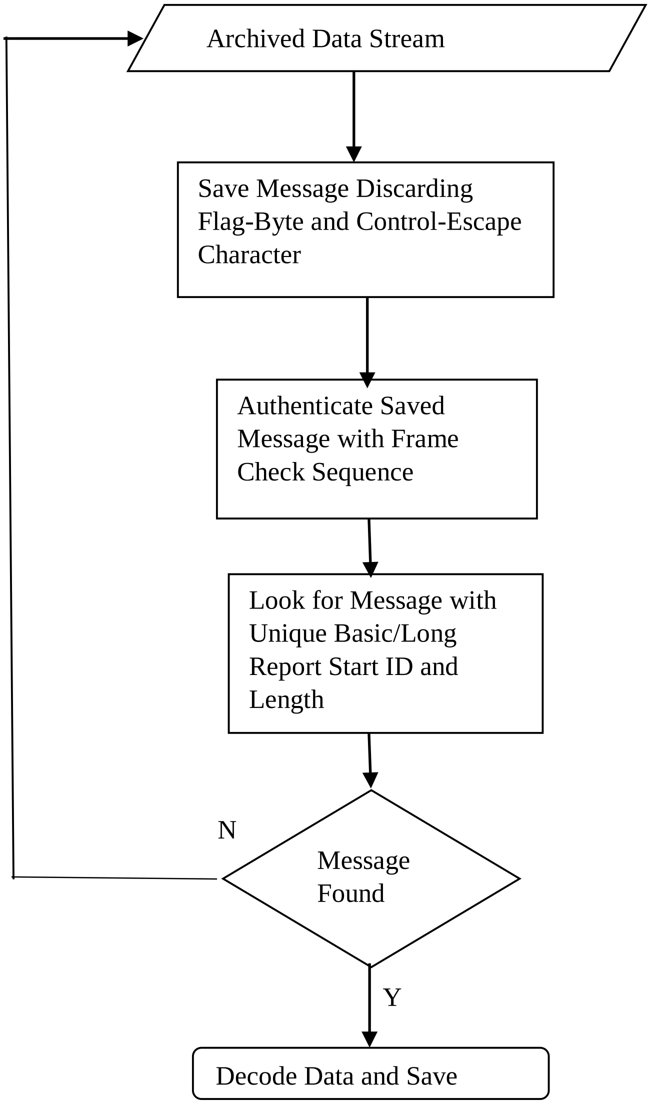


Figure 9:Algorithm for Data Decode

The module can process a single file or multiple files in batch depending on the option selected by the user. The decoded messages are saved into a .csv file. After that the binary data are decoded, the readable message needed to prepare for further analysis. Note that decoded basic and long message were saved in between two heartbeat messages. A total of four weeks of data is analyzed in this study. ADS-B outputs one text at file every minute, 1440 files every day and thus four weeks of data brought about 43200 archived text data files. Decoded data were saved to a .csv file. Each .csv file contains eight hours of data. The decoded message file size is about 4.10 GB. To prepare the data for analysis first task was to assign the timestamp in each stream and separate the long and basic messages. Data stream received in between two stamps belong to the preceding time stamp. The basic and long messages are separated based on the type code. There is a lot more information present in the payload elements and not all of them are discussed in this study. Prior assessing the messages, a list of message fields for analysis were selected based on FAA's Performance Analysis reports for ADS-B [35] and several flight test reports [36], [25]. The data sorting, and filtering were carried out in MATLAB. The data were further sorted by aircraft ID and stored in .mat file. Table 5 provides a notion of data filtration and Table 6 listed the message fields description considered in this study.

Table 5: Data Removal Summary

Entire data rows	Removed data rows	Saved data rows
186477411	173624802	12852609

About 6.89% of the entire data is considered in this study, which are the UAT data transmitted from ICAO address assigned aircraft. It should be noted that the receiver also receives ADS-R and TIS-B. ADS-R is a client-based service that relays ADS-B information transmitted by an aircraft broadcasting on one link to aircraft equipped with

ADS-B In on the other link. For example, the information for an aircraft equipped with a 1090ES ADS-B Out system will be re-broadcasted to an aircraft equipped with ADS-B In 978MHz frequency, and vice versa. The percentage of ADS-R data was higher compared to ADS-B, as the all the commercial aircraft use 1090ES ADS-B which in turn transmitted via ground stations as ADS-R for UAT transceiver to receive. TIS-B is also a client-based service that provides ADS-B Out/In equipped aircraft with surveillance information about aircraft that are not ADS-B equipped. Further, the data contain ADS-B messages from different ground receiver, surface vehicles etc. Saved data rows belong to only UAT basic and long messages transmitted from the aircraft whose address was assigned by ICAO.

Table 6: Description of the Message Fields

Address Qualifier	Indicate what the 24-bit “ADDRESS” field represents. If the address qualifier value is 0, the message is considered from an ICAO target.
Address	Unique ICAO assigned address used to distinguish aircraft
Latitude, Longitude	Two-dimensional position
Primary Altitude	Altitude from barometer in feet
Secondary Altitude	Altitude from GPS sensor in feet
NICp	Navigation Integrity Category for the position, determine whether the reported position has an acceptable level of integrity for the intended use.
NACp	Navigation Accuracy Category for Position determine if the reported State Vector has sufficient position accuracy for the intended use
Aircraft State	Airborne or on ground condition
Vertical Velocity	Velocity in upward/downward in knots
Vertical Velocity Sign	Sign indicating the direction of vertical velocity field
East Velocity	Velocity in east/west direction in knots
East Velocity Sign	Sign indicating the direction of east velocity field
North Velocity	Velocity in north/south direction
North Velocity Sign	Sign indicating the direction of north velocity field in knots

*ADS-B message encodes velocity as knots, distance as NM and altitude as feet, these are standard units set by FAA and used by ATC for separation.

3.2 Performance Assessment of the ADS-B System

3.2.1 Performance parameters

There are certain parameters that define the performance standard for an ADS-B system.

i. **ADS-B Continuity:** It is the probability that the system performs its required function without unscheduled interruption. ADS-B shall provide surveillance information at a rate of 1Hz. The continuity of the ADS-B system depends on several factors such as the continuity of the satellite information, onboard navigation functions and continuity of datalinks etc.

ii. **ADS-B Accuracy:** ADS-B accuracy is defined as a measure of the difference between the aircraft position reported in the ADS-B message field and the true position. It is also defined as noise where the noise is assumed to follow a Gaussian distribution, and the RMS value is quoted [4]. This accuracy of the position information can be found in the ADS-B message itself from the quality indicator, Navigation accuracy category-position (NACp) value. The NACp specifies the accuracy of the aircraft's horizontal position information (latitude and longitude) transmitted from the aircraft's avionics. The ADS-B equipment derives a NACp value from the position source's accuracy output, such as the Horizontal Figure of Merit (HFOM) from the GPS. The NACp specifies 95% probability that the reported information is correct within an associated allowance. Table 7 shows the applicable NACp values with Estimated Position Uncertainty.

Table 7: NACp Values Assigned for Different Uncertainty Range. [34]

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

iii. **ADS-B Integrity:** ADS-B integrity is the level of trust that errors will be correctly detected. [4]. The NIC parameter specifies a position integrity containment radius. NIC is reported so that surveillance applications, such as ATC or other aircraft, may determine whether the reported geometric position has an acceptable level of integrity for the intended use [37]. When interfacing a GPS position sources, the NIC should be based on the Horizontal Protection Limit (HPL) or Horizontal Integrity Limit (HIL). However, while HPL values significantly smaller than 0.1 nm can be output from single frequency GNSS sources, the HPL may not actually achieve the reported level of protection as there are error contributions that are no longer considered negligible. Table 8 provides a summary of NIC value for different containment radius.

Table 8: NIC Value with Associated Containment Radius [34]

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

iv. **ADS-B Message Field Availability:** ADS-B message availability refers to the ability of the system to transmit all the message fields as defined. This depends on the proper function of the onboard navigation sources and the proper function of the ADS-B message generation functions.

Based on the performance parameters along with an extensive study of the overall ADS-B system and according to ADS-B performance assessment checklist provided by FAA [35] the inspection of the messages involves:

i. **Message Count Verification:** The total number of basic and long messages received in a second is reported in the consecutive heartbeat message. A number of messages received in a certain second and number of message parsed was matched to verify if all the received messages were authentic or not.

ii. **Missing Elements Identification:** Identify if there is any payload information missing in the report.

iii. **Message Discontinuation:** Identify discontinuation when update rate exceeds one second. This anomaly is called data dropout.

iv. **Integrity and Accuracy Check:** Check the position data integrity and accuracy for enhanced surveillance. The minimum NIC and NACp value to operate in the airspace is seven and eight respectively.

v. **Kinematic Check:** Includes reasonableness checks of changes in Baro/Geo altitude, horizontal position, and velocity. This involves a difference in Baro/Geo altitude, abrupt changes in position from the nominal value, etc.

3.3 Anomaly Detected in ADS-B Messages

This section introduces the anomalies detected following the inspection checklist provided in the previous section followed by a brief description, visual representation and detection algorithm of each type of anomalies. A small portion of data (2 days) was used to identify any anomalies associated with these inspections. The anomalies revealed in this step by step assessment can be divided into five distinct categories namely dropout, missing payload, low confident data, data jump and altitude discrepancy.

3.3.1 Dropout

The first and foremost performance metric for any surveillance system is the continuous transmission as well reception of the message. Each surveillance sensor has a defined update rate or scan rate based on the capability and requirements. ADS-B is designed to update every second to provide better traffic scenario, enhance situational awareness and address the limitation of ground-based surveillance sensors. Dropout refers to a discontinuation of an update within one second. Though it is expected and designed that ADS-B will update information at a 1Hz rate, primary inspection reveals that the update rate is often much longer than 1 second. Dropouts occurred in flight multiple times, and they were of different time durations. Figure 10 is a visual presentation of discontinuation of update in a flight. Latitude data is used as a reference of discontinuation of the overall message frame.

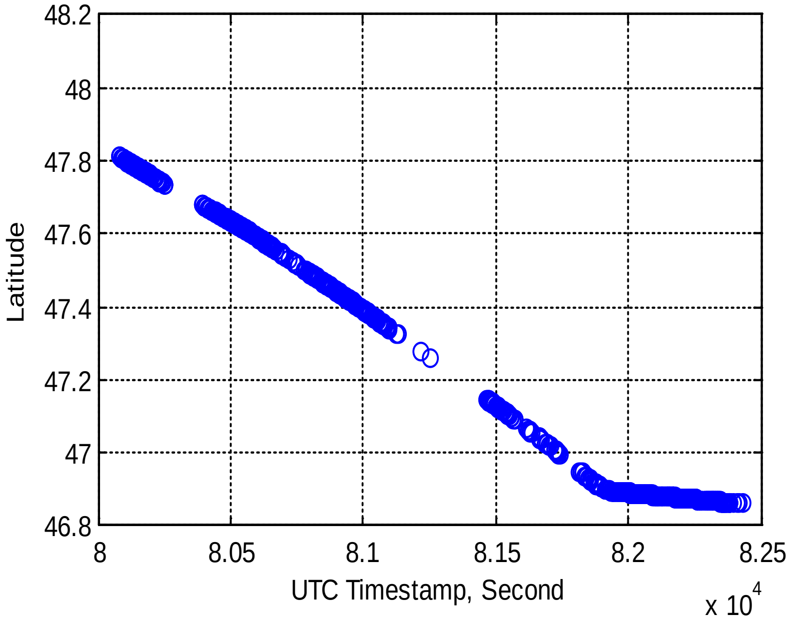


Figure 10: Multiple Dropout in A Flight. Latitude Data is Used to Represent the Data Gap. In the 70 Minutes’ Flight Span, Data Were Missed Several Times.

As in enroute the update interval must not exceed three seconds [37], in this study if the time between two consecutive updates is equal to or exceeds the threshold of three seconds it is considered as a dropout. The dropout was further classified in a different group. Chapter four will provide in detail description of each group of dropouts. A descriptive statistic will also be provided. There are cases where the same aircraft flew multiple times a day. This made an aircraft appear with a large data gap in between updates. So, in this analysis, a threshold of 60 mintues was chosen arbitarily. If the data set interval is more than 60 minutes, it is considered as a different flight. Also, there were cases when the aircraft was not updating data for more than 10 minutes, those were considered as out of range data. Reappearing after 10 minutes, it was considered as different flight.

3.3.2 Missing payload

Missing payload refers to two different anomalies. In some cases, the whole basic and long messages are missed and in some cases, part of message fields are not present in the payload. The first task was to verify the total number of the reports received and parsed. According to the algorithm even if the data stream has a basic/long report it will not be considered as a valid report if it not of full length or if calculated Frame Check Sequence (FCS) doesn't match with FCS present in the report [34]. This verification discarded the messages which were not authentic. On an average, 87% of the received messages were full and authentic. Approximately 13% of the reports received that contained important navigation information were of no use. Even the successfully parsed messages missed some payload information. Most of the time this was Navigation Accuracy value for Position (NACp) and Secondary Altitude (essentially Geometric Altitude) value from the long report. NACp specifies the accuracy of the aircraft's horizontal position information which is vital for separation. In most airspaces, NACp must be greater than 8 [38]. The Navigation Integrity Category (NIC) values were also missing in some reports, although were not considered as severe as NACp. The percentage of payload presence in basic and long report are shown in Table 9.

Table 9: Percent Message Field Present in The Long and Basic Report Indicating Message Loss

Message Field	% Presence in data
Address Qualifier	100%
Address	100%
Latitude, Longitude	100%
Primary Altitude	100%
Secondary Altitude	95.00%
NICp	100%
NACp	99.50%
Aircraft State	100%
Vertical Velocity	100%
Vertical Velocity Sign	100%
East Velocity	100%
East Velocity Sign	100%
North Velocity	100%
North Velocity Sign	100%

So, 95% of the long message report geometric altitude in the secondary altitude field and 5% message suffered from losing geometric altitude which is one of the essential elements. Also, NACp value wasn't present in 0.50% of the data which is crucial information to determine the accuracy of the position information. Other than these two fields, all the other information were available from all aircraft in all data frames.

3.3.3 Data Jump

Data jump is a situation where any data point deviates significantly from its previous and next sample. This anomaly mostly occurred in latitude and longitude data. This also refers to a dispersed data from a regular set of data. It looks like a jump when represented graphically. Thus, a jump is the event when one data point deviates significantly from its previous and next sample. As the data jump occurred for latitude and longitude data only, the most probable reasons behind are data encoding issue. Either from the GPS end or ADS-B message generation end. The FAA also reported on ADS-B position jumps in their early implementation experiences and justified the cause as being a position encoding issue [4]. Experts from UND aerospace also explained this fact as the transponder issue. Figure 11 illustrates the jump in latitude data from a nominal value.

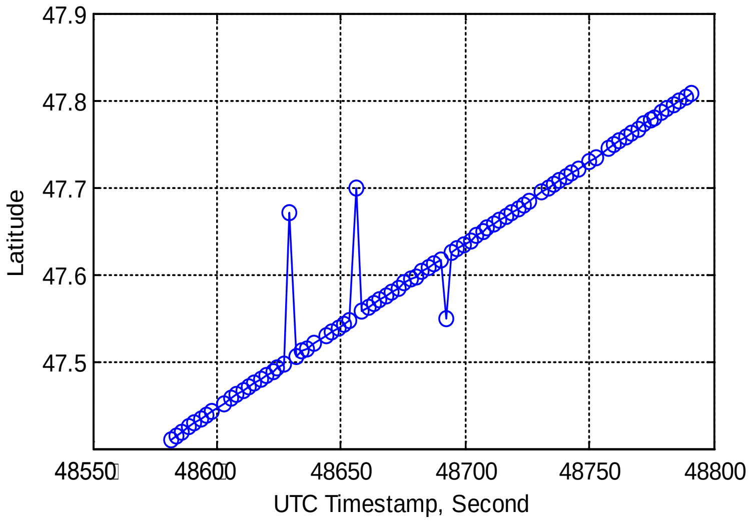


Figure 11: Jump In Latitude Data from Continuous Nominal Value.

This situation is also known as “ghost traffic” to the air traffic controller, where an aircraft is detected in an area but in real there’s no traffic at all.

3.2.3 Altitude discrepancy

From the long reports, two different altitudes are available, one from the pressure sensor and another from GPS/WAAS. Barometric altitude has long been used by aviation industry for measuring altitude and separation. Deviations between barometric and geometric altitude were observed from the analysis of the long report. A visual example of deviation between altitudes is presented in Figure 12.

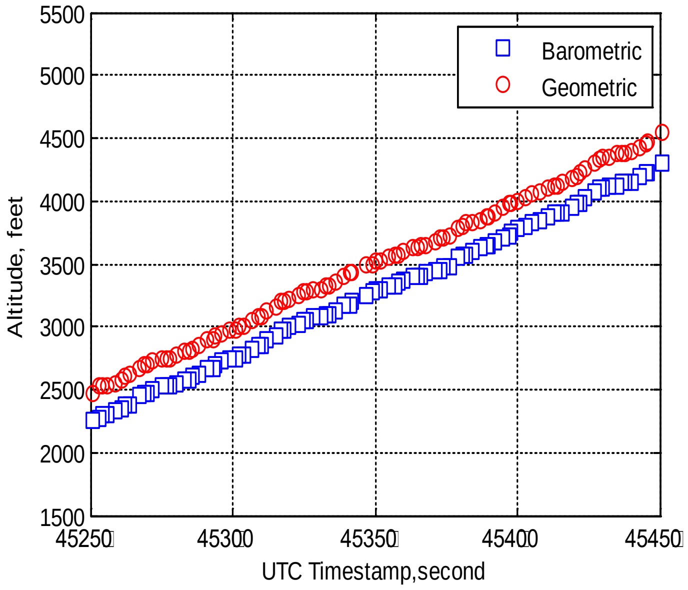


Figure 12: Altitude Discrepancy in Climbing Phase of Flight. Blue Rectangles Describe Barometric Altitude, and Red Circles Describe Geometric Altitude.

Although it is not entirely an anomaly from the ADS-B system itself, while using geometric altitude from ADS-B message for separation, this deviation might cost safety. Pressure altitude is used for separation by convention [23], geometric altitude will be used in the case when barometric altitude is not available. Also, as for sizing and weight capacity, not all UAS in NAS will have a pressure sensor installed. So, to address the potential risk associated with using multiple sources information for separation an in-depth analysis of the altitude deviation was carried out in Chapter five.

3.3.5 Low confident data

It is expected that the ADS-B position report will have an NIC value greater than eight and an NACp value greater than seven. However, ADS-B system reports position with lower than the expected value in some cases. The data is called precision condition data when NIC > 8 or NACp > 7. According to NIC, about 3% of the data are non-precision condition data, and for 1.82% the integrity was unknown. The highest NIC value observed was ten, where the maximum NIC value possible is 11. Figure 13 shows the percent of the data integrity in a bar graph.

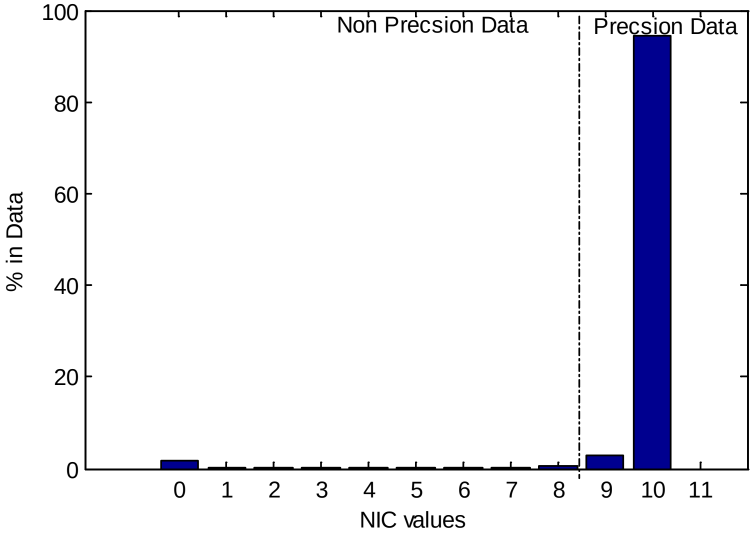


Figure 13: Data Integrity Distribution Bar Graph, No Data Were Found Having Maximum Integrity. Dashed Line Distinguishes the Precision and Non-Precision Range

No data were found to have the maximum integrity in this dataset. Similar percentage was obtained from the accuracy indicator. The highest value for the accuracy indicator was 10, although the maximum possible accuracy indicator value is 11. An NACp value of 10 implies that the estimated position uncertainty of the GPS position data was less than 10 meters. That means all the position data reported by ADS-B in the airspace surrounding Grand Forks have uncertainty of less than 10 meter. The highest accurate data would reduce the uncertainty range from 10 meters to 3 meters.

3.4 Data Filtering for Extensive Study

After the anomalies were identified primarily the data sorting algorithm were regenerated. The data filtering flow chart is provided in Figure 14.

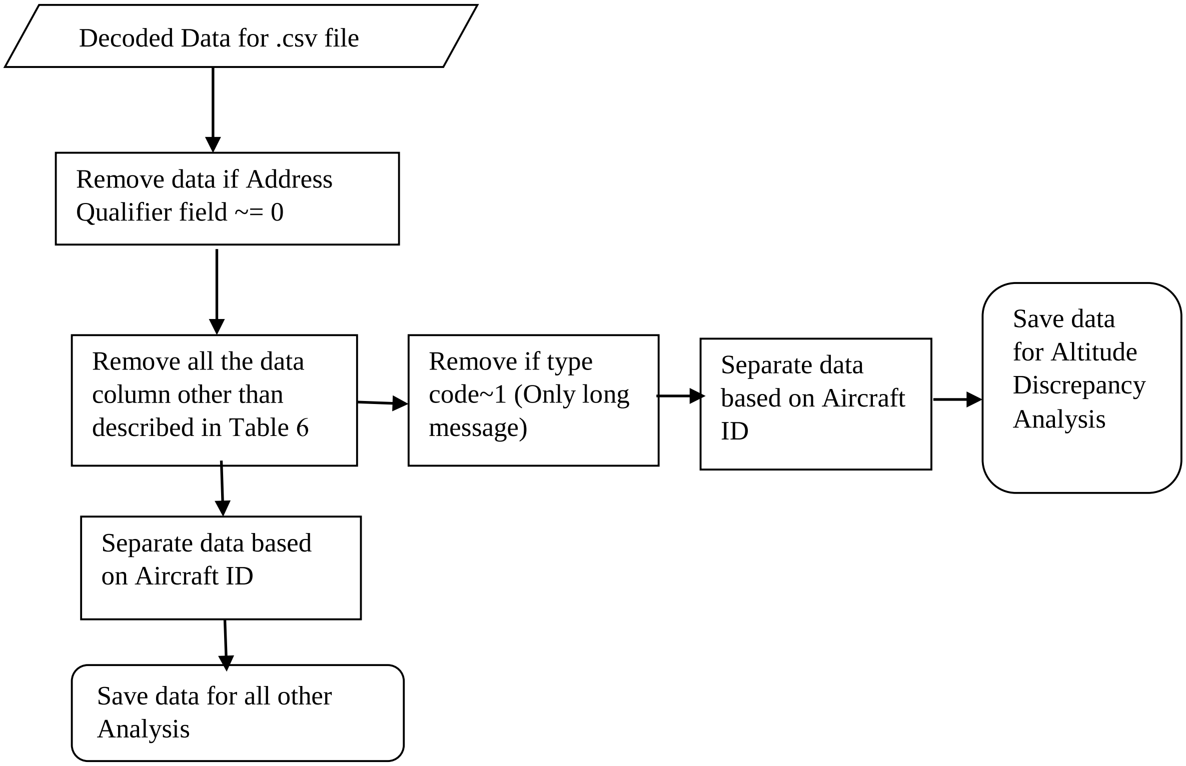


Figure 14: Data Sorting and Filtering Flow Chart Depicts the Steps Use to Filter and Sort the Data

Data are saved in two different formats, one is for altitude discrepancy analysis, and another is for the rest three analysis. This is because not all the aircraft transmit both long and basic message; some aircraft just transmit basic, or some transmit the long message only while some transmit both alternately. To analyze altitude discrepancy, only long messages are of interest as the basic message does not contain secondary altitude information. All other assessments need both basic and long messages. So, the message fields described in Table 9 from both basic and long messages are saved in cell array based file. While each cell contains payloads from certain aircraft.

For extensive analysis with the altitude discrepancy, the phase of flight is needed to be detected. Two different message fields were used to detect the phase of flight. One is vertical velocity rate, and another is vertical velocity sign. Table 10 presents the value to detect the different phase of flight. The vertical velocity selected is nominal descend and ascend rate for general aviation aircraft.

Table 10: Phase of Flight Detection with Different Threshold Value.

Vertical Velocity Rate	Vertical Velocity Sign value	Phase of flight
Is greater than 150 knots	1	Ascending
Is greater than 150 knots	0	Descending
Is lower than 150 knots	~	Level Flight

The different phase of flight data was further used in different analysis and will be discussed in chapters four and five.

CHAPTER IV

ANALYSIS OF DROPOUT & ALTITUDE DISCREPANCY

Among all the anomalies detected dropout and altitude discrepancy were found to be more frequent. Considering the versatile features and danger being imposed by them, an in-depth analysis was carried out for both dropout and altitude discrepancy. This chapter will expose some of the factors that characterize and affect them. Section 4.1 outlines dropout, classifies them into different groups and explores some factors that have significant effects on dropout. Altitude discrepancy is covered in section 4.2 which investigate the potential factors affect and characterize it. Later the discrepancy is also classified in different groups to understand the level of severity and features of each category.

4.1 Dropout

Dropout, an incident where ADS-B message is not continuously updated at 1Hz rate. ADS-B continuity is the probability that the system performs its required function without unscheduled interruption, assuming that the system is available when the procedure is initiated [39]. ADS-B continuity includes the continuity of the

i. functions that affect all aircraft (e.g., satellite and ground data acquisition) expressed regarding number of disruptions per year,

ii. functions that affect only one aircraft (e.g., transponder) expressed per flight hour, and

iii. navigation sources (including satellite constellations) of sufficient quality in the region which affects many aircraft.

The continuity of ADS-B system is measured in seconds at which rate the message received on the ground receiver. Continuity is one of the crucial metrics for considering the performance of the surveillance system. The expected continuity or update rate for different surveillance systems according to International Civil Aviation Organization (ICAO) [10] is presented in Table 11.

Table 11: Surveillance Sensor Performance Characteristics

Surveillance System	Range	Update Rate
Primary Surveillance Radar	S-Band: 60-70 NM L-Band: 160-220 NM	4-15 seconds
Secondary Surveillance Radar (Mode A/C)	200-250 NM	4-15 seconds
Secondary Surveillance Radar (Mode S)	200-250 NM	4-12 seconds
ADS-B	200-250 nm	0.5-2 seconds

ADS-B is envisioned to address the limitations of radar systems, with a lower update rate, with an update rate of less than 2 s, significantly higher than the radar system's 4–15 s. The preliminary analysis of the test data demonstrates that approximately 67.51% of the messages were updated within the specified update rate. Dropout were those 32.49% instances where update rate exceeds 3s.

To understand the factors behind the dropout, a comprehensive review of ADS-B system was carried out. The analysis comprises of investigation of data and assessment of the systems. The investigation of data includes analyzing the flight information available from the messages. Four essential pieces of information from the flight data are considered as potential factors behind drop which referred as airborne factors. These are:

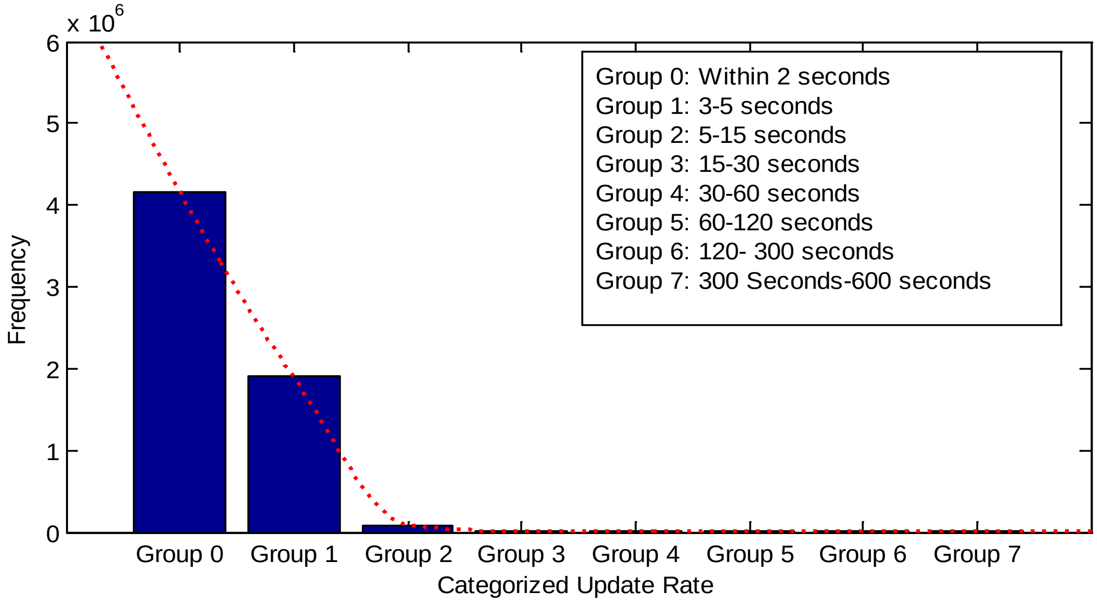
i. Flight Level (Altitude),
ii. Distance from the Ground Receiver (Range)
iii. Heading and
iv. Position (Latitude, Longitude).

To reveal the effect of airborne factors statistical hypothesis testing was carried out. Prior conducting any statistical test, it is mandatory to know the data distribution. To conduct the test, dropout occurrence was categorized based on their duration. Table 12 illustrates the update rate category based on the duration of update interval occurred. It represents the update rate categorized in eight different group, the frequency of each group dropout occurrence along with their percentage.

Table 12: Update Rate Categorizations

Category	**Duration**	**Times occurred, Frequency**	**%**	**Remarks**
Group 0	Within 2 seconds	4161116	67.51	Not Dropout
Group 1	3 seconds to 5 seconds	1898598	30.80	Dropout
Group 2	5 seconds to 15 seconds	86876	1.42	Dropout
Group 3	15 seconds to 30 seconds	6175	0.10	Dropout
Group 4	30 seconds to 60 seconds	5223	0.08	Dropout
Group 5	60 seconds 120 seconds	3330	0.05	Dropout
Group 6	120 seconds to 300 seconds	1365	0.03	Dropout
Group 7	More than 300 seconds to less than 600 seconds	451	0.01	Dropout

The update interval of Group 0 was within 2 seconds which is the expected update rate for ADS-B system and over 67% of the data belong to this group. Group 1 to group 8 are remarked as dropout and 32.49% of the data update rate were belong to these eight groups. Figure 15 shows the histogram of categorized update rate which clearly indicates update rate duration follows non-normal distribution particularly an exponential distribution.



(a)

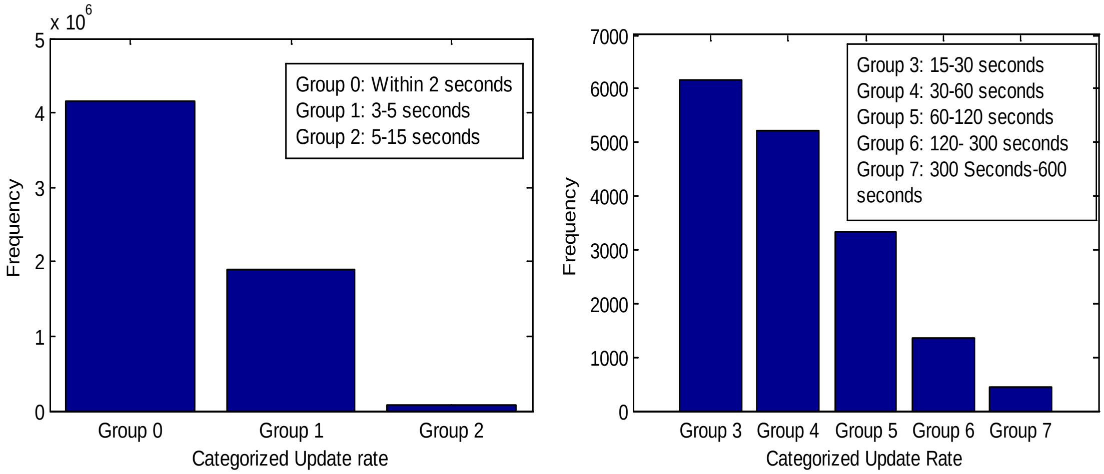


Figure 15: Histogram of Categorized Update Rate (a) All category (b) Shorter Duration (c) Longer Duration.

Most of the dropouts (30.80%) are of group 1, group 2 consists 1.42% of dropouts, group 3 consists 0.10% of dropouts. The percentage of dropout in rest four groups is 0.17%. Only 0.01% of dropout duration were in between 300 to 600 seconds. The most prolonged time interval with no update was 520 seconds.

An exponential distribution describes a process which occurs continuously and independently at a constant average rate. This kind of distribution was expected as all the update rate category are independent of each other, and longer duration of the update is minimally wanted. As all the group update changes exponentially, the bar for Group 3 to Group 4 are not visible in Figure 15 (a). Thus Figure 15 (b) and Figure 15 (c) is used to illustrate the dropout frequency. The dropout frequency is a term used to represent the number of event occurred in the dataset. The frequency of Group 0, Group 1 and Group 2 are higher than the rest of the group. Group 0 update rate was the successful update rate, where the remaining groups were marked as dropouts. Figure 15 (b) represents the frequency of comparatively shorter duration of dropout with a magnitude of 10^5. The longer duration dropout frequency histogram is shown in Figure 15 (c), and the frequency for each group are in a magnitude of 10^3. To confirm data distribution Shapiro–Wilk normality test was carried out. This test compares the sample data to a normally distributed set of data with the same mean and standard deviation. All hypothesis tests ultimately use a p-value to weigh the strength of the evidence [40]. A small p-value (typically ≤ 0.05) indicates strong evidence against the null hypothesis, so you reject the null hypothesis. If the test is non- significant ($p>0.05$), the sample distribution is not significantly different from a normal distribution. If, however, the test is significant ($p<0.05$), then the sample distribution is different from a normal distribution. The p value of test data, $p_{test} = 0.03 < .05$ proves that the data are not normally distributed and conforms to non-linear function.

As the data distribution doesn’t follow normality, non-parametric hypothesis testing “Friedman Test” was adopted to test significance of the factors in dropout. The Friedman test is used to test for differences between two or more groups when the dependent variable being measured is ordinal [41], or the continuous data deviates from normality, and the independent variable is categorical. It is a non-parametric hypothesis testing. This test was chosen because the characteristics of our data agree with the fundamental assumption of this hypothesis testing. This test assumes[41] that data are not normally distributed, each group is measured on a different occasion for our case different altitude/heading/range, the response measured in a continuous level (i.e., dropout in flight time is continuous). Like other hypothesis testing if the p-value is lower than 0.05, it implies that there’s significant difference between the group in a different category. The test was carried out in Minitab which a statistical software [42]. The hypothesis was:

H_o: There is no significance difference between dropout occurrence and factor levels (Flight Level, Range, Heading)

H_1: There is significant difference between dropout occurrence and factor levels (Flight Level, Range, Heading)

The test also provides a rank to each level. In non-parametric statistics, ranks transform the numerical values of each group in ascending order which describes the changes in the group. An overall chi-square value is also provided which is calculated from sum of squared errors.

4.1.1 Effects of Flight Level

To understand the effects of altitude, the categorized dropout were again grouped in different flight level. Four different flight levels are chosen, and the number of dropout occurred are expressed in per flight hours. FL 1 is a region where the altitude less than 4000 feet, FL 2 is the region of 4000 feet-8000 feet, altitude region of 8000 feet- 12000 feet is depicted as FL 3 and the altitude region of 12000 feet-18000 feet is referred to as FL 4. For Group 1 to Group 5, the frequency of dropout per flight hours decreases until the flight level 3 and it increases again. Group 6 and 7 follows the same trend as the dropout frequency decreased until flight level 2 and increased in higher altitude. The frequency of each group of dropouts in different flight level is listed in Table 13.

Table 13: Frequency of Categorized Dropout in Different Flight Level

Altitude		Frequency of Occurrence Per Flight Hour						
		Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7
Less than 4000 feet	FL 1	0.132184	0.132184	0.000711	0.000254	0.000112	4.09E-05	1.88E-05
4000-8000 feet	FL 2	0.132675	0.007446	0.000668	0.000238	0.000104	3.77E-05	1.84E-05
8000-12000 feet	FL 3	0.126544	0.008489	0.001384	0.000706	0.000279	7.43E-05	9.29E-06
12000-18000 feet	FL 4	0.090449	0.017193	0.003164	0.000897	0.000475	0.000633	5.27E-05

Figure 16 shows grouped drop out frequency changes with different flight level. The Figure indicates to the fact with flight level the frequency of drop out changes.

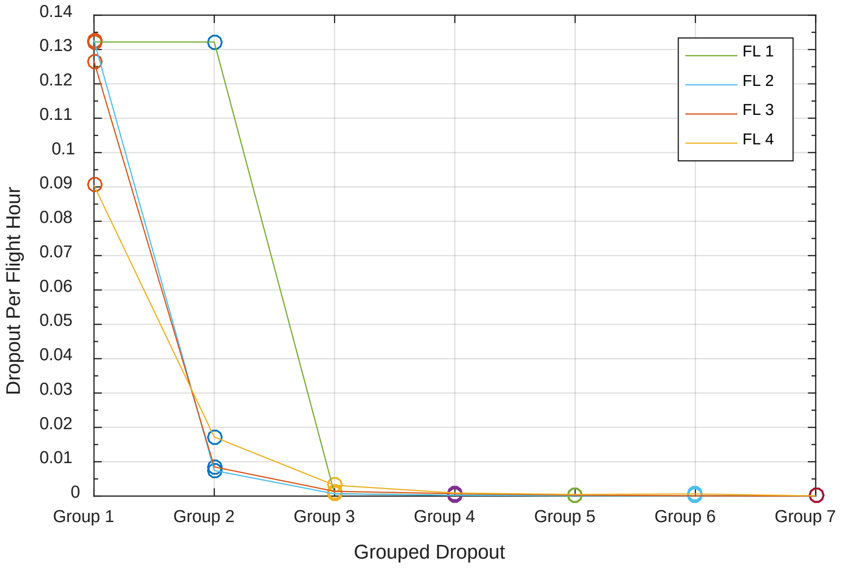


Figure 16: Grouped Drop Out vs Dropout Per Flight Hour for Four Different Flight Level

The test result for different flight level dropout frequency indicates there is a significant difference in dropout frequency in different flight level. Table 14 represents the statistical results; the p-value is 0.03 which reveals the significance of flight level in dropout occurrence.

Table 14: Test Statistics for Different Altitude Level

Fight Level Group	Rank	Test Statistic		
		Chi-Square	df	P value
FL 1	2.28	23.68	27	.03 <0.05
FL 2	1.57			
FL 3	2.57			
FL4	3.57			

From Table 14 the rank tells the occurrence of dropout in ascending order. FL4 has the highest rank which interprets the dropout frequency is higher in that altitude region. FL1 and FL3 suffered from the dropout mostly after FL4. FL2 suffered least from dropout according to the rank associated. Thus, it reveals that flying in the altitude level 4000 feet to 8000 feet will result in less ADS-B message dropout in turn more continuous surveillance during flight.

4.1.2 Effect of Range

A similar statistical testing was carried out to examine the effects of the range of the aircraft and the ground receiver. The range was calculated using haversine spherical formula [43]. The haversine formula determines the great-circle distance between two points on a sphere given their longitudes and latitudes. As in the pass-through interface, data were saved based on range, only the aircraft that were within 120 NM of the receiver was found. This range is further divided into four categories based the air traffic density. Table 15 listed the dropout frequency in a different group in a different range.

Table 15: Frequency of Categorized Dropout in Different Range

Range	Frequency of Occurrence Per Flight Hour						
	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7
Within 20 NM, A	0.127236	0.005834	0.00428	0.000353	0.000229	9.55E-05	3.04E-05
20- 50 NM, B	0.12773	0.005881	0.000393	0.00350	0.000211	7.99E-05	2.81E-05
50-80 NM, C	0.12742	0.005796	0.000378	0.000338	0.000224	8.35E-03	3.25E-05
80- 120 NM, D	0.12757	0.005772	0.000330	0.000331	0.000217	8.11E-05	3.12E-05

Figure 17 showed grouped drop out vs drop out frequency per flight hour for four different ranges. A small change in frequency in group 3 and group 4 can be seen from the Figure however, statistical test is required to reveal the significance of this change.

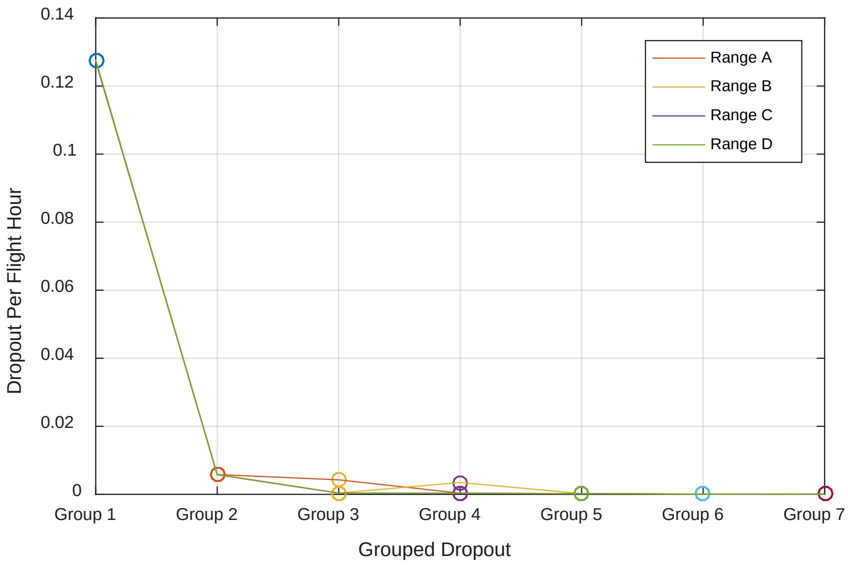


Figure 17: Grouped Drop Out vs Dropout Per Flight Hour in Different Range

From 'Friedman test,' it is found that there is no significant difference between dropout frequency and range. It should be noted that the effective range of ADS-B is 200-250 NM. All the test data are found within half of the maximum range. This might be a reason why the dropout frequency is not significantly different. The test statistics are given in Table 16.

Table 16: Friedman Test statistics for Ranges

Range Group	Rank	Test Statistic		
		Chi-Square	df	P value
Range A	2.85	2.49	27	0.47<0.05
Range B	2.57			
Range C	2.71			
Range D	1.88			

The p-value is way much higher than 0.05 depicting no significance of difference range in frequency of dropout.

4.1.3 Effects of Heading

The effect of heading on dropout was also studied using statistical significance test. Figure 18 provides a visual notion of the heading zone. The heading information is extracted from velocity sign field, North Velocity sign implies north-south direction, and East velocity sign implies the east-west direction. Table 17 presents the categorized dropout for a different zone. It should be noted that traffic density was not equal in the different zones. Most of the aircraft were found in Zone B and Zone D. Probably this is because of the approach path to the airport.

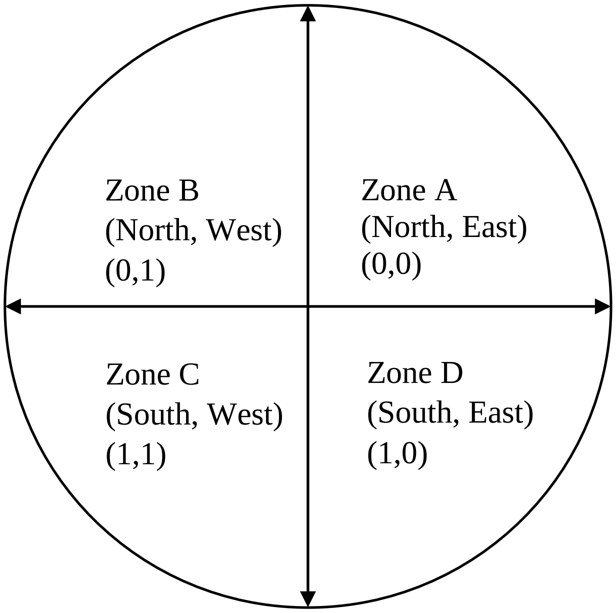


Figure 18: Four Different Zones Based on Aircraft Heading

Table 17: Listed Frequency of Dropout in Different Zone.

Zone	Frequency of Occurrence Per Flight Hour						
	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7
Zone A	0.126784	0.005384	0.000352	0.000359	0.000272	1.31E-03	2.23E-05
Zone B	0.126363	0.005104	0.000385	0.000397	0.000189	2.33E-05	3.75E-05
Zone C	0.126493	0.005121	0.000357	0.000363	0.000268	1.32E-05	2.42E-05
Zone D	0.12645	0.005342	0.000356	0.000387	0.000231	3.26E-05	2.73E-05

From a visual perspective from Table 17 and Figure 19, the frequency of dropout doesn’t differ in between zones. However, that does not infer that heading does not have any impact on dropout frequency. Like previous analysis, the decision made is based on the hypothesis testing.

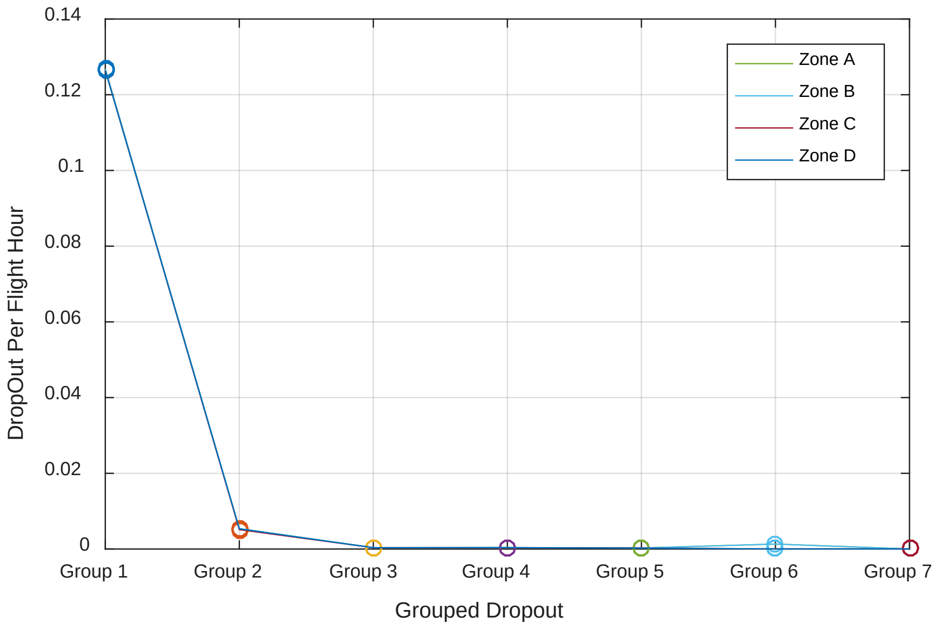


Figure 19: Grouped Dropout vs Dropout Per Flight Hour in Different Zone

The test statistics as shown in Table 18 refers a p-value which is higher than 0.05 indicating to the fact that heading does not have a significant effect on dropout occurrence.

Table 18: Friedman Test Statistics for heading effects

Fight Level Group	Rank	Test Statistic		
		Chi-Square	df	P value
Zone A	2.71	0.4286	3	0.93>0.05
Zone B	2.57			
Zone C	2.28			
Zone D	2.42			

The p-value of 0.93 (>.05) concluded that heading does not influence the dropout occurrence. The value of the ranks for the different zone is not much scattered (i.e., doesn't differ much) rather they differ just after the decimal value which also indicates the dropout occurrence is similar in any heading.

4.1.4 Effects of Position

The position (Latitude, Longitude) data where the higher duration of dropout (Group 5-Group 7) and the position where they recovered was extracted for this analysis. The aim was to examine if a certain position is prone to ADS-B message loss. As position is discrete in nature, this was not categorized in groups, rather, it was checked if certain latitude or longitude data has more than one dropout. It is found that multiple numbers of dropout appeared at certain longitudes. Latitude did not show any characteristics like longitude. This refers to the fact that individual longitude lines are susceptible to lose ADS-B signal. A histogram of number of dropout at certain longitudes is presented in Figure 20. The maximum number of dropout at certain longitude value was as high as 107.

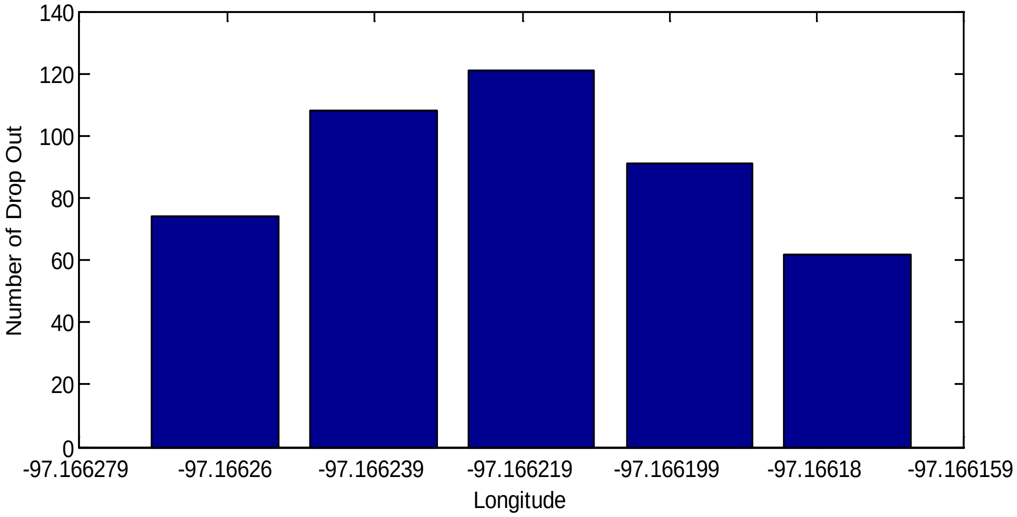


Figure 20: Histogram of Dropout at certain longitude

For a better understanding the longitude along with their latitude where dropout occurred most were drawn on a map. Figure 21 shows the map where the red dot indicates the position of most dropout occurrence.

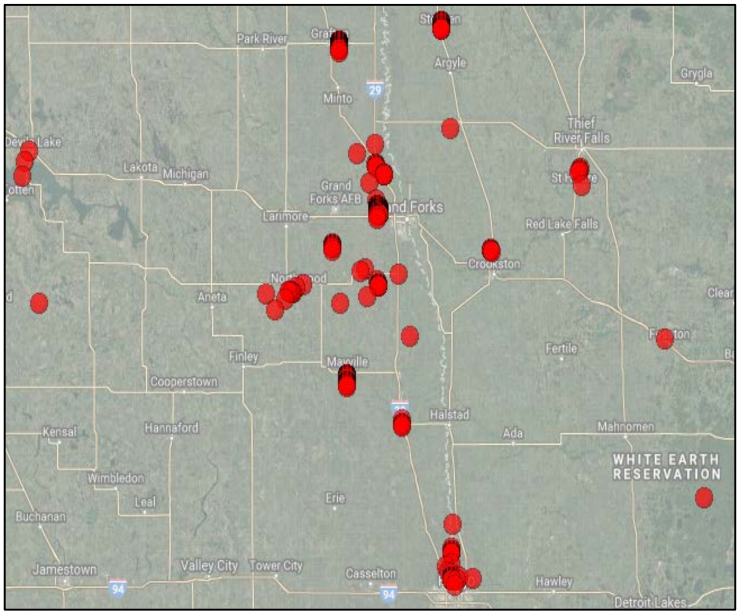


Figure 21: Location of the Dropout in Google Map

There are certain places which effected most by dropout. Referring to Figure 18 some places have a cluster of red dots. To locate those position, a zoomed given the clustered red dot is illustrated in Figure 22.

(a) (b)

Figure 22: Location of the Clustered Dropout (a) Grand Forks International Airport UND Aerospace Runway, Grand Forks, ND (b) Hutson Field Runway, Grafton, ND

Figure 22 (a) and 22(b) describe the fact that dropout occur mainly at the approach path in the terminal area and all of them occurred under the altitude of 1200 feet. It is further reveals that this clustered dropout was due to the traffic density at those locations. According to FAA in 2015, the enroute traffic density was 17.1% and terminal traffic density was 82.9%, based on the statistics of nation’s 34 important airports. [44]. The airport regions have higher traffic than any other location, hence the cluster red dots appeared. An analysis on range effects already reveals the fact that the frequency of dropout per flight hour is similar within range of ground receiver. The map also indicates to a similar conclusion as we can see discrete positions also causing higher duration of dropout. After analyzing further, it is found that the aircraft either perform a touch and go landing or go around in terminal area. A touch and go landing is a common maneuver when learning to fly a fixed-wing aircraft [45]. Figure 20 illustrates the altitude and trajectory pattern of go around.

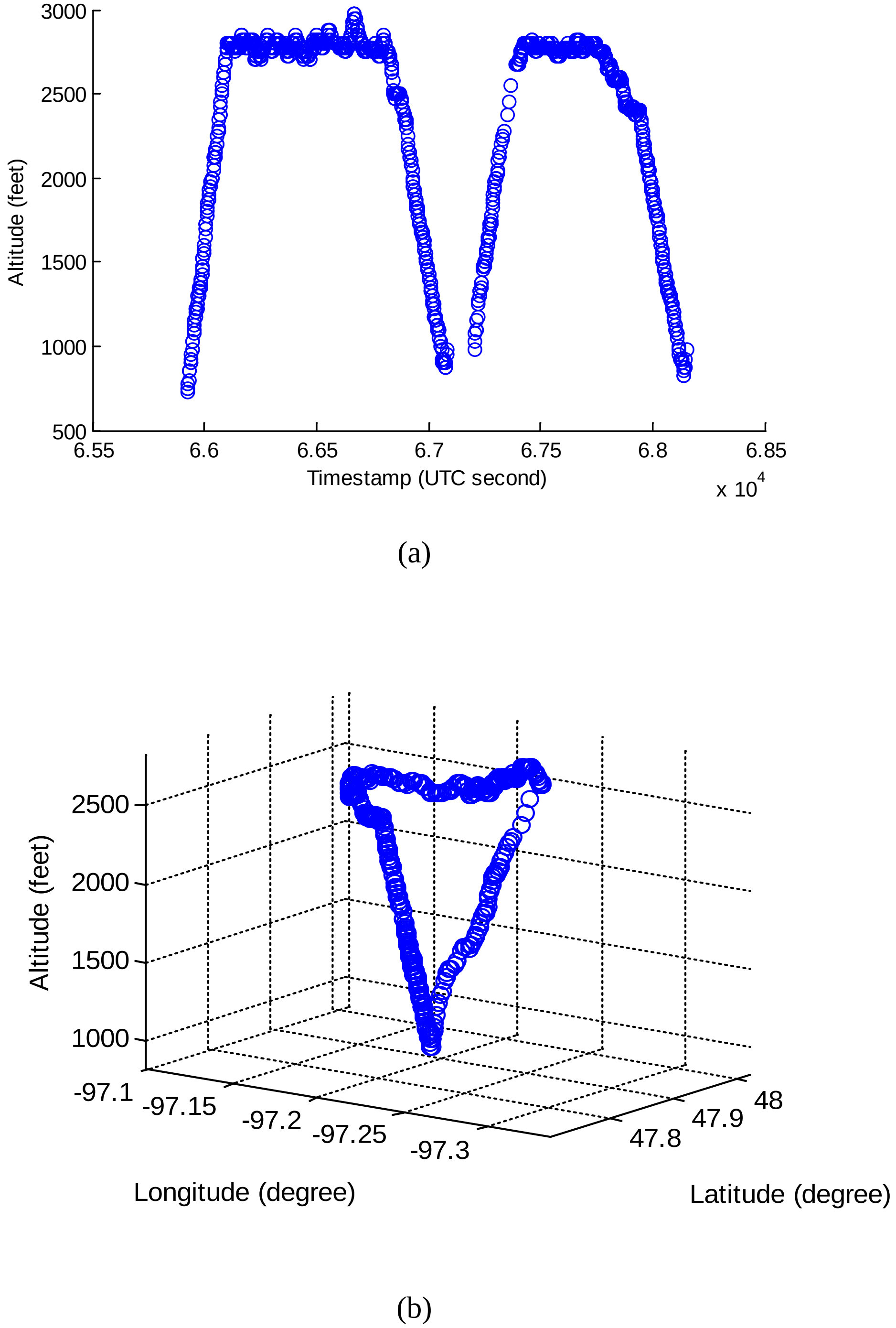


Figure 23: (a) Altitude Profile during Go Around (b) Simplified Trajectory Pattern, the Trajectory only Includes the Go Around Pattern for Better Understanding

Touch and go involves landing on a runway and taking off again without coming to a full stop. A go-around is a maneuver of aborting landing during final approach [46]. This happens when ATC orders to do so, or pilot does not feel safe to land, or there's an error. This maneuver is also initiated by the student pilots for learning purpose [45]. This is assumed to occur because of the line of sight communication loss with the ground receiver. ADS-B signal is prone to signal loss in lower altitude due to ground infrastructure. This might be potential reasons for the occurrence of longer duration of dropout at the time of these special maneuvers in the terminal area.

In the discrete random places other than any airfield, the dropout occurred at an altitude higher than 6000 feet. No definite pattern or causes have been found, and these might be due to multiple reasons such as path loss, transponder issues, onboard sensor, etc.

The findings of the dropout analysis are:

i. Altitude plays a key role in dropout frequency. The lower the altitude, the more chances that a dropout will occur in the ground receiver.

ii. Range does not have any significant role in the frequency of dropout given that the data received were within the effective range of the receiver.

iii. Aircraft heading is not a significant factor for dropout.

iv. Some position may affect the dropout occurrence if that causes a line of sight communication loss.

4.2 Altitude Discrepancy

In aviation, altitude is one of the most crucial pieces of information for navigation and vertical separation[47]. Barometric altitude also known as pressure altitude has long been used by aviation industry for measuring altitude and separation standard. Pressure altitude is the height above a standard datum plane (SDP), which is a theoretical level where the weight of the atmosphere is 1,013.2 mb as measured by a barometer [48]. By measuring changes in atmospheric pressure from the aircraft static port, onboard barometric altitude converts the pressure into altitude in accordance with calibrated reference pressure level. The calibration assumes that the pressure drops at a standard rate as altitude is gained [49]. It is important to tune the altimeter based on whether the aircraft is above or below transition altitude. The concepts of altimeter setting with transition altitude is comprehended in Figure 24.

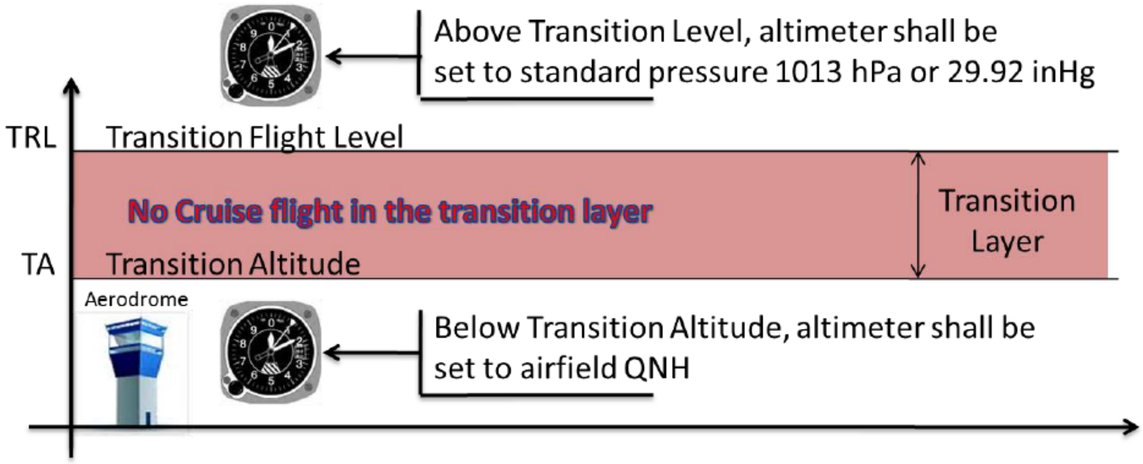


Figure 24: Illustration of Altimeter Setting Above and Below Transition Altitude [23]

Transition altitude is the altitude at or below which the vertical position of an aircraft is controlled by reference to altitudes. The tuning is known as altimeter setting and categorized in three different setting, i) set on local QNH (Query: Nautical Height), ii) set on standard QNE (Query: Nautical Equivalent), and iii) set on QFE (Query: Field Elevation). The barometric altitude is referenced to QNE (standard sea level pressure at 1013.25 hPa at 15°C) whenever the aircraft is above the transition altitude or the local sea level pressure provided by the ATC whenever the aircraft is below the transition altitude. The altimeter for aircrafts flying below the transition altitude will be set to local QNH; which is an altimeter setting based on the local sea level pressure supplied by the ATC. Thus, the altimeter will indicate the vertical distance of an aircraft above mean sea level (MSL).

Geometric altitude was brought to modern aviation by Global Satellite Navigation System (GNSS). The geometric altitude, derived from GNSS sensor, indicates the vertical distance of an aircraft from a reference ellipsoid, WGS-84. WGS-84 is a good approximation to the mean sea level around the planet, however, shows some errors concerning the geoid. The geoid is defined as the equipotential surface that coincides with mean sea level, and that may be imagined extending through the continents where this surface is everywhere perpendicular to the force of gravity [27].

There is no technical reason why geometric altitude cannot be used in ATC applications in future [50]. The availability of altitude data from a barometric altimeter, however, is better since the altimeter only measures atmospheric pressure and does not require a power source or satellites to function [28].

The discrepancy between the geometric and barometric altitude is categorized in five different classes. Table 19 illustrates the range and class for deviation. Deviation starts from 25 feet as the altitude encoded in ADS-B UAT messages as 25 feet increment.

Discrepancy observed in all phases of flight. Figure 25 referred to the altitude data throughout a flight which shows the presence of discrepancy during whole flight time. One important observation is that throughout the flight, one of the sources constantly showed higher value either geometric altitude or barometric altitude. That depicts either one of the sources showed higher value throughout the value throughout the flight. The discrepancy was not constant; rather it fluctuated over the duration of the flight. That is the deviation offset wasn't fixed in flight as they were changing. Figure 25 and Figure 26 provides a visual illustration of the fact where geometric altitude values change in some instances.

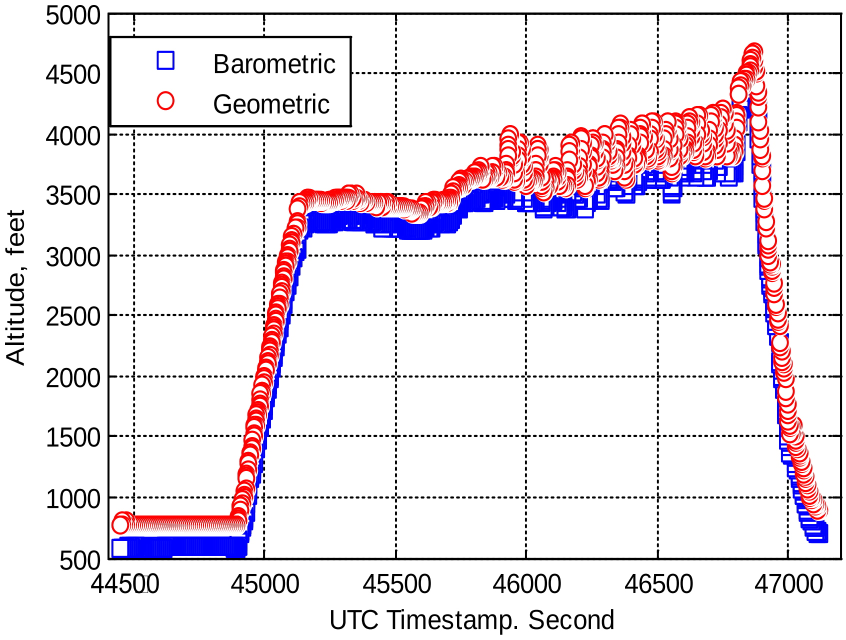


Figure 25: Altitude discrepancies in all phase of flight.

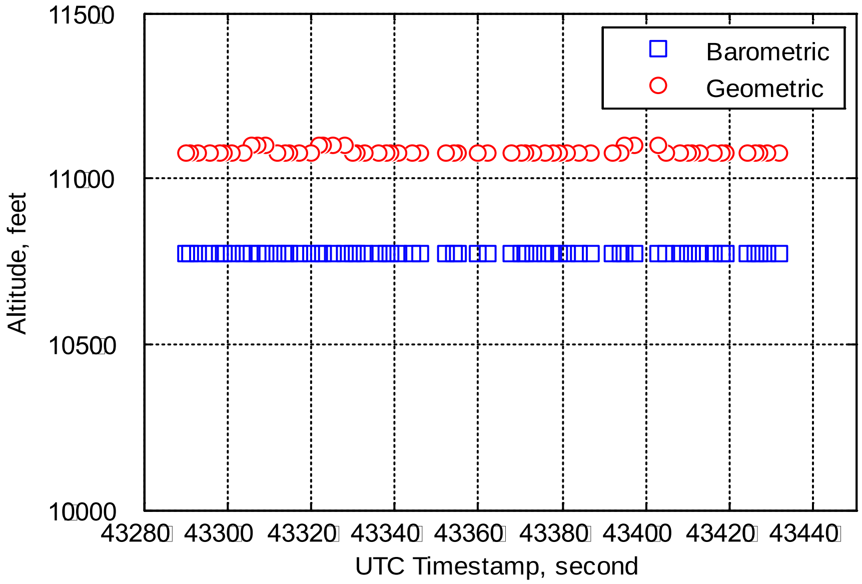


Figure 26: Instances of Geometric Altitude Fluctuation.

Among 1389 aircraft, 1305 aircraft exhibit discrepancy in altitudes. As the discrepancy was fluctuating in nature; the classification is based on dataset. The difference between geometric and barometric altitude were measured for each dataset. After that, they are classified into five distinct categories as described in Table 19. Table 19 also provides the percentage of discrepancy in the dataset.

Table 19: Discrepancy Classification

Category	Discrepancy Range	Percentage
Class 1	25 feet- 100 feet	44.65%
Class 2	101 feet- 200 feet	38.04%
Class 3	201 feet -300 feet	14.18%
Class 4	301 feet-500 feet	2.94%
Class 5	> 500 feet	0.19%

Approximately 45% of the data have a discrepancy within 100 feet. Less than 40% of the data exhibit discrepancy of 101 feet to 200 feet. Around 3% of the deviation were higher than 300 feet. To understand what causes higher deviation two factors were chosen to analyze. One is phase of flight, and another is flight level i.e. altitude. These are selected because during climbing and descending the abrupt changes in the environment might degrade the barometric altimeter performance and as in higher altitude, the atmospheric condition changes barometric altitude tends to give less accurate reading. The next section analyzes the characteristics of both altitude data in flight and discusses how they varied.

4.2.1 Phase of Flight

To assess the effect of phase of flight on altitude discrepancy, the overall mean discrepancy, mean discrepancy of maximum deviation for each aircraft, mean discrepancy of minimum deviation of each aircraft was calculated. Table 20 describes the mean discrepancies.

Table 20: Mean Discrepancies in Different Phase of Flight

Phase of Flight	Overall Mean (feet)	Mean value of minimum discrepancy (feet)	Mean value of maximum discrepancy (feet)
Asceding	117.62	27.43	243.70
Descending	109.78	28.22	225.66
Level	115.62	31.98	232.27

The same nonparametric hypothesis testing was carried out to discover significant factors. The test statistics reveals that there is a significant difference between mean discrepancy in a different phase of flight (p<.05). Table 21 presents the test statistics.

Table 21: Test Statistics for Mean Discrepancy in Different Phase of Flight

Phase of Flight	Rank	Test Statistic		
		Chi-Square	df	P value
Ascending	2	6.0	2	0.04<0.05
Descending	1			
Level	3			

The overall mean and mean value of maximum discrepancies for ascending phase and level flight is higher, which means these two phases suffer from discrepancies more. According to the rank, the overall level flight is prone to altitude discrepancies. Descending phase showed lowest mean discrepancies than two other phases, and also it ranked lowest indicating the fact that deviation is lower when aircraft is in descend.

4.2.2 Flight Level

The regions of flight levels are similar as described in section 4.1.1. Table 22 shows the mean value for a different flight it is clear from the Table that in higher altitude the mean discrepancy value increases. That means, at higher altitude, it is most vulnerable to use barometric and geometric altitude alternately. Table 22 represents the mean discrepancy value in different flight level, and Table 23 shows the test statistics. Flight level categories are same as selected in drop out analysis.

Table 22: Mean Discrepancy Value in Different flight level

Flight Level	Overall Mean (feet)	Mean value of minimum discrepancy (feet)	Mean value of maximum discrepancy (feet)
FL 1	23.65	18.25	129.88
FL 2	78.16	58.26	181.21
FL 3	148.62	122.45	225.97
FL 4	206.93	141.32	285.36

Table 23: Test Statistics for Mean Discrepancy in Different Flight Level

Phase of Flight	Rank	Test Statistic		
		Chi-Square	df	P value
FL 1	1	6.0	3	0.01<0.05
FL 2	2			
FL 3	3			
FL 4	4			

The p-value (0.01<0.05) from hypothesis testing also proves that altitude does have significance is altitude deviation. This can be aligned with the previous analysis of phase of flight, which showed that ascending and level flight mean discrepancy is higher than descending.

While descending the aircraft FL decreases with time, hence in the lower altitude the discrepancy is less. On the other hand, in level flight, the aircraft fly in higher FL, and the discrepancy in higher altitude is higher. This can be concluded that deviations mostly happen due to the outside environment; more specifically due to the dependency of barometric altimeter on temparature and pressure.

CHAPTER V

SEVERITY ANALYSIS IN UAS DAA

Safe integration of UAS into the National Airspace System requires that they interoperate with existing safety systems for manned aircraft. Federal regulations require manned pilots to “see and avoid” other aircraft to remain “well clear” [51]. Since UAS pilots are positioned at a ground control station (GCS) without the ability to visually detect potential threats from inside the cockpit, they will require a “detect and avoid” (DAA) system that provides the information necessary to identify a threat and make an appropriate maneuver with the command and control interface. DAA equipment onboard the UA consists of four major groups i) a set of surveillance sources, ii) a DAA processor, iii) the aircraft systems, and vi) CNPC equipment. The surveillance sources will be of two different class as per Minimal Operational Performance Standard (MOPS) [9]. Class 2 builds from Class 1 and provides additional capabilities while Class 1 contains the basic DAA equipment.

i. Class 1: It requires a minimum of three airborne surveillance technologies which include ADS B In, active airborne surveillance and an air-to-air radar system.
ii. Class 2: Class 1 with a compliant TCAS II system integrated with the DAA

The analysis was done under the assumption that no other UAS DAA system were in use except ADS-B In. This is a way of visualizing hazard and severity associated with single system error, failure, and malfunction.

5.1 DAA Well Clear

The concept of well clear has been proposed as an airborne separation standard to which an unmanned DAA system must adhere to perform self-separation correctly [52]. Well clear is the condition of maintaining a safe distance from other aircraft so that it would not be the cause of initiate a collision avoidance maneuver by either aircraft. The quantitative definition of well clear separation minima is based on acceptable collision risks in consideration of its operating environment and compatibility with aircraft collision avoidance systems [9]. Horizontal separation minima are based on the time-based parameter, and the vertical separation minima are based on distance. Well clear thresholds are estimated from the recommendation made by Special Committee -228 [53] and FAA stands with the recommendation with a slight modification of vertical separation changing vertical separation thresholds from 750 feet to 450 feet [54]. Table 24 represents the well-clear definition thresholds.

Table 24: Well Clear Thresholds

Vertical Separation Threshold, d_h^*	Horizontal Miss Distance Threshold, HMD*	Tau Modification Threshold, τ_{mod}^*	Distance Modification Threshold, DMOD
450 feet	2000 feet	35 seconds	4000 feet

The loss of well clear can be defined as the situation where UAS is near with another aircraft such that the following three conditions are concurrently true:

i. Current Vertical Distance $d_h \leq d_h^*$
ii. Horizontal Miss Distance HMD ≤ HMD^*
iii. Tau Modification, $\tau_{mod} \leq \tau_{mod}^*$

Current vertical distance is a spatial threshold in the vertical dimension which depicts the relative vertical distance between two aircraft. If h_1 and h_2 represents altitude of ownship and intruder than, current vertical distance is:

$$d_h = |h_2 - h_1| \tag{1}$$

The spatial threshold in horizontal dimension is horizontal miss distance (HMD), which is defined as the projected separation in the horizontal dimension at the predicted closest point of approach (CPA) using constant velocity extrapolation:

$$HMD = \begin{cases} \sqrt{(d_x + v_{rx}t_{CPA})^2 + \left(d_y + v_{ry}t_{CPA}\right)^2}, for\ t_{CPA} \geq 0 \\ -\infty\ for\ t_{CPA} < 0 \end{cases} \tag{2}$$

where $d_x = x_2 - x_1$, horizontal separation in x-dimension,$d_y = y_2 - y_1$, horizontal separation in y-dimension, $\dot{v}_{rx} = \dot{x}_2 - \dot{x}_1$, relative horizontal velocity in x-dimension, $\dot{v}_{ry} = \dot{y}_2 - \dot{y}_1$, relative horizontal velocity in y-dimension, $t_{CPA} = -\frac{d_x v_{rx} + d_y v_{ry}}{v_{rx}^2 + v_{ry}^2}$, time to closest point of approach (positive when aircraft are converging).

Modified tau, τ_{mod} is the temporal separation metric estimates the time to CPA between two aircraft using parameter known as "distance modification" (DMOD) to provide a minimum threat range boundary encircling the UAS.

Modified tau, τ_{mod} is defined as:

$$\tau_{mod} = \begin{cases} 0, when\ \dot{r}_{xy} > 0 \\ -\dfrac{\left(r_{xy}^2 - DMOD^2\right)}{r_{xy}\dot{r}_{xy}}, when\ r_{xy} > DMOD\ and\ \dot{r}_{xy} < 0 \\ \infty, when\ \ r_{xy} > DMOD\ and\ \dot{r}_{xy} \geq 0 \end{cases} \tag{3}$$

where DMOD is constant.

The loss of vertical well clear can be expressed as:

$$LoWCV = \ d_h \ \leq d_h^* \tag{4}$$

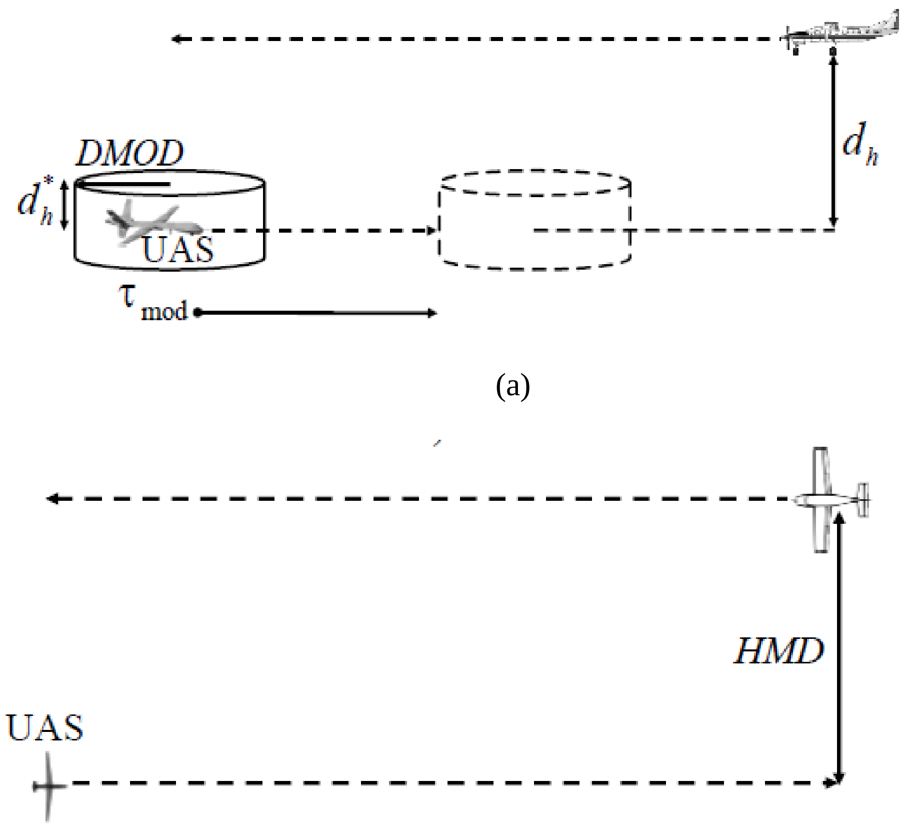
moreover, horizontal well clear can be expressed as:

$$LoWCH = 0 < \tau_{mod} < \tau_{mod}^*\ and\ HMD < HMD^* \tag{5}$$

together the loss of well clear is represented by:

$$LoWC = LoWCV\ and\ LoWCH \tag{6}$$

Figure 27 illustrates the concepts of well clear with an encounter between a UAS flying level heading east and a manned aircraft flying level heading west from two different views. The top view illustrates the concepts of horizontal miss distance and the side view illustrates modified tau and relative vertical distance.



(a)

(b)

Figure 27: Well Clear Illustration (a) Side view, (b) Top view. The dashed objects/lines are projection of future path[55].

5.2 Severity of Dropout in UAS DAA

Although the signal reception performance is different for air to air than air to ground. Study founds aircraft at some altitude, the transmission performance of ADS-B air to air links is poorer than the air than the ground links. That indicates that UAS or aircraft ADS-B In receiver might also experiences more dropouts as compared to the ground receiver. A head-to-head encounter between manned and UAS was set up to analyze the effect of different class dropout as show in Figure 28. The metric used to measure the gravity of dropout is “time to loss of well clear” [9].

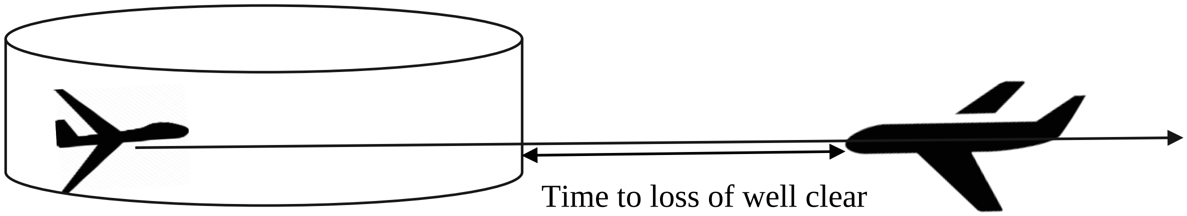


Figure 28: Time to Loss of Well Clear in Horizontal Direction

No particular simulation software was used for this analysis. The scenario is designed to experience a head-to-head encounter at the midway of the track. The horizontal velocity for the manned aircraft was 200 knots and the UAS was 80 knots, and these are kept constant for all dropout values. The DAIDALUS [56] software developed by NASA AMES can calculate the well clear parameters if the track, heading and velocity profile is known for the ownship and intruder. This study made of the use of that open source software to calculate "time to loss of well clear," the track and heading were generated from GPSVisualizer website which can estimate the track given two end points and velocity. The well-clear detection logic is implemented to determine the time to loss of well clear in a look-ahead time. Look-ahead time is a time interval [53] which is used to determine if two aircraft conflict within that time considering constant velocity. The predictions made by the detection logic are based on pairwise, constant-velocity projections. The logic returns empty if there is no loss of well clear within look-ahead time. The time to loss of well clear is used to alert the DAA pilot about potential risk level. Two different alert is triggered one is corrective, and another is a warning [57]. The DAA corrective alert is intended to get the Pilot In Command's (PIC) attention, get the PIC to determine a needed maneuver, start PIC coordination with ATC, and is the initiating point at which maneuvering will likely be started based on PIC judgment [9]. The DAA warning alert is intended to inform the PIC that immediate action is required to remain well clear. Table 25 shows the value of different alerting criteria based on time to loss of well clear.

Table 25: Alerting Criteria in DAA of UAS

Time to Loss of Well Clear	DAA Alert Level	Attention	Response
25 Seconds	Warning	Immediate	Immediate
55 Seconds	Corrective	Immediate	Subsequent

As the detection logic predicts the LoWC within look-ahead time, three different look-ahead time were used to study the severity of dropout duration. The first look-ahead time chosen was 180 seconds, second and the third look-ahead time was 120 seconds and 60 seconds, respectively. The different time window was chosen to clearly identify the severity and hazard associated with each group of dropouts. Table 26 summarize the alert triggered in three different look-ahead time.

According to encounter setup drop out will occur at the beginning of the look-ahead time. The different duration of dropout found from the test data was introduced in the setup. For simplicity, only one dropout was inserted in the scenario. The number of alerts triggered in while dropout is inserted for different group of dropouts was calculated. The alert count is based on the “time to loss of well clear.” If the time to loss of well clear is less than or equal to alert threshold, the associate alert is assumed to be triggered.

Table 26: Alert Triggered in Dropout and No Dropout Case.

Dropout Group	Look-ahead time, 180 seconds			Look-ahead time, 120 seconds			Look-ahead Time, 60 seconds		
	Loss	Warning	Corrective	Loss	Warning	Corrective	Loss	Warning	Corrective
Group 1	No	No	60	No	No	60	No	No	60
Group 2	No	No	60	No	No	60	No	No	60
Group 3	No	No	60	No	No	60	No	No	60
Group 4	No	No	60	No	No	60	2	48	10
Group 5	1	34	25	1	54	5	60	No	No
Group 6	60	No	No	60	No	No	60	No	No
Group 7	60	No	No	60	No	No	60	No	No

For example, if the "time to loss of well clear" is less than 25 seconds, a warning alert is counted. Otherwise a corrective alert is counted. Also, if the "time to loss of well clear" is greater than 55 seconds, it is counted as a corrective alert as eventually it will be generated. When any dropout duration was higher than the look-ahead those are automatically considered as the loss of well clear, as no information is available over the look-ahead time. As the dropout increases and the look-ahead time decreases the number of warning alerts increases. If there were no dropouts all the alerts triggered would be corrective, as DAA would detect the intruder at the appropriate time. The alert triggered for different look-ahead time is illustrated in Figure 29-31.

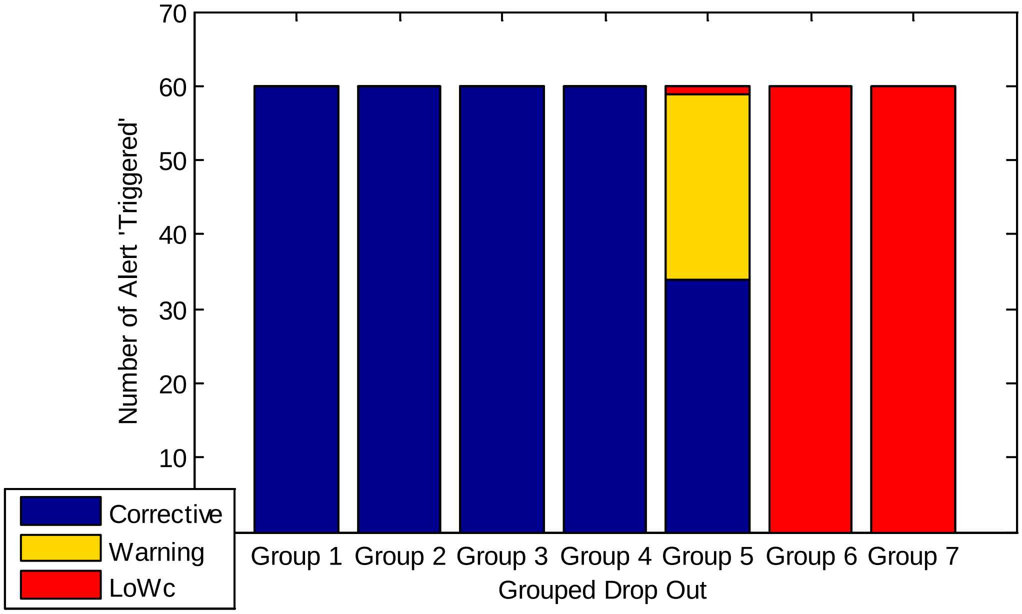


Figure 29: Change in Alert Type for Different Dropout with A Look-ahead Time of 180s

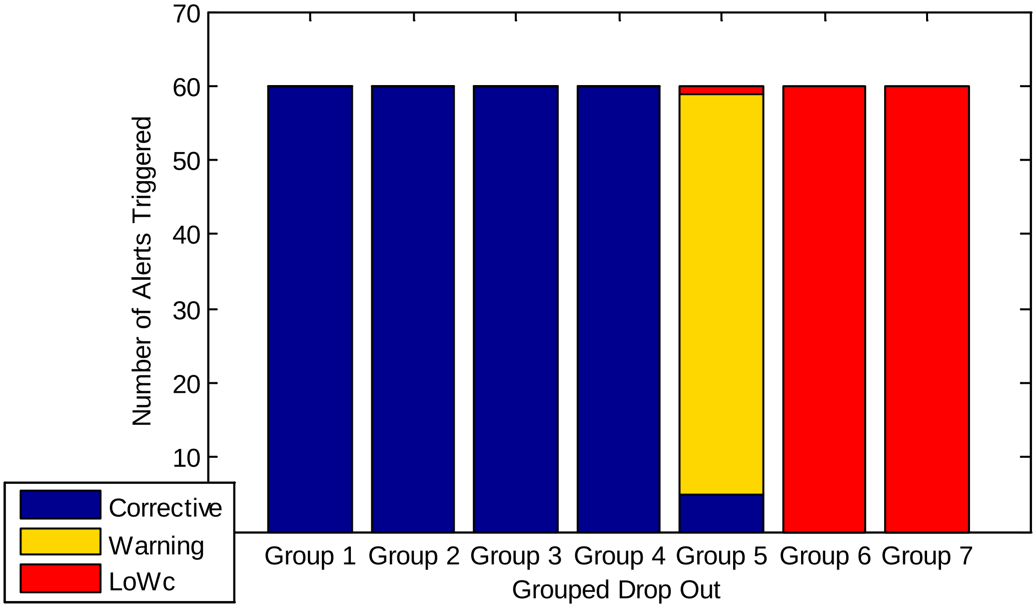


Figure 30: Change in Alert Type for Different Dropout with A Look-ahead Time of 120s

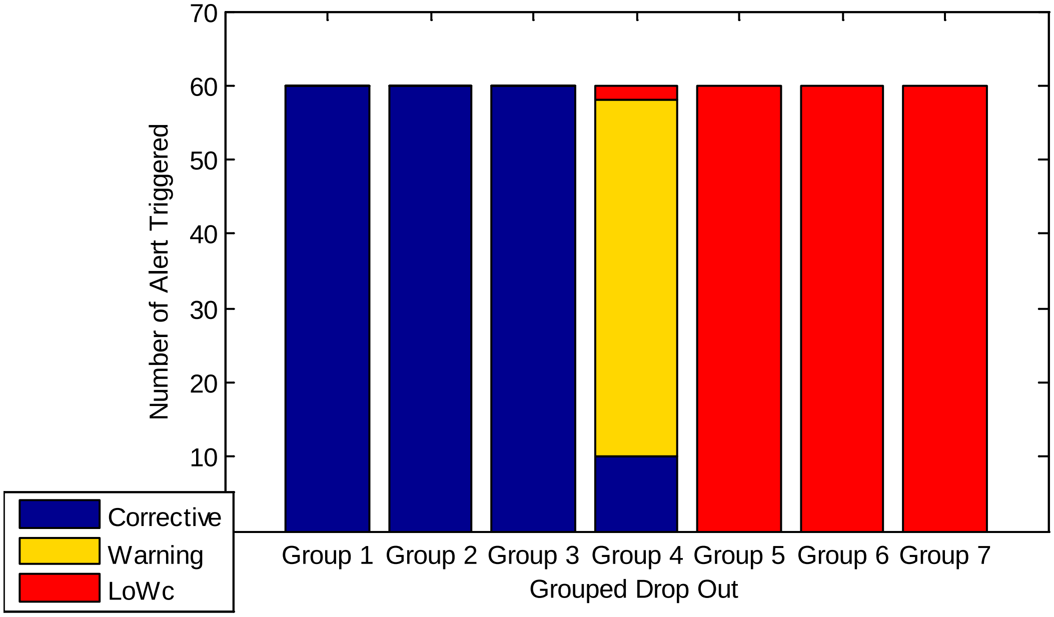


Figure 31: Change in Alert Type for Different Dropout with A Look-ahead Time of 60s

It should be noted that some groups contains more sample than other groups, so the number of alerts triggered for the group, except group 5, group 6 and group 7 where they were either multiplied or normalized by a factor before generating the bar graph. For example, for group 4 there were 30 different durations of dropout as the range was 30 seconds to less than 60 seconds. As per the algorithm, it triggered five corrective alerts, 24 warning alerts and 1 loss of well clear. All the triggered alert number was multiplied by 2 (sample in group 5/sample in group 4). For cases, where sample number was greater than 60, they are normalized by the factor. This is done so that each group has an equal number of scenarios which helps visualize the comparison. As the event of data loss, the DAA logic could not predict the encounter in a timely manner. This could lead to an abrupt maneuver of the ownship to avoid a potential well clear violation. The part of group 6 and group 7 dropout that couldn't be inserted as those are higher than the look-ahead time. This is a severe case where the uncertainty occurred with well clear, and the situational awareness was degraded. From the Figures 26-28, it can be seen that the change in alert depends on the look-ahead time and when the dropout takes place. When the look-ahead time is less; even small duration of dropout can lead to loss of well clear. With a bigger look-ahead time the alert was corrective until the group 4 dropout. The case where dropout was greater than the look-ahead time considered an obvious violation of well clear.

5.3 Severity of Altitude Discrepancy in UAS DAA

To understand and estimate the effect of altitude discrepancy, a series of geometric encounters were developed. Three different scenarios were selected with UAS as ownship and manned aircraft as an intruder. The aim of this experiment was to visualize the severity associated with using two different altitude sources for self-separation. For each intruder, three different deviation values (maximum, minimum and average) were added with primary separation. Theoretically this means changing the altitude source at that instant. The primary vertical separation was 600 feet assumed to measure with same altitude source, i.e., barometric altimeter. The vertical well clear separation minima is 450 feet, the value of 600 feet was arbitrarily chosen to keep them well separated at the beginning. At the beginning of all the encounters both aircraft were in a both vertically and horizontally well clear situation. The number of encounters that lost vertical well clear after introducing discrepancy was counted. Adding discrepancy depicts that separation was maintained with different altitude sources in this stage. The scenarios are:

i. UAS level flight and Manned Aircraft ascending
ii. UAS level flight and Manned Aircraft descending
iii. UAS and Manned Aircraft are on level flight and vertically separated

As the encounters were kept horizontally well clear though out each case, only vertical parameters were needed to simulate the study. The parameters for the well clear volume penetration analysis are described in Table 27.

Table 27: Simulation Parameters

Relative Vertical Distance, dh_1	Relative Vertical Distance with deviation, dh_2	Intruder Vertical Velocity
600 feet	(dh_1 ± deviation) feet, deviation extracted from datasets	Extracted from datasets, knots

5.3.1 UAS level flight and manned aircraft ascending

The first scenario analyzed assumes ownship UAS is in level flight and intruder manned aircraft is ascending. At any given instant, ownship is in both horizontal and vertical well clear with the intruder. At this point the vertical separation was maintained with the same altitude sources. Figure 32 (a) illustrates this stage. After that the deviation is added with manned aircraft altitude which means separation is now maintained with two different altitude sources. It should be noted, both cases occurring at the same instant. The aim is to visualize what it would looks like if there are two same altitude sources and different altitudes sources separation at any time, t.

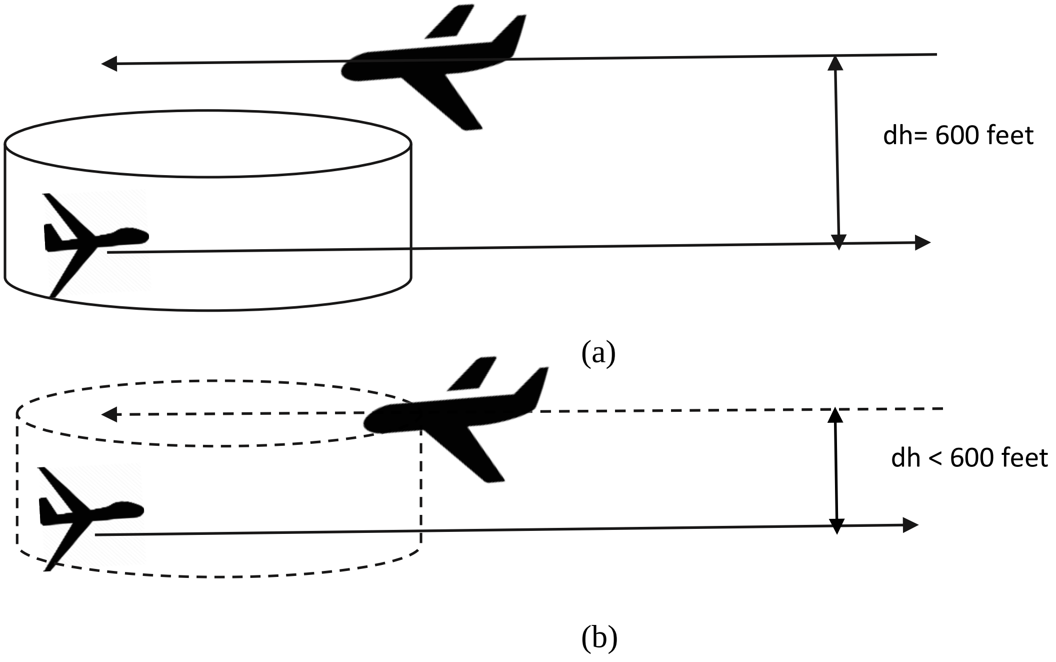


Figure 32: (a)Vertical Separation Using Intruder's Barometric Altitude Sources at Time, t (b) Vertical Separation Using Intruder's Geometric Altitude Sources At The Same Time, t (In Case Where Geometric Altitude Having Smaller Value Than Barometric)

A total of 1400 manned aircrafts' ascending data were used in this study. The bar diagram in Figure 33 represents the results. The bar represents the number of geometry that remain well clear. The blue bar shows the initial well clear state; red bar delineates the number of geometries that remain well clear after adding deviation. As mentioned earlier, the minimum, maximum and average deviation in all phase of flight for each aircraft were measured. Those values were introduced this penetration analysis. The minimum deviation ranges from 0 to 125 feet; maximum deviation ranges from 275 to 625 feet and the average deviation is ranges from 115 to 255 feet. Referring to chapter four where the discrepancy was classified in different ranges. According to Table 19, the minimum discrepancy belongs to class 1 and class 2, the average discrepancy represents part of class 2 and class 3. The maximum discrepancies are the member of the part of class 3, class 4 and class 5.

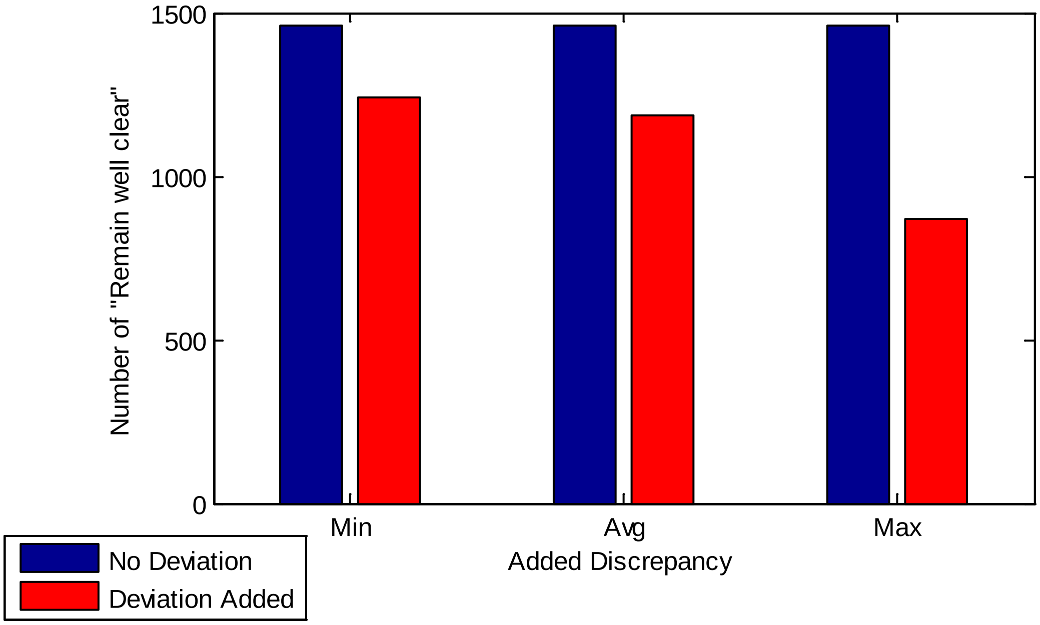


Figure 33: Well Clear Remaining for scenario 1.

Figure 33 describes that, with minimum deviation, the number of geometries lost well clear were minimal, it increases with the deviation increased. In case of maximum deviation, almost half of the cases loss well clear. That means class 3, class 4 and class 5 deviation will result in a situation where confidence level of the well clear state will be lower indicating the fact that using alternate source during flight in a congested airspace might lead to well clear violation.

5.3.2 UAS level flight and manned aircraft descending

The second scenario involves UAS with manned aircraft in descending phase. A total of 1389 aircrafts' descending phase data were utilized in this scenario. Figure 34 is visual representation of the geometry.

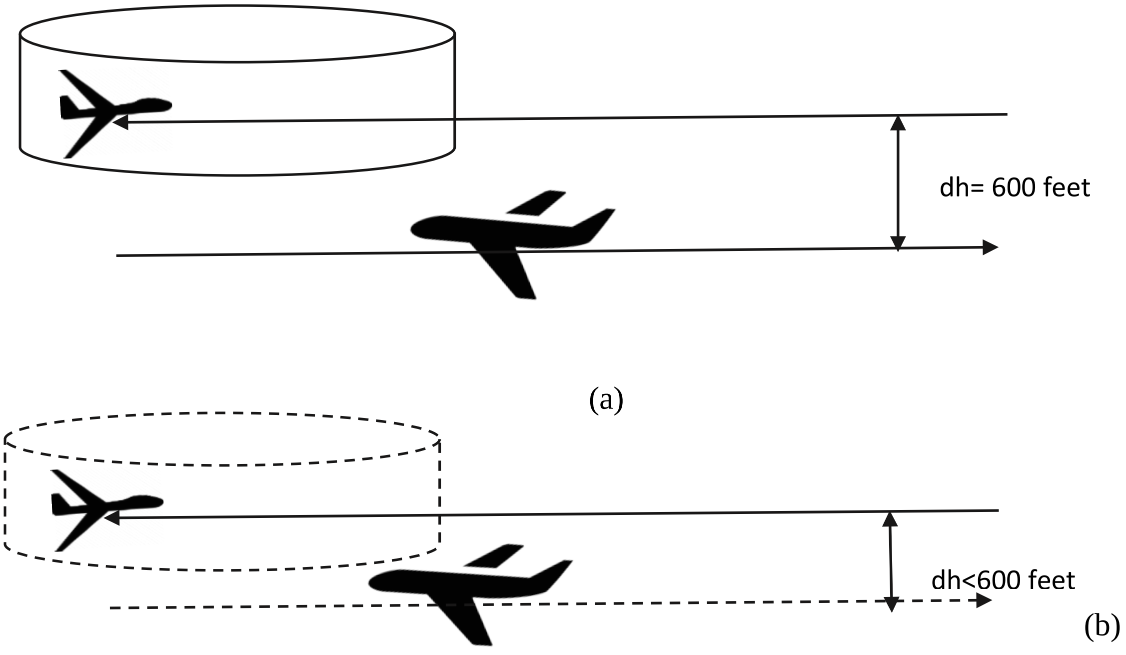


Figure 34: (a) Vertical Separation Using Intruder's Barometric Altitude Sources at Time, t, (b) Vertical Separation Using Intruder's Geometric Altitude Sources at The Same Time, t

Scenario 2 produces the similar results as scenario 1. Almost 40% of the geometries lost well clear when maximum deviation in flight were introduced, as seen in Figure 35.

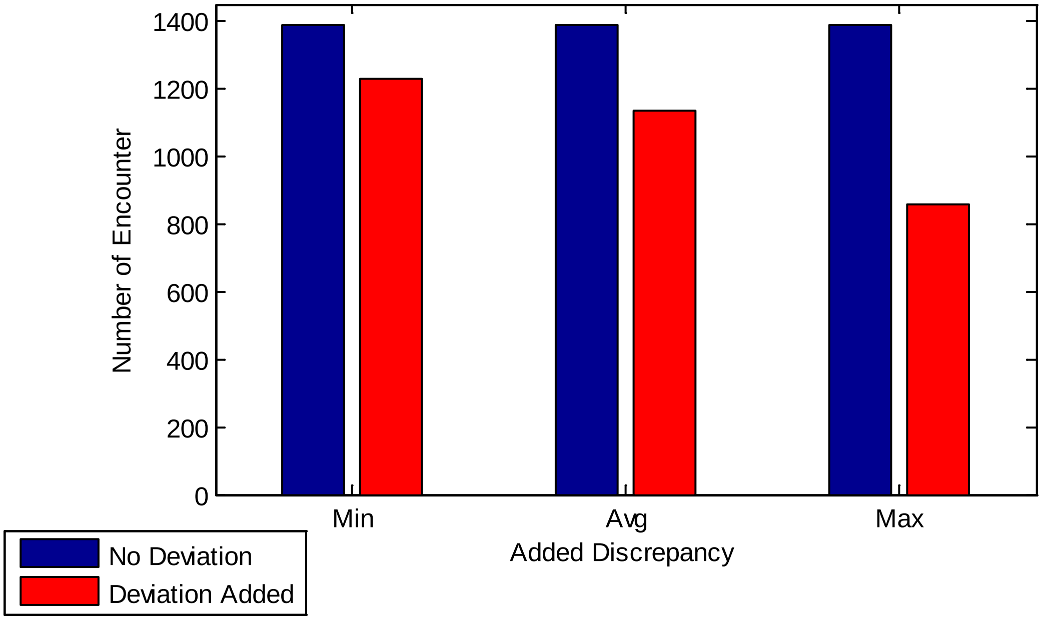


Figure 35: Well Clear Remaining for scenario 2.

It is observed that, the number of loss of well clear encounters is lower when manned aircraft is flying above the UAS. This is because it depends on which altitude value is higher. If the geometric altitude value is higher and manned fly above the UAS, the separation will increase. On the other hand, if the barometric altitude is higher in that case for scenario 2, separation will decrease, hence the number of loss of well clear will increase.

5.3.3 UAS and manned aircraft is on level flight and vertically separated

To understand the effect of the higher value, i.e. whether geometric altitude is higher than barometric altitude or the other way, another scenario was set up. In this case, both the UAS and the manned intruder are on level flight and vertically separated by 460 feet. A small change in value will violate well clear. As there is no vertical velocity, the loss of well clear it entirely depends on the deviation between barometric and geometric altitudes. This scenario has two different case one if UAS is above the manned aircraft and another is UAS is below the manned aircraft. Chapter four discussed the fact that, it is not constant which altitude will be of higher value. It changes from flight of flight. This fact effects the well clear penetration. To visualize this two-different case is created with similar parameters. Cases are illustrated in Figure 36.

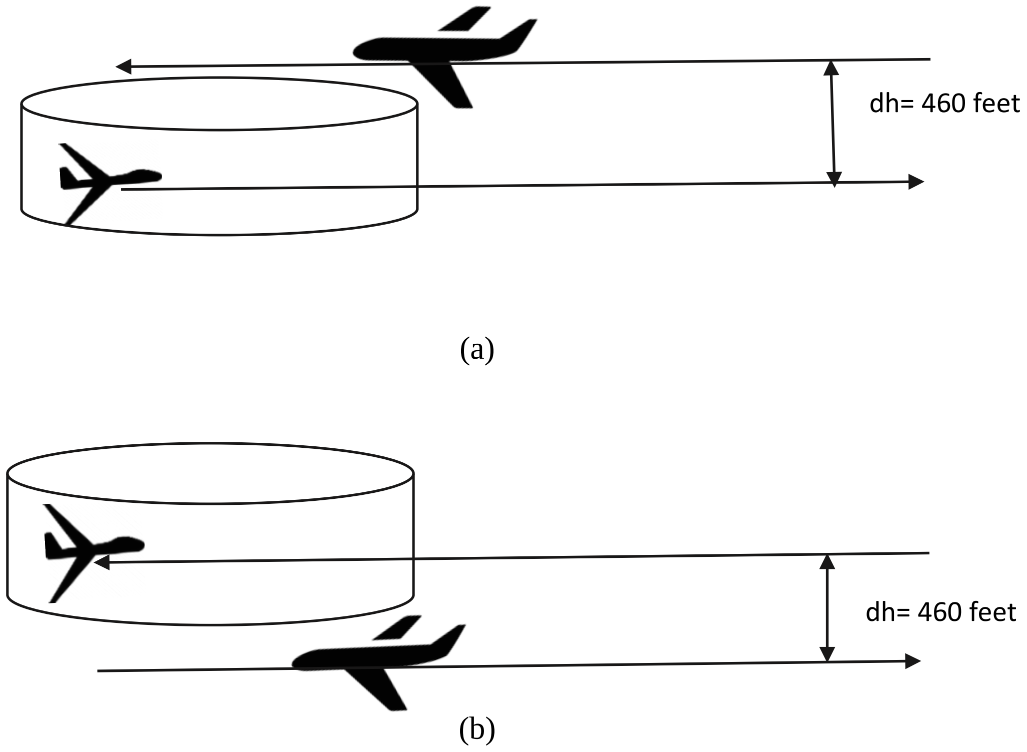
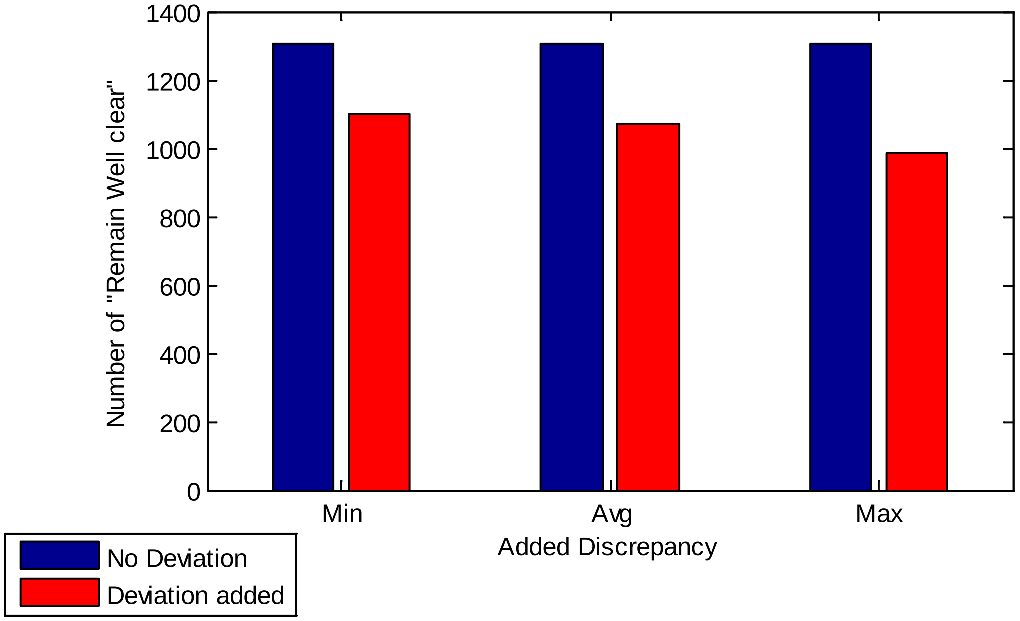
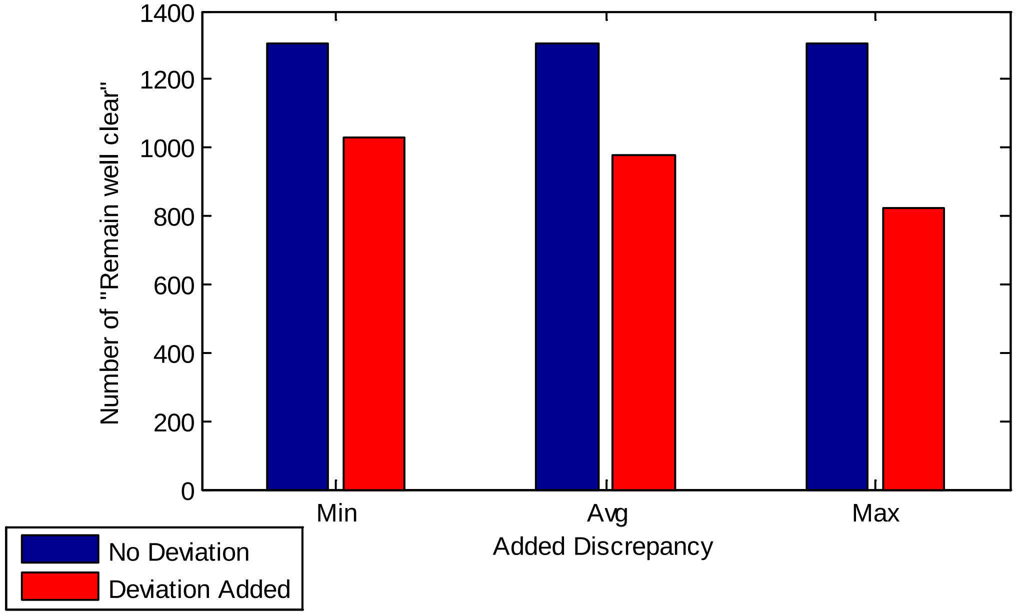


Figure 36: (a) UAS and Manned intruder are on level flight vertically separated by 460 feet, UAS flying in lower Flight level, (b) UAS and Manned intruder are on level flight vertically separated by 460 feet, UAS flying in Upper Flight level

The bar diagram clearly indicates the difference in penetration. Figure 37 (a) shows the penetration results for case 1 and 37 (b) shows the penetration results form case 2. As revealed in chapter four in most cases barometric altitude is higher than geometric altitude so the violation of well clear will increase when UAS flying at lower flight level.



(a)



(b)

Figure 37: (a) Well Clear Remaining for scenario 3(a), (b) Well Clear Remaining for scenario 3(b)

This is because the geometric altitude will lower the flight level of manned intruder hence the violation will occur. On the other hand, if the UAS fly in upper flight level than the manned intruder it will increase the vertical separation. In most of the test data, barometric altitude was higher as a result while UAS was flying at upper flight level, the number of remaining well clear geometry is higher than UAS flying at lower flight level than the manned intruder.

5.4 Hazard Analysis

Hazard analyses are performed to identify and define hazardous conditions/risks for the purpose of their elimination or control. One of the crucial step is to perform a risk assessment of the severity of consequence and likelihood of occurrence. To assess risk, the FAA and other organizations use Safety Risk Management (SRM), which is a process to analyze, assess, and accept risk for designs, policies, and many other aspects. Identification of a risk is the first step in the risk control process. According to [58] evaluation of risks requires determination of how frequently a risk occurs and how severe it could be if and an accident occurs as a result of the hazards. A severe risk that has a realistic possibility of occurring requires action; one that has an extremely remote chance may not require action. Similarly, a non-critical accident that has a realistic chance of occurring may not require further study. The frequency may be characterized qualitatively by terms such as "frequent" or "rarely." It may also be measured quantitatively such as by a probability. Hazard analyses can be performed in either a qualitative or quantitative manner or a combination of both. A qualitative analysis is a review of all factors affecting the safety of a product, system, operation, or person. It involves examination of the design against a predetermined set of acceptability parameters. In a quantitative analysis, the risk probability is expressed using a number or rate. Probability is the expectation that an event will occur a certain number of times in a specific number of trials. Actuarial methods employed by insurance companies are a familiar example of the use of probabilities for predicting future occurrences based on past experiences. Reliability engineering uses similar techniques to predict the likelihood (probability) that a system will operate successfully for a specified mission time. Reliability is the probability of success. It is calculated from the probability of failure, in turn calculated from failure rates (failures/unit of time) of hardware (electronic or mechanical).

A risk matrix is one of the tools that helps quantify the amount of risk. The risk matrix considers the severity and likelihood of an event, then using the combination of both interactions, assigns a rating in terms of risk: unacceptable risk, acceptable risk with mitigation, and acceptable risk. The FAA severity definitions, the FAA likelihood definitions and the generic FAA risk matrix are provided in Table 28, Table 29 and Table 30, respectively.

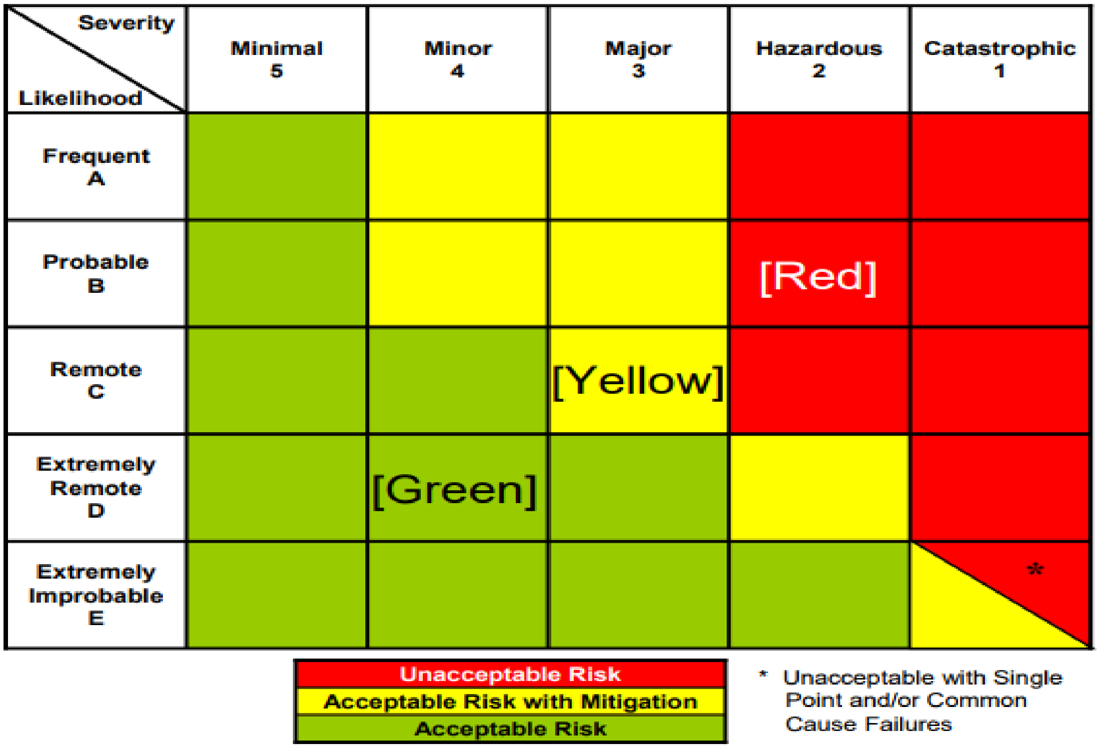
Table 28: Likelihood definition by FAA

Frequent, A	Expected to occur routinely
Probable, B	Expected to occur often
Remote, C	Expected to occur infrequently
Extremely Remote, D	Expected to occur rarely
Extremely Improbable, E	So unlikely that it is not expected to occur, but it is not Impossible

Table 29: Severity Definition as per FAA

Minimal, 5	Minor, 4	Major, 3	Hazardous, 2	Catastrophic,1
Negligible safety Effect	Physical discomfort to persons Slight damage to aircraft/vehicle	Physical distress or injuries to persons Substantial damage to aircraft/vehicle	Multiple serious injuries; fatal injury to a relatively small number of persons (one or two); or a hull loss without fatalities	Multiple fatalities (or fatality to all on board) usually with the loss of aircraft/ vehicle

Table 30: FAA Generic Risk Matrix



Severity / Likelihood	Minimal 5	Minor 4	Major 3	Hazardous 2	Catastrophic 1
Frequent A	🟩	🟨	🟨	🟥	🟥
Probable B	🟩	🟨	🟨	🟥 [Red]	🟥
Remote C	🟩	🟩	🟨 [Yellow]	🟥	🟥
Extremely Remote D	🟩	🟩 [Green]	🟩	🟨	🟥
Extremely Improbable E	🟩	🟩	🟩	🟩	🟨 🟥 *

🟥 Unacceptable Risk
🟨 Acceptable Risk with Mitigation
🟩 Acceptable Risk

* Unacceptable with Single Point and/or Common Cause Failures

5.4.1 Hazard analysis for dropout

A risk matrix for dropout was created based on the percent of dropout occurred in dataset and the value of time to loss of well clear. The severity matrix was developed based on "time to loss of well clear", t_{loss} value. A value of t_{loss} = 55 seconds will trigger a corrective alert where as a value of t_{loss}=26 seconds will also trigger a corrective alert, but the risk associated in both alerts isn't the same. As the time window to initiate a maneuver is less for the second one, there will be increased risk. The risk matrix developed is based on one head-to-head encounter scenario, hence the risk rating doesn't represent the overall risk of the airspace. The likelihood and the severity definition developed for the dropout hazard assessment is described in Table 31 and Table 32.

Table 31: Likelihood Definition for Dropout

Frequent, A	Occurred in more than 10% times in dataset
Probable, B	Occurred in less than 10% but more than 1 % times
Remote, C	Occurred in less than 1 % but more than 0.10 times
Extremely Remote, D	Occurred in less than 0.10% cases but more than 0.01% times
Extremely Improbable, E	Occurred in less than 0.01% times

Table 32: Severity Definition for Dropout

Minimal,1	Minor,2	Major,3	Hazardous,4	Catastrophic,5
t_{loss} is greater than 55 seconds	t_{loss} is in between 40 -55 seconds	t_{loss} is in between 25-40 seconds	t_{loss} is in between 10-25 seconds	t_{loss} is less than 10 seconds

Based on the definition, the number of alert triggered for two different look-ahead time are placed on the risk matrix. To establish, the number of alert triggered from t_{loss} less than 55 seconds were counted and which group of dropouts caused this trigger was estimated. The occurrence frequency of that group of dropouts determines the likelihood of this alert. The risk rating matrix is shown in Table 33- Table 35.

Table 33: Risk rating with look-ahead time 180 Seconds

Severity Likelihood	Minimal, 5	Minor 4	Major 3	Hazardous 2	Catastrophic 1
Frequent, A	298	--	--	--	--
Probable, B	--	12	--	--	--
Remote, C	--	--	8	--	--
Extremely Remote, D	--	--	--	42	--
Extremely Improbable, E	--	--	--	--	60

Table 34: Risk rating with look-ahead time 120 seconds

Severity Likelihood	Minimal, 5	Minor 4	Major 3	Hazardous 2	Catastrophic 1
Frequent, A	245	--	--	--	--
Probable, B	--	15	--	--	--
Remote, C	--	--	16	24	--
Extremely Remote, D	--	--	--	--	60
Extremely Improbable, E	--	--	--	--	60

Table 35: Risk rating with look-ahead time 60 seconds

Severity / Likelihood	Minimal, 5	Minor 4	Major 3	Hazardous 2	Catastrophic 1
Frequent, A	137	--	--	--	--
Probable, B	--	54		--	--
Remote, C	--	--	66	48	--
Extremely Remote, D	--	--	--	--	90
Extremely Improbable, E	--	--	--	--	65

As seen from Tables 33-35, when the look-ahead time decreases the alert number severity increases. A small look-ahead time window made DAA alert more severe, which indicates to the fact that the time at what dropout occur in crucial for alert. Thus, indicates that the time when a dropout occurred is crucial for DAA. This provides the pictures of DAA alerting using ADS-B as a single means of surveillance. It should be noted DAA computer discards an aircraft as a potential threat if the data isn’t updated for certain time period, and this time defined by user. This pointed to the facts that in the event of dropout, a potential threat might be excluded and will not be considered as a threat anymore. This might lead to abrupt maneuvers when reappeared and in the worst-case a near midair collision.

5.4.2 Hazard analysis of altitude discrepancy

The risk matrix of altitude discrepancy is based on the number of loss of well clear each time when discrepancy was added. The vertical penetration into the well clear volume was calculated and depending on the depth of the penetration the severity was measured. The metric used to measure how acute the well clear violation, is severity of loss of well clear (SLoWC). It calculates the penetration into the well-clear zone, ranges from 0% to 100%. A SLoWC of 0% means well clear and 100% means zero horizontal and vertical separation.

The vertical penetration is expressed as:

$$VertPen = MIN\left(\frac{dh}{450}, 1\right) \tag{7}$$

where dh is the relative vertical distance at that instant. NMAC could occurred when the vertical penetration is greater than 55%. The likelihood definition developed for the altitude discrepancy hazard is described in Table 36.

Table 36: Likelihood Definition for Altitude Discrepancy

Frequent, A	Occurred in more than 45% cases
Probable, B	Occurred in less than 45% but more than 15 % cases
Remote, C	Occurred in less than 15 % but more than 1% cases
Extremely Remote, D	Occurred in less than 1% cases but more than 0.5% cases
Extremely Improbable, E	Occurred in less than 0.5% cases

Definition for the severity for altitude discrepancy is developed in Table 37, where the level of severity is defined based on the penetration percentage. The higher the penetration, the more severe the hazard.

Table 37: Severity Definition for Altitude Discrepancy

Minimal	Minor	Major	Hazardous	Catastrophic
Penetration less than 5%	Penetration of less than 5~20%	Penetration within 20~40%	Penetration within 40~55%	Penetration more than 55%

Out of 13776 geometry penetration, 5029 cases lost vertical well clear. The risk rating for different scenario is presented in Table 38 – 40 showing the risk rating for different measure of deviation.

Table 38: Risk rating for Minimum discrepancy

Severity Likelihood	Minimal, 5	Minor 4	Major 3	Hazardous 2	Catastrophic 1
Frequent, A	1298	--	--	--	--
Probable, B	--	--	--	--	--
Remote, C	--	--	--	--	--
Extremely Remote, D	--	--	--	--	--
Extremely Improbable, E	--	--	--	--	--

Table 39:Risk rating for Average discrepancy

Severity Likelihood	Minimal	Minor	Major	Hazardous	Catastrophic
Frequent, A	1069	--	--	--	--
Probable, B	--	426	--	--	--
Remote, C	--	--	--	--	--
Extremely Remote, D	--	--	--	--	--
Extremely Improbable, E	--	--	--	--	--

Table 40: Risk rating for Maximum discrepancy

Severity Likelihood	Minimal	Minor	Major	Hazardous	Catastrophic
Frequent, A	--	--	--	--	--
Probable, B	--	1018	--	--	--
Remote, C	--	--	860	--	--
Extremely Remote, D	--	--	--	321	37
Extremely Improbable, E	--	--	--	--	-

Table 40 displays the risk level of the penetration where 37 cases would turn to catastrophic failure if two different sources were used as the separation standard. Although the biggest percent of loss of well clear severity were minimal, a more complex geometry might change the severity level. Around 40% of the encounter severity (yellow blocks) belongs to the acceptable risk with mitigation. That means tracking and monitoring is required in those case such that they do not bring out more severity in congested airspace. Based on the penetration analysis and the severity of penetration, risk rating is also assigned to the classes of discrepancy.

Class 1 discrepancy occurred frequently and from the penetration analysis it is revealed that even it led to loss of well clear in some cases, the penetration is small (within 5% of the volume) and this poses the minimal amount of severity. Most of the class 2 and class 3 discrepancy causes a penetration of less than 20% and less than 40%, respectively. These belongs to the risk acceptable with mitigation category. Class 4 and Class 5 poses most threat to vertical separation and aerospace safety. Both classes could lead to a near midair collision. Though the likelihood of class 5 discrepancy is extremely improbable by our definition, they did occur in the test data.

CHAPTER VI

DISCUSSION

This chapter links probable causes of the dropout and altitude discrepancy through a system level assessment. A system level assessment starts from the main event and go down to all probable causes that lead to that event in that system. For altitude discrepancy, a model to compare two measurement systems is introduced, to understand their agreement and conditions. The brief description is provided in what perspective ATC is being affected with these anomalies and how these have adverse effect in congested airspace.

6.1 System Level Assessment for Dropout

For dropout system-level assessment comprises of two different end systems; transmitter end and receiver end. Based on this, the loss of message from ADS-B at any instant are due to following factors:

i. ADS-B out system failed to send message,
ii. Ground Receiver failed to receive and/or decode the message

6.1.1 ADS-B out system fails to send message

ADS-B is dependent onboard GPS system. Temporary unavailability of the GPS system may result in an error in message generation. After gathering the information from GPS and flight computer, ADS-B generates the message. Fault in ADS-B message assembly can be caused by data processing error, data encoding errors and bugs in the module [30]. Another potential reason of unavailability is the failure of the antenna to transmit the signal.

6.1.2 Ground receiver fails to receive/decode the message

The reasons behind Ground Receiver not to be able to receive the message are related to UAT signal loss event due to multipath, interference and path loss.

- Multipath Effect: A theoretical signal analysis used collected on-air data to examine the error induced by multipath showed that maximum error level is about twice that of Mode S ES collected at the same bandwidth [59].
- Interference: Interference can be from radio frequency or from electromagnetic field. During heavy traffic interference from other aircraft signal might cause ADS-B signal loss. Also closely located Distance Measuring Equipment (DME) antenna can degrade the ground receiver performance [60]. Heavy electronic machines installed near airport are the potential reason of electromagnetic interference which also affect reception of ADS-B signal [61].
- Path Loss: The power of transmitted signal decreases as the distance between transmitter and receiver increases. ADS-B signal is affected by path loss and the probability of message reception decreases with the distance [62].
- CRC Check: A cyclic redundancy check (CRC) is an error-detecting code commonly used to detect accidental changes to raw data. ADS-B uses cyclic redundancy check to validate the correctness of received message [34]. Messages with bit errors are discarded at reception [20].

In dropout encounters, one of the most common solutions is to use path prediction algorithms. But the problem with the path prediction algorithms is that, it predicts path until a certain time threshold, if any update is not received within that threshold, the algorithm discards that aircraft from a potential threat list. As the dropout duration is varying, the path prediction might not work for some of the dropout cases. Another means is multi sensor fusion, as described this analysis is based on considering ADS-B as a single means of surveillance, the input from other DAA surveillance wasn't taking into account. To reduce the severity, it is important to have sensor fusion with ADS-B, so that in the event of ADS-B unavailability other DAA can detect the potential threats.

6.2 System Level Assessment for Altitude Discrepancy

To analyze system level error for discrepancy, it is assumed that neither barometric nor geometric altitude is true, rather the both have some error. This can be analyzed from two different ends, one from sensor end and another from the ADS-B system end.

6.2.1 Error induced in sensor end

For barometric altimeter

- Error in pitot static tube: Pitot static tube measures the outside air flow velocity which is used to calculate the barometric altitude. Any malfunction in pitot tube will be lead to erroneous altitude value.
- Error in encoding: Error introduced while encoding altitude

6.2.2 Error induced in ADS-B system

- Message generation error: As the altitude was encoded in a 25-foot resolution, rounding error introduces discrepancy.

Whatever the potential reason is, as described in chapter four, the discrepancy is degrading the safety. It is known to both pilot and ATC that the two altitudes are not same [37]. Still they are by law can be used as an alternate. While in manned aircraft pilot has the provision of “eye” and also communication advantages with ATC, UAS lacks these benefits. So, altering the source of separation might not be that safe for UAS as in manned aircraft. Thus, it is essential to understand the agreement between two altitudes to what extent is it safe interchanging barometric and geometric regardless flight conditions. Choosing the right tool while describing their relationship with each other is crucial. Two most widely-used concepts to determine the association between variables are agreement analysis and correlation. Though both methods seem alike they represent completely different perceptions of relationship. Assessing agreement between variables assumes that the variables measure the same construct, while the correlation of variables can be evaluated for variables that measure entirely different constructs [63]. Assessing agreement focuses on how much two measurement system agrees with each other, it is a simplified approach in biostatistics and medical device research. Whenever a new measurement system is introduced; the concordance in the results between new one and an established one is analyzed to understand if they are interchangeable. Moreover, to decide whether two measurement systems agree sufficiently to be used interchangeably, one must compare the agreement with an acceptable difference. In other word, they can be used interchangeably if the difference between single measurements from two systems falls within the range that is deemed to be acceptable [64].

Among a number of statistical methods for assessing agreement such as comparing mean and variance [65], regression [66], limit of agreement [67]; a regression approach is adapted as it is most compatible with test data. The basis of the regression technique lies in the comparison of the fitted regression line to the line of equality. The idea is that the further the fitted line, the more evidence that the measurement agreement is lower. The common convention to describe a linear mixed effects structural model for regression is,

$$Y_{i2} = \alpha + \beta Y_{i1} + M_i \tag{8}$$

where Y_{i2} and Y_{i1} are the random variable measured by system two and one respectively, (α, β) are the parameters that quantify absolute biases and M_i is the measurement error. α is the fixed bias since it increases or decreases the average measurement of the second system by a fixed amount and β the proportional bias as it influences the second system's measurements by an amount that is proportional to the true value [64]. However, because of measurement system are not free from error and thus the true values of the measured are unknown it is not possible to estimate the absolute value of α and β, rather the relative biases $\hat{\alpha}$ and $\hat{\beta}$ are estimated.

6.2.3 Model checking for intended analysis

Several regression approaches are available to estimate model parameters and the difference lies in the estimation procedure and its underlying assumptions. Simplest method to carry out a regression analysis is Ordinary Least Squares (OLS). The assumptions for OLS are:

i. The measurements made by reference measurement systems are error free, and
ii. The error in the measurements made by the second system have a constant error.

But these assumptions don't hold true for the test data. As barometric altitude is used for separation by convention, this is considered as the reference system variable and second system variable is the geometric altitude. Although barometric altitude is by convention used by pilots and ATC, it is not free from errors. The calculation of barometric altitude depends on weather components and error can induced from sensor. Also, the altimeter setting during flight is prone to human errors. As the reference measurement system is not error free, ordinary least squares cannot be used for this comparative study.

The second approach is ordinary deming regression which assumes measurement error for both systems and considers error made by second measurement system is constant. So, unless the errors are known this assumption is unreasonable. A more complex yet widely applicable approach is weighted deming regression. The advantages of this method are; it allows for measurement error to exist in both measurement systems, and introduce non-constant variability. It minimizes the sum of the weighted squared deviations from the fitted line, and the angle at which the deviations are minimized is determined by the ratio of two variances. Considering the facts that none of our measurement systems are error-free and error is not constant weighted deming regression is adopted.

Let, barometric altitude and geometric altitude are represented as y_b and y_g respectively. If $\varepsilon_b$and ε_g are the respective measurement error than

$$y_b = Y_b + \varepsilon_b \tag{9}$$

$$y_g = Y_g + \varepsilon_g \tag{10}$$

where Y_b and Y_g depicts the true value. With the fixed and proportional bias (α, β) the second measurement system regression equation becomes:

$$\hat{y}_g = \alpha + \beta \hat{y}_b \tag{11}$$

$\hat{y}_g$ and $\hat{y}_b$ are the estimates of true value.

The slope estimate, β is computed as

$$\beta = \frac{(\lambda q_w - u_w) + \sqrt{(u_w - \lambda q_w)^2 + 4\lambda p_w^2}}{2\lambda p_w} \tag{12}$$

and, the intercept α, is estimated as:

$$\alpha = \bar{y}_{gw} - b_1 \bar{y}_{bw} \tag{13}$$

A detailed parameter estimation can be found in Appendix B. Ascending or descending phase of each flight considers as one subject, this is because the slops for these two phases are clearly distinct so assuming one entire flight as one subject would induce error while estimating parameters. The altitude data found in taxiing and level flight are taken as a replicated measurement as they were no vertical displacement. So, the error variance is calculated using these replicated measurements. Taking replicate in two different phases introduce error that resulted from different flight condition.

6.2.4 Analysis of model parameters

As discussed, the values of model parameters not only decide how well they agree with each other but also describes the relation between two values in flight. Both the sign and value of (α, β) are important to understand the characteristics of the deviation. If the estimated value of proportional bias is greater than one and the estimated value of fixed bias, β has negative sign depicts that the barometric altitude is higher than the geometric one. If the sign is positive indicates geometric altitude is higher than barometric. The study reveals that the model parameters are not same for different flights. As the weather conditions were different for each day and the modeling parameters varies significantly. The absolute fixed bias ranges from 3 feet to 374 feet. Where fixed bias differs remarkably, the changes in proportional bias is not that notable. As the proportional bias is the multiply factors, a consistence value of α indicates the system consistency. And the changes in β value concludes the fact that, the deviation induced mostly due to the weather effect. This leads to a conclusion that, it is hard to come up with a system comparison model of altitude deviation. Because each flight faces unique environmental condition. This leads to the need for direct modelling of altitude conversion considering weather factors. Barometric altitude mostly depends on the weather conditions such as temperature and pressure, and geometric altitude is affected by clouds and atmospheric layers. Though there is no established conversion model of two altitudes yet, some provision should be made while using an alternate source for separation in congested airspace. An analysis is further carried out as to see if any offset value exclusively calculated at first few minutes of flying could make the scenario better. Using the deming regression, the (α, β) value was calculated for each flight using first 5 minutes of data (includes more than 250 data points on average for each aircraft). Referred to section 5.3 in the well clear penetration analysis, the associated offset value calculated for that flight was inserted further. The sign of β determines whether to add the offset or to subtract. This was done to see if adding an exclusively calculated offset value and introducing them while using secondary altitude for separation could reduce the loss of well clear., though not fully but about 95% cases regain well clear using offset value if the deviation was minimum and average, the percent of well clear regain is slight less (90%) for the cases where deviation were maximum. The green bar shows the number of cases where well clear is regained. The offset inserted in level flight was the offset that are calculated in the ascending phase of that flight. Figure 35-37 depicts the results.

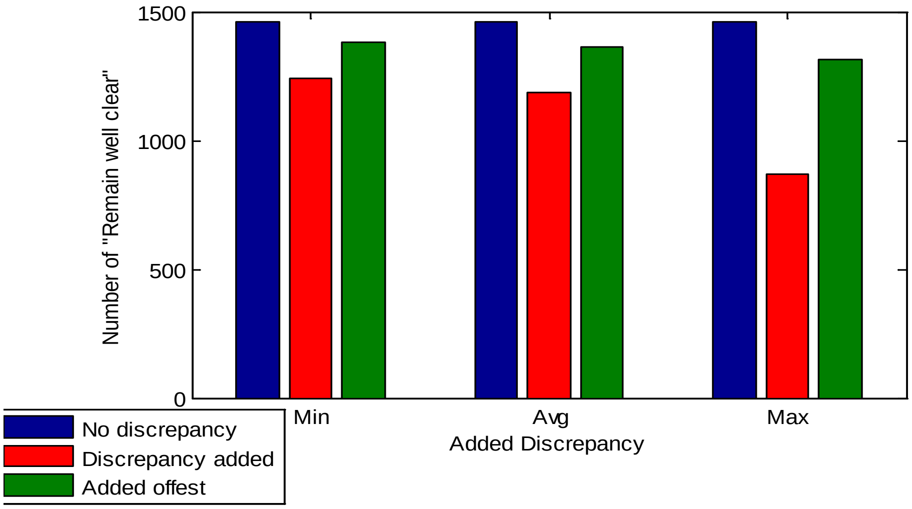


Figure 38: Well clear Regain using "offset value" in ascending flight scenario

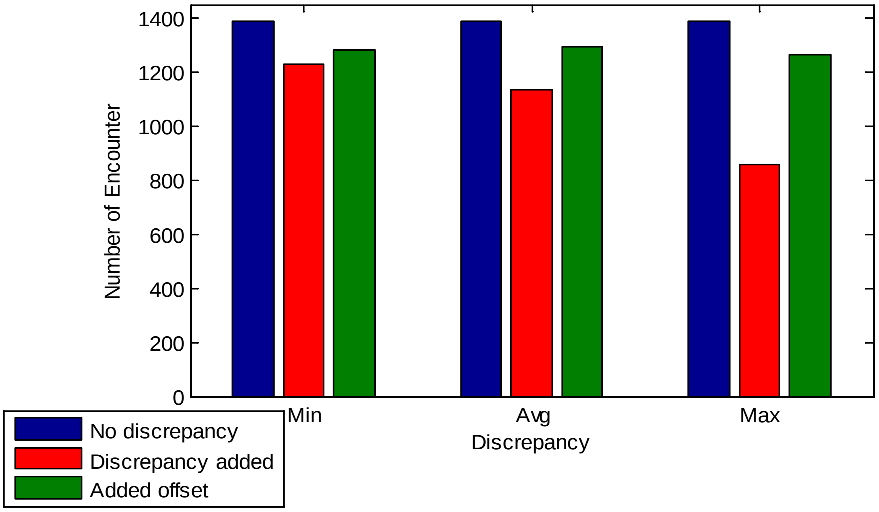
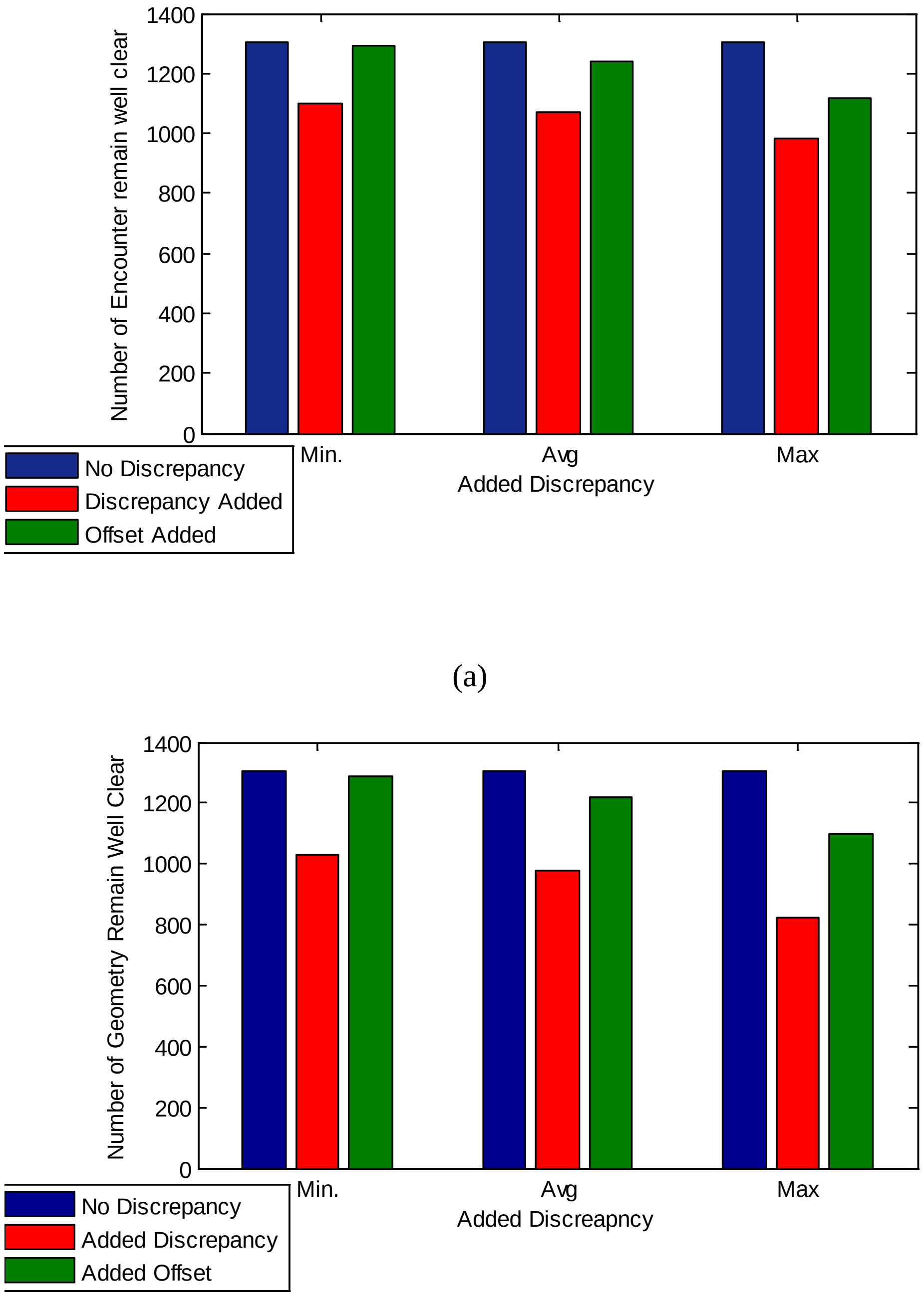


Figure 39:Well clear Regain using "offset value" in descending flight scenario



(a)

(b)

Figure 40: Well clear Regain using "offset value" for level flight

Though a conversion model that consider weather effect and satellite geometry would be a robust and effective way to approach the discrepancy problem. This study initiates the fact that a conversion offset will enhance the safety and will reduce the vertical loss of well clear in a congested airspace.

CHAPTER VII

CONCLUSION

The aim of this study was to understand the current state of ADS-B system surveillance and understand its vulnerabilities in the future congested airspace. To fully utilize the airspace and to accommodate increasing traffic it is important to address the issues and factors regarding ATC surveillance. This work starts with chapter II stating the past and present of surveillance system, and the need for the newly designed ATC surveillance concept named NextGen. Chapter II also introduces the backbone of the NextGen ATC, ADS-B system. The technical aspects start in chapter III which contain ADS-B message definition, message extraction and performance parameters. Five different anomalies were identified, namely dropout, low confident data, message loss, data jump and altitude discrepancy. This chapter also describes how the entire volume of data was sorted for analysis and how the inspection process to detect anomalies.

An in-depth study was carried out for two main types of anomalies: dropout and altitude discrepancy in chapter IV. These are chosen because of their frequent presence in the test data and their nature of occurrence. The dropout duration was further classified in different groups and statistical tests were carried out for some flight conditions and factors. It was found that altitude plays a vital role in dropout occurrence frequency. Higher altitude levels showed longer duration of dropout. In some positions ADS-B signal were more frequently lost due to higher traffic density. This happens when the altitude is lower than 1000 feet.

This was the situation when the aircraft was on the approach path to runway, and as there was more ground infrastructure it was considered as a line of sight communication loss. For altitude discrepancy, both phase of flight and altitude have significant effects on deviation. The deviation was more when the aircraft was on level flight and lowest when the aircraft was on the descending phase of flight. Also as the altitude increases the deviation increases. This can be co-related with the phase of flight. When an aircraft is flying at cruise altitude, it is flying at the highest altitude of its entire flight profile. And while descending, the altitude is decreasing and thus in descending and lower altitude the deviation is less. At higher altitudes the temperature profile is not the same as the lower altitude. As barometric altitude is entirely dependent on the outside conditions, thus varying temperature profiles, from low to high altitude induce varying deviation. The severity of this varying amount of deviation is further highlighted in chapter V.

Once all the analysis was done, the results were further utilized to assess the severity of the anomalies. As introducing UAS in NAS is a concern for future ATC operation some hypothetical encounter scenarios were introduced to quantify the risk of dropout and altitude discrepancy. For dropout, the scenario was based the horizontal well clear violation and for altitude discrepancy the scenarios were vertical well clear violations. The DAA well clear logic was recommended by RTCA SC-228, approved by FAA and developed by NASA. Risk matrix established is based on the simulation scenarios and doesn’t represent the overall risk of the airspace. Time to loss of well clear metric was used to measure the severity of different durations of dropout. The results revealed that with a lower look-ahead window, the severity of dropout increased. The longer the duration of dropout posed more severity than the shorted duration dropout. Risk from altitude discrepancy was assessed using vertical penetration to the well clear volume, the more it penetrated the more likely it was to occur a near midair collision. It was found that, the class 1 and class 2 discrepancy have minimal effect while class 4 and class 5 pose catastrophic severity.

Finally, chapter VI ties the anomalies to the system where they could have induced. It starts with the top event and goes all the way down each systems and sub systems which individually or collectively lead to the anomaly. A system comparison model was described for the geometric and barometric altitudes to find agreement between them. The offset values found using deming regression were different for different flight for same aircraft. This lead to the conclusion to the fact that, it wouldn't be beneficial to generalize a model for all flight conditions, because every flight experience separate and unique environment. But it is also important to measure the difference of altitude with some sort of offset or conversion model while flying in reduced vertical minima. If any offset can be calculated for each flight exclusively and could be used while alternating the source that would keep the aircraft well clear from each other.

Analyzing all the anomalies leads to the conclusion that these failures can affect ATC operation from two different perspectives as follows:

i. From Airspace Perspective
    - Dropout
    - Low confident data
ii. From Aircraft Perspective
    - Data jump
    - Partial message loss
    - Altitude discrepancy

Dropout and low confident data can affect the airspace because some dropout seems to appear more in some distinct position where it is assumed they lost the line of sight communication. Also, if in certain area the satellite geometry is poor the ADS-B will lack integrity and accuracy. In both cases, air to ground surveillance will be degraded for that certain airspace. In this case, all the aircraft entering that area will suffer in low situational awareness and possibly experience loss of data. data jump, partial message loss. Altitude discrepancy will affect the particular aircraft mostly, but will generally not degrade the scenario of the whole airspace. In future, where it is expected that the airspace will be utilized fully, in the presence of congested traffic, aircraft in the vicinity of the victim aircraft would suffer from degrading situational awareness. So, although some anomalies affect only one aircraft that doesn't mean other aircraft in that airspace are safe. The safety of the airspace wouldn't degrade significantly as a whole but would decrease the safety and reliability.

Both class 1 and class 2 UAS DAA systems are provisioned to have ADS-B IN system for surveillance, as the "human eye" is absent, it is important to have more robust and effective ADS-B system in terms of continuity, availability and integrity. Especially for the class 1 DAA system, where the surveillance information received from ADS-B In will be utilized by DAIDALUS to trigger alerts. Although class 1 DAA will have air to air Radar for noncooperative traffic and Mode S surveillance system to get the overall picture of the airspace, as a single system ADS-B In needs to be more resilient to signal and message loss. This study only made use of Ground Receiver Data, which may not provide a complete scenario of air to air data anomalies. The characteristics and the vulnerabilities might be less or more severe for air to air than air to ground. Hence, a data anomaly study for air to air received data is recommended. Also, this research found that no two flights are same. There is difference in the anomalies in different flights, thus a periodic check of ADS-B system might be beneficial if the detected anomalies appeared on regular basis. It is a matter of interest that if the real-time anomalies differ from the anomalies detected in the archived data. One of the future extension of this work can be compare the real time recorded ADS-B data and raw pass through data.

The information and results presented in this document can be used by developers of DAA logic for UAS and autonomous ATC systems. For full utilization of airspace, understanding the anomalies of ADS-B and knowing how to deal and handle these anomalies is crucial. As ADS-B is envisioned to lead future ATC, provision should be made to approach the current weakness and limitations of the system.

APPENDIX A

DATA SORTING IN MATLAB

```
clc
close all
clear all

filename= 'outfile_Dec15.xlsx';  %name of the file
adsb_data=xlsread(filename,'A:AG'); %33 column data extracted from
archived data

%% insert time to each message and remove heartbeat message

count=size(adsb_data)
m=count(1,1)-1;
 for i=2:m
    if adsb_data(i+1,1)> 500 & adsb_data(i,1)< 500
        adsb_data(i+1,1)= adsb_data(i,1);
    else if  adsb_data(i+1,1)< 500
             adsb_data(i+1,1)= adsb_data(i+1,1);
        end
    end

 end

  for i=2:m
    if adsb_data(i+1,4)> 86400 & adsb_data(i,4)< 86400
        adsb_data(i+1,4)= adsb_data(i,4);
    else if  adsb_data(i+1,4)< 86400
             adsb_data(i+1,4)= adsb_data(i+1,4);
        end
    end

end

 adsb_data = adsb_data(~any(isnan(adsb_data),2),:);

%% filter ICAO addressed aircraft
clear m count
count=size(adsb_data);
m=count(1,1);

for i=1:m;
     if adsb_data(i,5)~=0  %address qualifier data is availble in
column 5 and the value for ICAO is 0
         adsb_data(i,5)=-999;
    end
end

rows_to_remove = any(adsb_data==-999, 2);
adsb_data(rows_to_remove,:) = [];
```

```
%% Remove all ground aircraft

clear m count

count=size(adsb_data);
m=count(1,1);

for i=1:m
     if adsb_data(i,9)== 1;  %a/g state data is saved in coumn 9, 1 indicate the aircraft is on ground
         adsb_data(i,9)=-999;
    end
end

rows_to_remove = any(adsb_data==-999, 2);
adsb_data(rows_to_remove,:) = [];

%% delete all other messages execpt the message described in table 9

for i=25:33;
adsb_data(:,i)=NaN;
end

adsb_data( :, all( isnan( adsb_data ), 1 ) ) = [];

%% save long and all message in different file

save('full_adsb_report_dec15.mat','adsb_data');

clear m count
count=size(adsb_data);
m=count(1,1);

for i=1:m;
     if adsb_data(i,4)~=1  %type code is availble in column 4 and the value for long message is 1
         adsb_data(i,4)=-999;
    end
end

rows_to_remove = any(adsb_data==-999, 2);
adsb_data(rows_to_remove,:) = [];

save('long_adsb_report_dec15.mat','adsb_data');
```

DROPOUT CALCULATION

```
clc
close all
clear all

%load mat file

load('full_adsb_report_dec15.mat')

%matrix into a cell array based on the aricraft ID number
adsb_split=arrayfun(@(x)  all_report(all_report(:,6) == x, :), unique(
all_report(:,6)), 'uniformoutput',false);

%% calculate dropout duration
[m k]=size(adsb_split);

for j=1:m

    adsb_split{j}= sortrows(adsb_split{j},1);
    [r c]=size(adsb_split{j});

        for i=1:r

            if i==1
                adsb_split{j}(i,24)=0;
            else
                adsb_split{j}(i,24)=adsb_split{j}(i,1)-adsb_split{j}(i-
1,1);
                if adsb_split{j}(i,24)>= 900   %different flight
                    adsb_split{j}(i,24)=0;
                end
            end
        end
end

%% count different duration dropout
[k d]=size(adsb_split);
old=[];

for j=1:k


   [r c]= size(adsb_split{j});
   if r==0;
       continue
   end
   no_drop=0;
   drop_3=0; %less than or equal to 3 seconds update
   drop_5=0; %less than or equal to 5 seconds update
   drop_15=0; %less than or equal to 15 seconds update
   drop_30=0; %less than or equal to 30 seconds update
   drop_60=0; %less than or equal to 60 seconds update
   drop_120=0; %less than or equal to 120 seconds update
   drop_300=0; %less than or equal to 300 seconds update
```

```
   more_300=0; %more than 300 seconds
   airb=0;
   out_range=0;
   anom=0;
   dur_1=0;
   dur_3=0;
   dur_5=0;
   dur_15=0;
   dur_30=0;
   dur_60=0;
   dur_120=0;
   dur_300=0;
   dur_m=0;
   dur_o=0;
   id= adsb_split{j}(1,6);

   for i=1:r
        if adsb_split{j}(i,24)<=2;
            no_drop=no_drop+1;
            dur_1=dur_1+adsb_split{j}(i,24);
        else if adsb_split{j}(i,24)<=3 && adsb_split{j}(i,24)>2 ;
                drop_3=drop_3+1;
                dur_3=dur_3+adsb_split{j}(i,24);
        else if adsb_split{j}(i,24)<=5 && adsb_split{j}(i,24)>3 ;
                drop_5=drop_5+1;
                dur_5=dur_5+adsb_split{j}(i,24);
            else if adsb_split{j}(i,24)<=15 && adsb_split{j}(i,24)>5;
                    drop_15=drop_15+1;
                    dur_15=dur_15+adsb_split{j}(i,24);
                else if adsb_split{j}(i,24)<=30 &&
adsb_split{j}(i,24)>15;
                        drop_30=drop_30+1;
                        dur_30=dur_30+adsb_split{j}(i,24);
                    else if adsb_split{j}(i,24)<=60 &&
adsb_split{j}(i,24)>30;
                            drop_60=drop_60+1;
                            dur_60=dur_60+adsb_split{j}(i,24);
                        else if adsb_split{j}(i,24)<=120 &&
adsb_split{j}(i,24)>60;
                                drop_120=drop_120+1;
                                dur_120=dur_120+adsb_split{j}(i,24);
                            else if adsb_split{j}(i,24)<=300 &&
adsb_split{j}(i,24)>120;
                                    drop_300=drop_300+1;

dur_300=dur_300+adsb_split{j}(i,24);
                                else if adsb_split{j}(i,24)<=900 &&
adsb_split{j}(i,24)>300;
                                        more_300=more_300+1;

dur_m=dur_m+adsb_split{j}(i,24);
                                    else if adsb_split{j}(i,24)> 900
                                            out_range=out_range+1; %out
range <900

dur_o=dur_o+adsb_split{j}(i,24); %out of range duration
                                        end
```

```
                                    end
                                end
                            end
                        end
                    end
                end
            end
          end
        end
  duration=sum(adsb_split{j}(:,24)); %total flight time
  end




   contents=[id, no_drop,dur_1, drop_3+
drop_5,dur_3+dur_5,drop_15,dur_15,drop_30,dur_30,drop_60,dur_60,drop_12
0,dur_120,drop_300,dur_300,more_300,dur_m,out_range,dur_o,duration];

   total=[old;contents];
   old=total;
end


%% calculated overall results
total_flight= sum(old(:,20));
update_rate= sum(old(:,2));
dur_update=sum(old(:,3));
count_5=sum(old(:,4));
dur_5a=sum(old(:,5));
count_15=sum(old(:,6));
dur_15a=sum(old(:,7));
count_30=sum(old(:,8));
dur_30a=sum(old(:,9));
count_60=sum(old(:,10));
dur_60a=sum(old(:,11));
count_120=sum(old(:,12));
dur_120a=sum(old(:,13));
count_300=sum(old(:,14));
dur_300a=sum(old(:,15));
count_more_300=sum(old(:,16))
count_out_range=sum(old(:,18));
dur_mo=sum(old(:,17));
dur_out_range=sum(old(:,19));
totl_drop=dur_5a+dur_15a+dur_30a+dur_60a+dur_120a+dur_300a+dur_mo;
overall_dropout=[total_flight, update_rate,
dur_update,count_5,dur_5a,count_15,dur_15a,count_30,dur_30a,
count_60,dur_60a, count_120,dur_120a, count_300,dur_300a,
count_more_300, dur_mo,count_out_range,dur_out_range totl_drop];
```

DISCREPANCY ANALYSIS

```
[k d]=size(discrepancy_split);
old=[];
for i=1:k
   [r c]= size(discrepancy_split{i});
   no_gap=0; %no discrepancy
   gap_25=0; % 25 feet discrepany
   gap_50=0; %discrepancy 25-50
   gap_100=0; %discrepancy 25-50
   gap_200=0; %discrepancy 25-50
   gap_350=0; %discrepancy 25-50
   gap_500=0; %discrepancy 25-50
   gap_more=0; %discrepancy 25-50

   id= discrepancy_split{i}(1,4);

   for j=1:r
       if discrepancy_split{i}(j,11)==0;
               no_gap=no_gap+1;
           else if (discrepancy_split{i}(j,11)>0 &&
discrepancy_split{i}(j,11)<=25)
                   gap_25=gap_25+1;
               else if (discrepancy_split{i}(j,11)>25 &&
discrepancy_split{i}(j,11)<=50)
                       gap_50=gap_50+1;
                   else if (discrepancy_split{i}(j,11)>50 &&
discrepancy_split{i}(j,11)<=100)
                           gap_100=gap_100+1;
                       else if (discrepancy_split{i}(j,11)>100 &&
discrepancy_split{i}(j,11)<=200)
                               gap_200=gap_200+1;
                           else if (discrepancy_split{i}(j,11)>200 &&
discrepancy_split{i}(j,11)<=350)
                                   gap_350=gap_350+1;
                               else if (discrepancy_split{i}(j,11)>350
&& discrepancy_split{i}(j,11)<=500)
                                       gap_500=gap_500+1;
                                   else
(discrepancy_split{i}(j,11)>500)
                                       gap_more=gap_more+1;
                                   end
                               end
                           end
                       end
                   end
               end
           end


   end


contents=[airb id no_gap gap_25 gap_50 gap_100 gap_200 gap_350 gap_500
gap_more];
total=[old;contents];
```

```
old=total;
end

outfile = 'discrepancy.xlsx';
xlrange = 'A1';
sheet=1;
xlswrite(outfile,total,sheet,xlrange);

%% detect phase of flight for severity analysis
level=[];
ascend=[];
descend=[];
count=size(discrepancy_split);
for i=1:count(1,1)
    n_count=size(discrepancy_split{i,1});
    for j=1:n_count(1,1)
        if discrepancy_split{i,1}(j,20)< 250
            level=[level;discrepancy_split{i,1}(j,:)];

        else if discrepancy_split{i,1}(j,19)==0 &&
discrepancy_split{i,1}(j,20)>= 250
                ascend=[ascend;discrepancy_split{i,1}(j,:)];
            else if  discrepancy_split{i,1}(j,19)==1 &&
discrepancy_split{i,1}(j,20)>= 250
                    descend=[descend; discrepancy_split{i,1}(j,:)];
                end
            end
        end
    end
end

%% sorting for different aircraft
level_split=arrayfun(@(x) level(level(:,6) == x, :), unique(
level(:,6)), 'uniformoutput',false);
ascend_split=arrayfun(@(x) ascend(ascend(:,6) == x, :), unique(
ascend(:,6)), 'uniformoutput',false);
descend_split=arrayfun(@(x) descend(descend(:,6) == x, :), unique(
descend(:,6)), 'uniformoutput',false);



%%  for  descend  flight  calculating  mean  avg  and  max  deviation  for  each

aircraft along with offset from regression


c=size(descend_split);
res_2=[];

for i=1:c(1,1)

    [m n]=size(descend_split{i,1});
    if m<30
        continue
    else
        XData=descend_split{i,1}(:,10);
```

```
        YData=descend_split{i,1}(:,11);
        [Err P]=fit_2D_data(XData, YData);
        avg=mean(abs(descend_split{i,1}(:,10)-
descend_split{i,1}(:,11)));
        ma=max(abs(descend_split{i,1}(:,10)-descend_split{i,1}(:,11)));
        mi=min(abs(descend_split{i,1}(:,10)-descend_split{i,1}(:,11)));
        fst=descend_split{i,1}(1,10);
        lst=descend_split{i,1}(m,10);
        gap=ma-mi;
        res_2=[res_2; long_split{i,1}(1,6) P avg mi ma gap Err];
    end

end
%% for ascending flight calculating mean avg and max deviation for each
aircraft along with offset calculated with regression

clear c
c=size(ascend_split);
res_1=[];

for i=1:c(1,1)

    [m n]=size(descend_split{i,1});
    if m<30
        continue
    else
        XData=ascend_split{i,1}(:,10);
        YData=ascend_split{i,1}(:,11);
        avg=mean(abs(ascend_split{i,1}(:,10)-ascend_split{i,1}(:,11)));
        ma=max(abs(ascend_split{i,1}(:,10)-ascend_split{i,1}(:,11)));
        mi=min(abs(ascend_split{i,1}(:,10)-ascend_split{i,1}(:,11)));
        [Err P]=fit_2D_data(XData, YData)
        gap=ma-mi;
        res_1=[res_1; long_split{i,1}(1,6) P avg mi ma gap Err];
    end

end

%% for level flight calculating mean avg and max deviation for each
aircraft

clear c

c=size(level_split);
res_3=[];


for i=1:c(1,1)

    XData=level_split{i,1}(:,10);
    YData=level_split{i,1}(:,11);
    avg=mean(abs(level_split{i,1}(:,10)-level_split{i,1}(:,11)));
    ma=max(abs(level_split{i,1}(:,10)-level_split{i,1}(:,11)));
    mi=min(abs(level_split{i,1}(:,10)-level_split{i,1}(:,11)));
    gap=ma-mi;
```

```
    res_3=[res_3; level_split{i,1}(1,6)  avg mi ma gap];

end
```

PENETRATION IN WELL CLEAR BOUNDARY

```
% +-------------------------------------------------------------------
--+
% |   Filename           : WCBoundary_Tcpa.m
|
% |   Description        : Well-clear model for penetration         |
% |   Created by         : C. Munoz, J. Upchurch, A. Narkawicz
  |   modified by        : Asma Tabassum
%
|
% +-------------------------------------------------------------------
--+

function [ Rz, Tcoa,WCVz, WCV ] =
WCBrange_Tcpa(DTHR,TCPA,ZTHR,TCOA,s_z, zodot, zidot)

% Inputs:
%  DTHR       : Horizontal distance thresholds
%  TCPA       : Time to CPA threshold
%  ZTHR       : Altitude threshold
%  TCOA       : Time to co-altitude threshold
%  (xo,yo,zo) : Ownship eastern, northern, and altitude positions
%  (xodot,yodot,zodot) : Ownship eastern, northern, and altitude speeds
%  (xi,yi,zi) : Intruder eastern, northern, and altitude positions
%  (xidot,yidot,zidot) : Intruder eastern, northern, and altitude
speeds

% Outputs:
%  Rxy    : Horiztonal range
%  Dcpa   : Distance at closest point of approach
%  Tcpa   : Time to closest point of approach
%  Rz     : Relative altitude
%  Tcoa   : Time to co-altitude
%  WCVxy  : Horizontal well-clear violation
%  WCVz   : Vertical well-clear violation
%  WCV    : Well-clear violation

% % absolute position and velocity of ownship
% s_o = [xo;yo];
%s_oz = zo;  %  v_o = [xodot;yodot];
v_oz = zodot;
%
% % absolute position and velocity of intruder
% s_i = [xi;yi];
%s_iz = zi;  %  v_i = [xidot;yidot];
v_iz = zidot;

% relative position and velocity
```

```
 %s_z = (s_oz-s_iz);
 v_z = (v_oz-v_iz);

% horizontal dimension outputs


% vertical dimension outputs
Rz = abs(s_z) % relative altitude
cz = s_z*v_z; % cz < 0 iff aircraft are converging in vertical plane
if cz < 0
    Tcoa = -s_z/v_z; % time to co-altitude
else
    Tcoa = -1;

end


WCVxy=0;      % keeping horizontal well clear

%================= VERTICAL WELL CLEAR VIOLATION DEFINITION
===============
WCVz = Rz <= ZTHR || (0 <= Tcoa && Tcoa <= TCOA);
%=================================================================
====

%================= WELL CLEAR VIOLATION DEFINITION ===============
WCV = WCVxy && WCVz;
%=================================================================
====

end
```

APPENDIX B

DEMING REGRESSION DETAILS

If $\varepsilon_b$and ε_g are the respective measurement error than

$$y_b = Y_b + \varepsilon_b$$

$$y_g = Y_g + \varepsilon_g$$

where Y_b and Y_g depicts the true value. With the fixed and proportional bias (α, β) the second measurement system regression equation becomes:

$$\hat{y}_g = \alpha + \beta \hat{y}_b$$

$\hat{y}_g$ and $\hat{y}_b$ are the estimates of true value.

The measurement error ratio is calculated by

$$\lambda = \frac{var(\varepsilon_b)}{var(\varepsilon_g)}$$

Multiple measurements within each subject is required to estimate the error ratio. If $\bar{y}_b$ and $\bar{y}_g$ denotes the means of individual replicate than the variance of measurement error for barometric and geometric altitude can be expressed as:

$$var(\varepsilon_b) = \frac{\sum_{b=1}^{N} \sum_{j=1}^{k_{y_b}} (y_{b,j} - \overline{y_b})^2}{\sum_{b=1}^{N} (k_{y_b} - 1)}$$

$$var(\varepsilon_g) = \frac{\sum_{g=1}^{N} \sum_{j=1}^{k_{y_g}} (y_{g,j} - \overline{y_g})^2}{\sum_{g=1}^{N} (k_{y_g} - 1)}$$

$$\text{where } \overline{y_b} = \frac{\sum_{j=1}^{k_{y_b}} y_{b,j}}{k_{y_b}}$$

$$\overline{y_g} = \frac{\sum_{j=1}^{k_{y_g}} y_{g,j}}{k_{y_g}}$$

The sum of squares for weighted approach is

$$SS_w = \sum_{i=1}^{N} w_i(y_{b_i} - \hat{Y}_{b_i})^2 + w_i(y_{g_i} - \hat{Y}_{g_i})^2$$

w_i be the weight of the model.

The weights are estimated as

$$\hat{w}_i = \frac{1}{\left[\frac{y_{b_i} + \lambda y_{b_g}}{1+\lambda}\right]^2}$$

As the least squares regression approach minimizes the sum of squares, the biases are determined by differentiating SS_w with respect to y_b and y_g.

The slope estimate, β is computed as

$$\beta = \frac{(\lambda q_w - u_w) + \sqrt{(u_w - \lambda q_w)^2 + 4\lambda p_w^2}}{2\lambda p_w}$$

with $u_w = \sum_{i=1}^{N} \hat{w}_i\left(y_{b_i} - \bar{y}_{bw}\right)^2$

$$q_w = \sum_{i=1}^{N} \hat{w}_i\left(y_{g_i} - \bar{y}_{gw}\right)^2$$

$$p_w = \sum_{i=1}^{N} \widehat{w}_i \left(y_{b_i} - \bar{y}_b\right)\left(y_{g_i} - \bar{y}_g\right)$$

$$\bar{y}_{bw} = \sum_{i=1}^{N} \widehat{w}_i y_{b_i} \,/\, \sum_{i=1}^{N} \widehat{w}_i$$

$$\bar{y}_{gw} = \sum_{i=1}^{N} \widehat{w}_i y_{g_i} \,/\, \sum_{i=1}^{N} \widehat{w}_i$$

And, the intercept α, is estimated as:

$$\alpha = \bar{y}_{gw} - b_1 \bar{y}_{bw}.$$

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