Article

UAT ADS-B Data Anomalies and Effect of Flight Parameters in Dropout

Asma Tabassum [1,] * and William Semke [2]

[1] University of North Dakota; asma.tabassum.ashraf@gmail.com
[2] University of North Dakota; william.semke@engr.und.edu
* Correspondence: asma.tabassum.ashraf@gmail.com; Tel.: +61-423170890

Abstract: An analysis of the performance of Automatic Dependent Surveillance-Broadcast (ADS-B) data received from the Grand Forks, North Dakota International Airport was carried in this study. The purpose was to understand the vulnerabilities of UAT ADS-B system 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 are being integrated into the aviation industry. As a fundamental component of future surveillance system, the anomalies and vulnerabilities of ADS-B system need to be identified to enable a fully utilized airspace with enhanced situational awareness. The anomaly detection of ADS-B messages was based on the Federal Aviation Administration's (FAA) ADS-B performance assessment report. Data investigation revealed ADS-B message suffered from different anomalies including drop out; missing payload; data jump; low confident data and altitude discrepancy. Among all the anomalies detected message discontinuation or dropout was found to be most frequent. Considering the potential danger being imposed, an in-depth analysis was carried out to characterize message dropout. Three flight parameters were selected to investigate their effect on drop out. Statistical analysis identified that altitude affected drop out more than any other flight parameters.

Keywords: UAT ADS-B; GDL-90; Anomalies; Drop Out; Friedman Test.

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1. Introduction

In order to meet the 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) established a committee on Future Air Navigation Systems (FANS) to develop a plan and program for future air traffic [1]. As a result, a new surveillance technology referred to as Automatic Dependent Surveillance-Broadcast (ADS-B) was proposed by the ICAO and is envisioned to fill the gaps in the current surveillance systems.

In the United States ADS-B works in two distinct frequencies one is 1090ES, and another is 978 MHz. 1090ES is of international standard and aircraft must be equipped with 1090ES transponder in order to fly above the transition altitude which is 18,000 feet in US. 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 [2], 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 US. Therefore, an in-detail study mentioning and recognizing the anomalies is crucial to ensure safe ATC surveillance.

2. Background of ADS-B and Related Work

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 that make use of satellite navigation such as GPS for generating surveillance information.

2.1. ADS-B as A Surveillance System

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.

Ground station includes a receiver which relays the message to ATC and sends out some additional reports such as flight and 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 [3] 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.

2.2 Related work

As one of the fundamental components of NextGen, a lot of research has been done and is still going on different aspects of ADS-B. This includes but is not limited to security and verification of messages [4–7] experimental attack analysis [8–11] data quality analysis [12–16] safety assessment [17], flight testing [12,18,19] 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 tries to listen in on periodic ADS-B messages to obtain unique identifiers or position trajectory of communicating aircraft without necessarily disrupting the system [5]. 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. [8] 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 techniques were discussed to adopt while verifying original ADS-B messages. These include traditional Kalman filtering, Group Validation [5], cryptography [4], Identity-Based Signature with Batch Verification [20]. Each of the solutions is yet to be implemented in the real-time ADS-B network.

A small 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 [1]. 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 a ground station [16]. 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) values.

Nur et al.[15] 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 [12] 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 modes [17].

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 [19] Project by EUROCONTROL, tested to confirm the quality of the ADS-B Out information from the reference aircraft regarding update interval and accuracy.

Although much data evaluation work has been done on 1090ES ADS-B data, no study , until writing this review on UAT data evaluation, was available to the public. One of the reasons may be that UAT ADS-B is new comparative to 1090ES and only used by general aviation aircraft in United States' airspace. An initial study was carried out as a part of Assure A6: Surveillance Criticality [21] project with 7-days of data. The initial results are also available in [22].

This work is carried out on a large scale in comparison to others, 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. [12] which considered 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 paper is novel in the 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.

3. Data Description

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 [23]. 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 received over the UAT data link, without modification. Due to constraints on the interface bandwidth, received UAT messages are filtered by range from ownship [24]. 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 [25].

2.1. Message Definition

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

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

"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 [24]. 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 3010 and long UAT is 3110. The format of UAT message in GDL 90 interface is shown in Table 1.

Table 1. 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 010. 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 [25]. "Payload Type Code" for basic and long messages are 0 and 1 respectively. The composition of ADS-B payload is presented in Table 2.

Table 2. 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.

2.2. Message Decode

A python module was 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. 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. Table 3 listed the message fields description considered in this study.

Table 3. Description of the Message fields

Data	**Description**
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

1. 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. This work adheres to units set by FAA for UAT ADS-B.

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 [26] and flight test reports [18,27]. The data were further sorted by aircraft ID.

3. Data Anomalies

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, the inspection of the messages involves:

- 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.
- Missing Elements Identification: Identify if there is any payload information missing in the report.
- Message Discontinuation: Identify discontinuation when update rate exceeds one second. This anomaly is called data dropout.
- 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.
- 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.

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. Among all the anomalies detected dropout and altitude discrepancy were found to be the most frequent. Considering the danger being imposed by them, an in-depth analysis was carried out for dropout.

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 a 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 1 is a visual presentation of discontinuation of the updates in a flight. Latitude data is used as a reference of discontinuation of the overall message frame. As in enroute the update interval must not exceed three seconds [28], therefore 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.

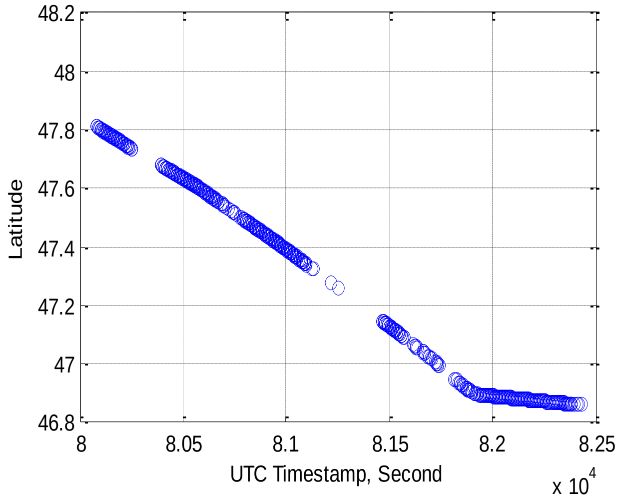

Figure 1. Multiple dropout in a flight. Latitude data is used to represent the data drop out for 70 minutes' flight span.

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 [24]. This verification discarded the messages which were not authentic. In this study a total of 12852609 payloads were archived and subsequently analyzed. 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 [29]. The Navigation Integrity Category (NIC) values were also missing in some reports, although were not considered as severe as NACp. 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. 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 [1]. Experts from UND aerospace also explained this fact as a potential transponder issue. Figure 2 illustrates the jump in latitude data from a nominal value.

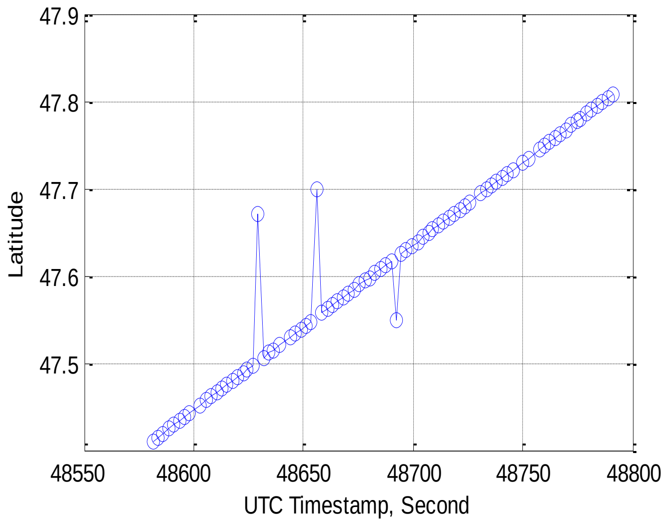

Figure 2. Jump in latitude data from a continuous nominal value.

3.4. 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 3.

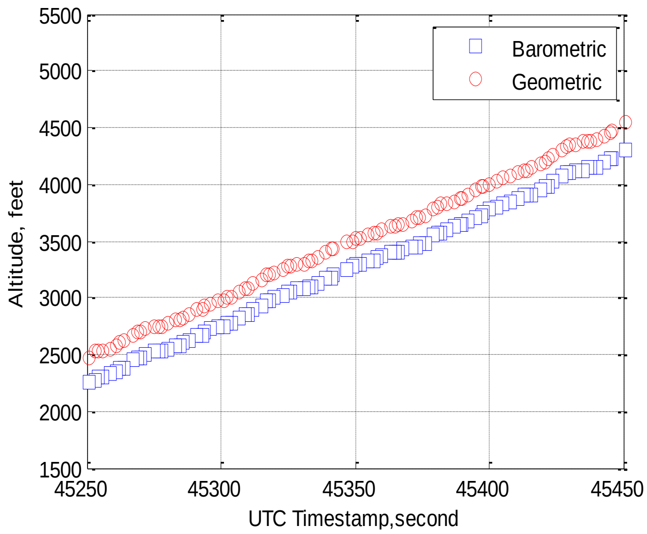

Figure 3. Altitude Discrepancy in Climbing Phase of Flight. Blue Rectangles Describe Barometric Altitude, and Red Circles Describe Geometric Altitude.

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.

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 4 shows the percent of the data integrity in a bar graph.

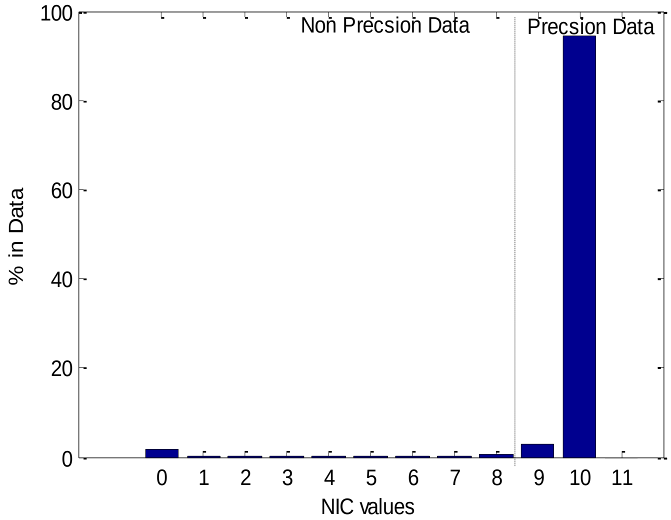

Figure 4. Data integrity distribution bar graph, no data were found having maximum integrity. Dashed line distinguishes the precision and non-precision range

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.

4. Dropout and Effect of Flight Parameters

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 [30]. 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. Three essential pieces of information from the flight data are considered as potential factors behind drop which referred as airborne factors. These are:

- Flight Level (Altitude),
- Distance from the Ground Receiver (Range)
- Heading

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 4 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. 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.

Table 4. Update Rate Categorization

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 5 shows the histogram of categorized update rate which clearly indicates update rate duration follows non-normal distribution particularly an exponential distribution. Figure 5 shows the histogram of categorized update rate which clearly indicates update rate duration follows non-normal distribution particularly an exponential distribution.

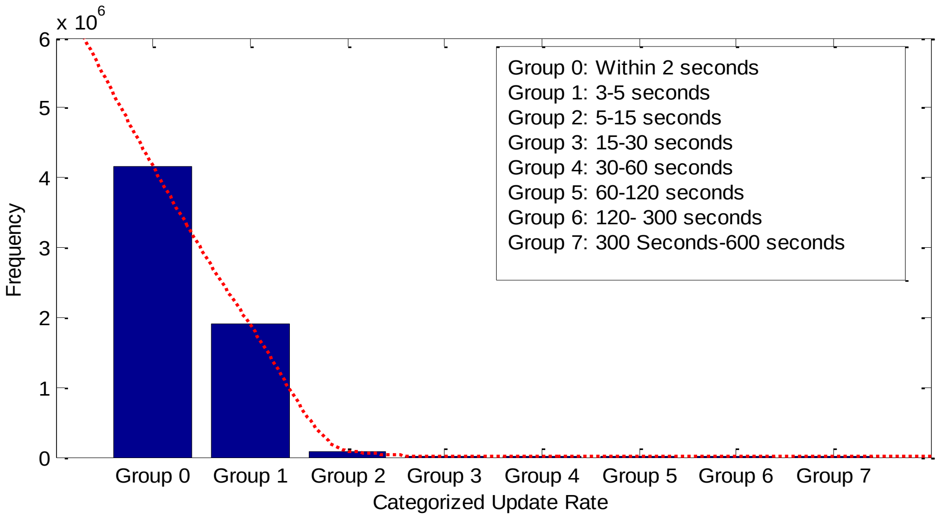

Figure 5. Histogram of categorized update rate

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. 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.

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. A small p-value

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(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. Th 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 [31], 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 [31] 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 [32]. The hypothesis was:

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

H1: 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. Effects of Flight Level

To understand the effects of altitude, the categorized dropout was 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 5.

Table 5. 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

The test result for different flight level dropout frequency indicates there is a significant difference in dropout frequency in different flight level. Table 6 represents the statistical results; the p-value is 0.03 which reveals the significance of flight level in dropout occurrence.

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Table 6. Test Statistics for Different Altitude Level

Fight Group	Level	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			

Figure 6 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.

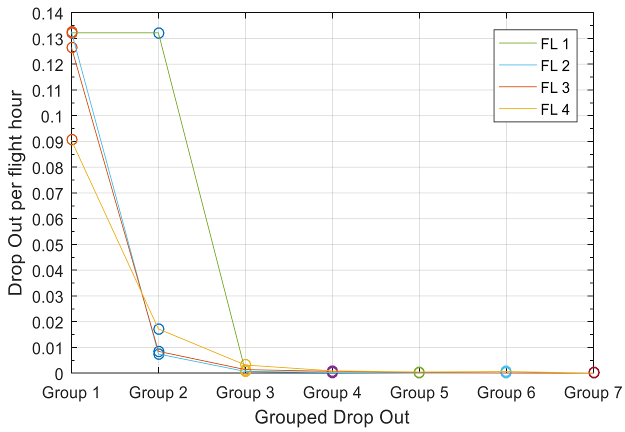

Figure 6. Grouped Drop Out Vs Dropout per flight hour for four different flight level

From table 6 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.

4.2. 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 [33]. 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 7 listed the dropout frequency in a different group in a different range.

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Table 7. 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 7 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.

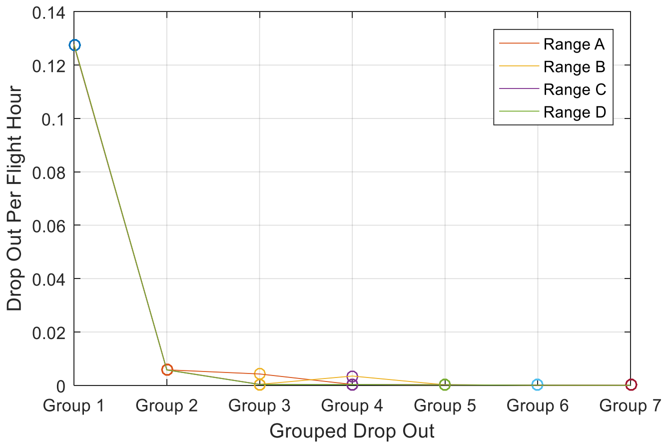

Figure 7. Grouped Drop Out Vs Dropout Per Flight Hour in Different Range

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 8.

Table 8. 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.

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4.3. 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 9 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.

Table 9. Frequency of Categorized Dropout in Different Range

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 10 and figure 8, the frequency of dropout doesn't differ in between zones.

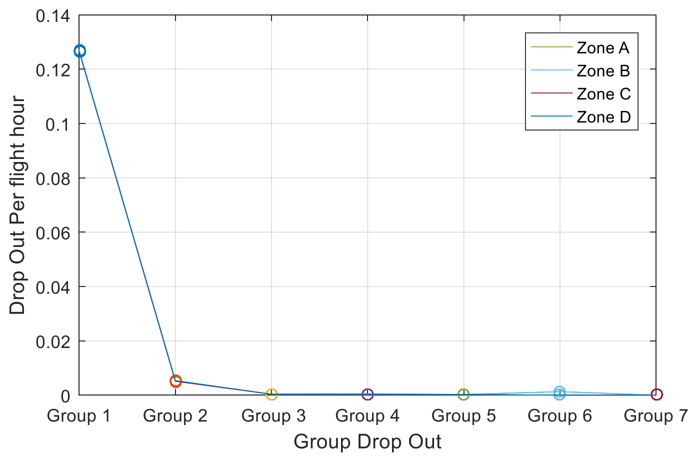

Figure 8. Grouped Dropout Vs Dropout per flight hour in different zone

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

Table 10. 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.

5. Dropout Mapping

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 9. The maximum number of dropout at certain longitude value was as high as 107.

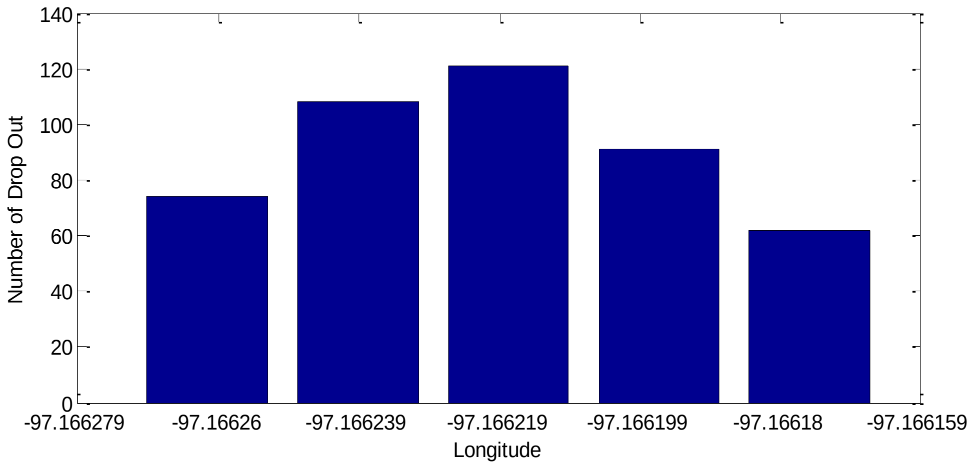

Figure 9. Histogram of Dropout at certain longitude

For a better understanding the longitude along with their latitude where dropout occurred most were drawn on a map. Figure 10 shows the map where the red dot indicates the position of most dropout occurrence.

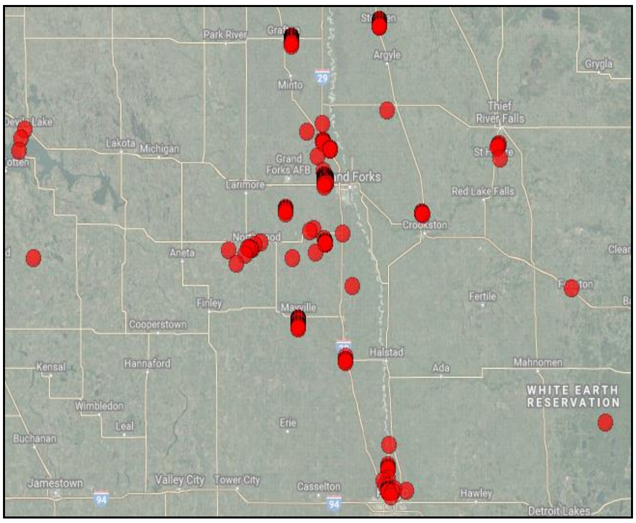

Figure 10. Location of The Dropout in Google Map

It was further revealed that the clustered dropout in some places was due to the heavy 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 [34]. 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. 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.

6. Conclusion and Future Work

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. The main findings of the dropout analysis can be listed as follows:

- Altitude plays a key role in dropout frequency. The lower the altitude, the more chances that a dropout will occur in the ground receiver.
- 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.
- Aircraft heading is not a significant factor for dropout.
- Some position may affect the dropout occurrence if that causes communication loss

From the statistical testing on different flight conditions and factors it is evident 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. It should be noted that 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 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 comparison of the real time recorded ADS-B data and raw pass through data. 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.

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Authors Contributions: Asma Tabassum developed UAT ADS-B data extraction algorithm and carried out the data analysis. William Semke directed and supervised the research work in all stages.

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