 doi:10.20944/preprints201804.0143.v1

Article

Severity and Effect of ADS-B Message Drop Out in Detect and Avoid of Unmanned Aircraft System

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Abstract: This work analyzes the severity and risk associated with Automatic Dependent Surveillance- Broadcast (ADS-B) message drop out in Detect and Avoid (DAA) for Unmanned Aircraft System (UAS). Performance assessment of UAT ADS-B message implies that ADS-B may fail to update within specified update interval which is referred to as drop out. UAT ADS-B is a fundamental surveillance sensor for both class 1 and class 2 DAA. Message discontinuation or drop out has been found as one of the anomalies of the ADS-B system. Hence to ensure safe and reliable operation of UAS; hazard and risk assessment is essential. The severity and risk associate with drop out was assessed in this work. The drop out induced in the simulation was identified from the UAT ADS-B archived data. The data were received from the Grand Forks International Airport, North Dakota. Simulation results depicts that both the duration of drop out and DAA look-ahead time effect the safe operation of UAS and as a repercussion result in degraded situational awareness. The risk was also quantified with risk matrix in order to measure the overall threat. A system level analysis was carried out to recognize the potential reasons behind ADS-B drop out.

Keywords: UAS; ADS-B; Drop Out; DAA; Well clear; Risk Matrix

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1. Introduction

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. FAA also states that more than 6,800 airspace waiver requests were submitted for operations in controlled airspace by the end of December 2016 [1]. 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. These statistics of UAS integration indicate towards a unified airspace for both manned and unmanned aircraft.

Next Generation Air Transportation System, in short NextGen, is a series of inter-linked programs, systems, and policies that implement advanced technologies and capabilities [2]. 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 [3] is introduced by the FAA to encourage and help owners to equip aircraft with the required avionics for NextGen. 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. 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

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aircraft state information such as horizontal position, altitude, vector, velocity and trajectory intent information.

Initial assessment of UAT ADS-B [5], [6], [7] showed significant message degradations. One of the anomalies of ADS-B is message discontinuation or drop out. This work emphasizes the severity and risk associated with drop out in UAS DAA. The investigation is based on the extended ADS-B data analysis carried out at be Semke et el [6]. The analysis predicts how ADS-B message drop out could affect UAS DAA system if used as a single means of surveillance. The drop out identified in that work is introduced in the simulation carried out in this study. A system level study ties the anomalies to potential technical reasons and discusses how ATC and aerospace personnel are impacted by drop out.

2. Background of ADS-B Message Drop out and UAS Well Clear

As one of the fundamental components of NextGen, significant research was done and is still going on various aspects of ADS-B. This includes but is not limited to security and verification of messages, experimental attack analysis, data quality analysis, safety assessment etc. A handful of studies were 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 [8]. 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 [9]. 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 and suffered from message discontinuation. A generalized linear model was also developed to model ADS-B message discontinuation.

2.1. UAT ADS-B Drop Out

Our initial work as a part of Assure A6 surveillance criticality team [5] studied drop out in UAT ADS-B. The test data received from Grand Forks International Airport 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 [10]. A python module was developed to decode the archived data as defined as RTCA DO 282B [11]. The anomalies revealed in step by step assessment can be divided into five distinct categories namely dropout, missing payload, low confident data, data jump and altitude discrepancy Later work [7] categorized drop out in different group and their occurrence in the messages.

International Civil Aviation organization listed some parameters in order to characterize any surveillance system. The characteristics are as follow [12]:

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.

Dropout, an incident where ADS-B message is not continuously updated at 1Hz rate. The continuity of ADS-B system is measured in seconds at which rate the message received on the ground

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receiver. The continuity of the data stream is one of the crucial metrics for considering the performance of the surveillance system. The expected continuity or update rate for ADS-B according to International Civil Aviation Organization (ICAO) [12] is less than 2 s, significantly faster than the radar system's 4–15 s update rate. Figure 1 is a visual presentation of discontinuation of an update in a flight. Latitude data is used as a reference of discontinuation of the overall message frame.

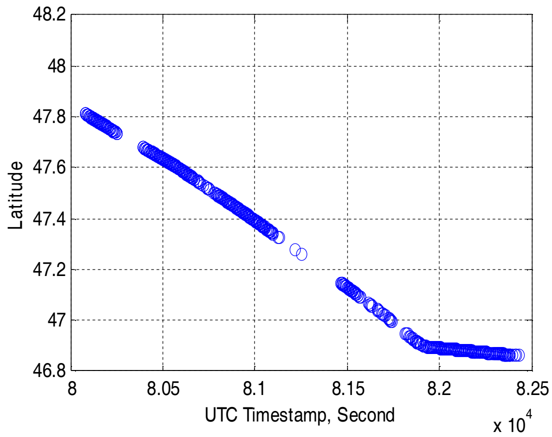

Figure 1. Multiple dropout in a flight. Latitude data is used to represent the data gap. In the 70 minutes' flight span, data were missed several times.

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. Table 1 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 1. Update Rate Categorizations

Category	Duration	%	Remarks
Group 0	Within 2 seconds	67.51	Not Dropout
Group 1	3 seconds to 5 seconds	30.80	Dropout
Group 2	5 seconds to 15 seconds	1.42	Dropout
Group 3	15 seconds to 30 seconds	0.10	Dropout
Group 4	30 seconds to 60 seconds	0.08	Dropout
Group 5	60 seconds 120 seconds	0.05	Dropout
Group 6	120 seconds to 300 seconds	0.03	Dropout
Group 7	More than 300 seconds to less than 600 seconds	0.01	Dropout

2.2. UAS 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 [13]. 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

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compatibility with aircraft collision avoidance systems [14]. 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 [14] and FAA stands with the recommendation with a slight modification of vertical separation changing vertical separation thresholds from 750 feet to 450 feet. Table 2 represents the well-clear definition thresholds and figure 2 illustrates the concepts of time to loss of well clear.

Table 2. 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

Hence, 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, $\tau_{mod} \leq \tau_{mod}^*$

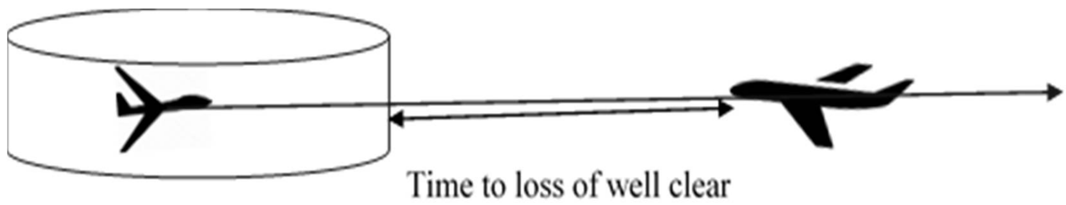

Figure 2. Time to Loss of Well Clear in Horizontal Direction

The DAIDALUS [13] DAA alerting criteria is based on "time to loss of well clear". 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 [15] 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. Table 3 shows the value of different alerting criteria based on time to loss of well clear.

Table 3. 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

Two different alerts are triggered; one is corrective, and the other is a warning [16]. 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

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will likely be started based on PIC judgment [17]. The DAA warning alert is intended to inform the PIC that immediate action is required to maintain well clear.

3. Simulation Scenario and Results

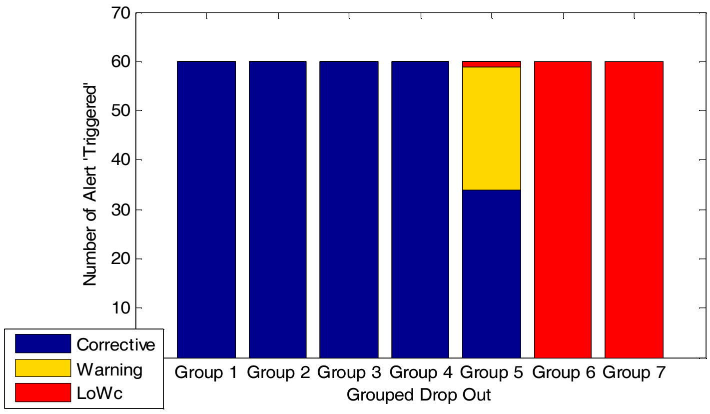
The simulation was carried out in MATLAB. A function detection_WCV [14] is used to calculate the time to loss of well clear. This function takes the relative position and velocity of the aircraft and a look-ahead time interval $[B, T]$ as inputs and returns a time interval [$t$in, $t$out] within [B,T]. B is typically 0 and T represents the look-ahead time. If tin ≤ tout, the time tin represents time to LoWC and tout represents the time to exit LoWC, assuming constant velocity. The returned time interval is empty, i.e., tin > tout, if the aircraft are not predicted to be a LoWC state within the interval $[B, T]$. The complete description of the logic can be found here [13].

The track co-ordinates were generated such that ownship-intruder 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. Both aircraft were assumed to fly level flight. 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 4 summarize the alert triggered in three different look-ahead times.

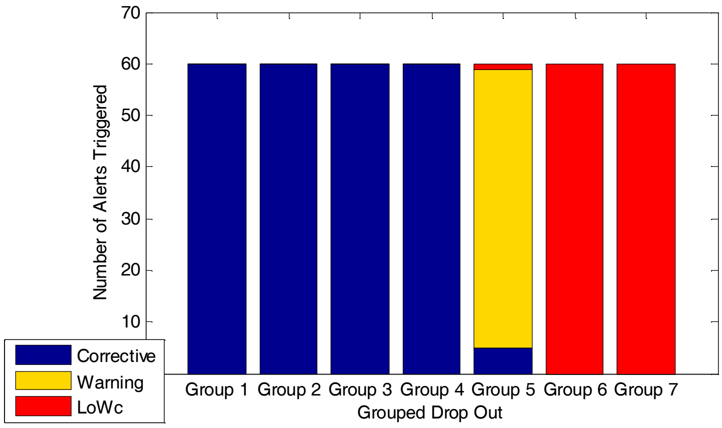
Table 4. Alert Triggered in different look-ahead time

Drop out Group	Look-ahead time, 180 seconds			Look-ahead time, 120 seconds			Look-ahead Time, 60 seconds		
	Loss	Warning	Correc-tive	Loss	Warning	Correc-tive	Loss	Warning	Correc-tive
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

According to the encounter setup, drop out will occur at the beginning of the look-ahead time. The different durations of dropout found from the data analysis 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 the different groups 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. 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 simulation results are presented through figure 3. The bar chart depicts the type of alert generated in presence of different duration of drop out. The blue bar indicates a corrective alert, yellow bar depicts a warning alert and red bar depicts violation of well clear.



(a)



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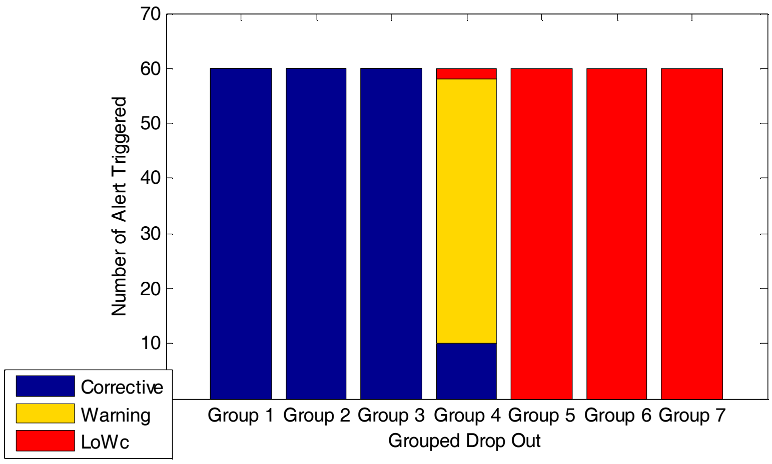

(c)

Figure 3. Change in Alert Type for Different Group of Drop out with (a) Look-ahead Time Of 180s, (b) Look-ahead time of 120s, and (c) Look-ahead time of 60s

It should be noted that some groups contain 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

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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 the 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 3, the change in alert depends on the look-ahead time and when the dropout takes place. When the look-ahead time is less; even a 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 was considered an obvious violation of well clear.

3. Hazard and Risk Assessment

Hazard analyses are performed to identify and define hazardous conditions/risks for 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. 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. 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 likelihood and the severity definition developed for the dropout hazard assessment along with the FAA severity definitions, the FAA likelihood definitions is described in Table 5 and Table 6.

Table 5. Likelihood Definition Summary

Frequency	FAA definition	Definition derived for this study
Frequent, A	Expected to occur routinely	Occurred in more than 10% times in dataset
Probable, B	Expected to occur often	Occurred in less than 10% but more than 1 % times
Remote, C	Expected to occur infrequently	Occurred in less than 1 % but more than 0.10 times
Extremely Remote, D	Expected to occur rarely	Occurred in less than 0.10% cases but more than 0.01% times
Extremely Improbable, E	So unlikely that it is not expected to occur, but it is not Impossible	Occurred in less than 0.01% times

The severity matrix was developed based on "time to loss of well clear", tloss value. A value of tloss = 55 seconds will trigger a corrective alert where as a value of tloss=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

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on one head-to-head encounter scenarios, hence the risk rating doesn't represent the overall risk of the airspace.

Table 6. Severity Definition Summary

Scale	Minimal,1	Minor,2	Major,3	Hazardous,4	Catastrophic,5
FAA definition	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
Definition derived for this study	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 tloss 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 7- Table 9.

Table 7. Risk Matrix 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*

 doi:10.20944/preprints201804.0143.v1

Table 8. Risk Matrix 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 9. Risk Matrix 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*

The green rectangle represents acceptable risk, yellow rectangle represents acceptable risk with mitigation, red rectangle represents unacceptable risk and bottom corner represents unacceptable with single/ common cause failure. As seen from Tables above, when the look-ahead time decreases the number of cases in yellow and red rectangle increases i.e. severity increases. A small look-ahead time window made DAA alert more severe, which indicates to the fact that the time the dropout occurred is crucial for alert.

This provides the example 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 a certain time-period, and this time is defined by the user. This points to the fact that in the event of dropout, a potential threat might be excluded and will not be considered as a threat anymore even when the threat is still present. This might lead to abrupt maneuvers when it reappears and in the worst-case scenario, a near midair collision. The change in risk with look-ahead time is illustrated in a bar chart in figure 4. It shows how with decreasing look-ahead time increases the number of unacceptable risk cases and decreases the acceptable risk cases.

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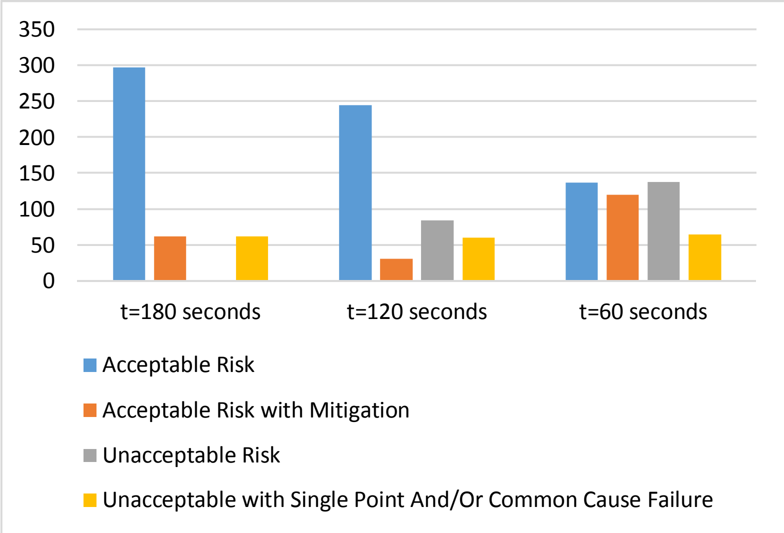

Figure 4. Change in Risk Rating with look-ahead time

4. Discussion

A system level assessment starts from the main event and go down to all probable causes that lead to that event in that system. The 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

4.1. ADS-B out system fails to send message

ADS-B is dependent on the 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 [18]. Another potential reason of unavailability is the failure of the antenna to transmit the signal.

4.2. 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 1090 ES collected at the same bandwidth [19].

- Interference: Interference can be from radio frequency or from electromagnetic fields. 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 [11]. Heavy electronic machines installed near airports are another potential reason of electromagnetic interference which also affect reception of ADS-B signal [20].

- 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 [21].

 doi:10.20944/preprints201804.0143.v1

- 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 [22]. Messages with bit errors are discarded at reception.

Analysis can be leads towards that drop out can affect ATC operation from two different perspectives; Airspace Perspective and Aircraft Perspective. Dropout will affect the airspace when it appears more in some distinct position where it is assumed they lost line of sight communication. Also, if in certain areas 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 and/or message discontinuation. In the presence of congested traffic, aircraft in the vicinity of the victim aircraft would also suffer from degrading situational awareness. The safety of the airspace wouldn't degrade significantly as a whole but the safety and reliability would be compromised.

5. Conclusion

Since introducing UAS in NAS is a concern for future ATC operations, some hypothetical encounter scenarios were studied 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, as approved by FAA and developed by NASA. The risk matrix established is based on the simulation scenarios and doesn't represent the overall risk of the airspace. The 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 produced a higher severity risk 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 a near midair collision was to occur. 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. For full utilization of airspace, understanding the anomalies of ADS-B and knowing how to deal with and handle these anomalies is crucial. As ADS-B is envisioned to lead future ATC, provisions should be made to properly address the current weaknesses and limitations of the system.

Acknowledgments:

This work is partially funded by ASSURE, an alliance of universities across the United States by the Federal Aviation Administration for System Safety of UAS.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. FAA, Unmanned Aircraft Systems Trends in UAS and Forecast.
2. Next Generation Air Transportation System (NextGen) – NextGen Works Available online: https://www.faa.gov/nextgen/works/ (accessed on Nov 6, 2017).
3. General Aviation ADS-B Rebate Program Available online: https://www.faa.gov/nextgen/equipadsb/rebate/ (accessed on Nov 6, 2017).
4. RTCA Inc Minimum Aviation System Performance Standards (MASPS) for Flight Information Services-

Broadcast (FIS-B) Data Link | Engineering360.

5. Snyder, K. UAS Surveillance Criticality Final Report. **2016**.
6. Semke, W.; Allen, N.; Tabassum, A.; McCrink, M.; Moallemi, M.; Snyder, K.; Arnold, E.; Stott, D.; Wing, M. Analysis of Radar and ADS-B Influences on Aircraft Detect and Avoid (DAA) Systems. *Aerospace* **2017**, *4*, 49, doi:10.3390/aerospace4030049.
7. Tabassum, A.; Allen, N.; Semke, W. ADS-B message contents evaluation and breakdown of anomalies. In *2017 IEEE/AIAA 36th Digital Avionics Systems Conference (DASC)*; IEEE, 2017; pp. 1–8.
8. Ali, B. S. A Safety Assessment Framework for Automatic Dependent Surveillance Broadcast (ADS-B) and its Potential Impact on Aviation Safety Busyairah Syd Ali A thesis submitted for the degree of Doctor of Philosophy of the Imperial College London Centre for Transp. **2013**.
9. Ali, B. S.; Ochieng, W. Y.; Zainudin, R. An analysis and model for Automatic Dependent Surveillance Broadcast (ADS-B) continuity. *GPS Solut.* **2017**, 1–14, doi:10.1007/s10291-017-0657-y.
10. GDL® 90 | Garmin Available online: https://buy.garmin.com/en-US/US/p/6436 (accessed on Oct 24, 2017).
11. RTCA, Minimum Operational Performance Standard for Universal Access Transceiver (UAT) Automatic Dependent Surveillence Broadcast (ADS-B).
12. Guidance Material on Comparison of Surveillance Technologies (GMST). **2007**.
13. Muñoz, C.; Narkawicz, A.; Hagen, G.; Upchurch, J.; Dutle, A.; Consiglio, M.; Chamberlain, J. DAIDALUS: Detect and Avoid Alerting Logic for Unmanned Systems. *AIAA/IEEE Digit. Avion. Syst. Conf. - Proc.* **2015**, 5A11-5A112, doi:10.1109/DASC.2015.7311421.
14. RTCA-SC-228 Draft Detect and Avoid (DAA) Minimum Operational Performance Standards for Verification and Validation. **2015**.
15. Monk, K. J.; Roberts, Z. Maintain and Regain Well Clear : Maneuver Guidance Designs for Pilots Performing the Detect-and-Avoid Task. **2017**.
16. Implementation Manual for the Universal Access Transceiver (UAT). *System* **2004**.
17. Monk, K.; Roberts, Z. UAS Pilot Evaluations of Suggestive Guidance on Detect-and-Avoid Displays. **2016**, 81–85, doi:10.1177/1541931213601018.
18. Ali, B. S.; Ochieng, W. Y.; Majumdar, A. ADS-B: Probabilistic Safety Assessment. *J. Navig.* **2017**, *70*, 887–906, doi:10.1017/S0373463317000054.
19. Chen, Y. H.; Lo, S.; Jan, S. S.; Enge, P. Evaluation & Comparison of Passive Ranging Using UAT and 1090. *IEEE/ION Position Locat. Navig. Symp.* **2014**.
20. Boci, E. RF Coverage analysis methodology as applied to ADS-B design. In *2009 IEEE Aerospace conference*; IEEE, 2009; pp. 1–7.
21. Langejan, T.; Sunil, E.; Ellerbroek, J.; Hoekstra, J. Effect of ADS-B Characteristics on Airborne Conflict Detection and Resolution. *Delft, the Netherlands* **2016**.
22. Garmin, GDL 90 Data Interface Specification. **2007**.