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Evaluating Alerting and Guidance Performance of a UAS Detect-And-Avoid System

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List of Acronyms and Abbreviations

ACES	Airspace Concept Evaluation System
ADS-B	Automatic Dependent Surveillance-Broadcast
ATC	Air Traffic Control
BADA	Base of Aircraft Data
C2	Command and Control
CA	Collision Avoidance
CFR	Code of Federal Regulations
CPA	Closest Point of Approach
CR	Correct Rejection
DAA	Detect and Avoid
DMOD	Distance Modification of Modified Tau
DR	Dead Reckoning
ETL	Estimated Time to LoWC
FA	False Alert
FP	Flight Plan
FAA	Federal Aviation Administration
FOR	Field of Regard
FPR	False Positive Rate
GCS	Ground Control Station
HITL	Human-in-The-Loop
HMD	Horizontal Miss Distance
IFR	Instrument Flight Rules
JADEM	Java Architecture for DAA Modeling and Extensibility
LoWC	Loss of Well Clear
MA	Missed Alert
MOPS	Minimum Operational Performance Standards
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NMAC	Near Mid-Air Collision
nmi	Nautical Miles
RADES	Radar Evaluation Squadron
ROC	Receiver Operating Characteristics
SAA	Sense and Avoid
SARP	Science and Research Panel
SC	Special Committee
SDT	Signal Detection Theory
SOC	Systems Operating Characteristics
SSM	Self Separation Maneuver
TA	True Alert
TCAS	Traffic Alert and Collision Avoidance System
TPR	True Positive Rate
UAS	Unmanned Aircraft System
VFR	Visual Flight Rules

Summary

A key challenge to the routine, safe operation of unmanned aircraft systems (UAS) is the development of detect-and-avoid (DAA) systems to aid the UAS pilot in remaining "well clear" of nearby aircraft. The goal of this study is to investigate the effect of alerting criteria and pilot response delay on the safety and performance of UAS DAA systems in the context of routine civil UAS operations in the National Airspace System (NAS). A NAS-wide fast-time simulation study was conducted to assess UAS DAA system performance with a large number of encounters and a broad set of DAA alerting and guidance system parameters. Three attributes of the DAA system were controlled as independent variables in the study to conduct trade-off analyses: UAS trajectory prediction method (dead-reckoning vs. intent-based), alerting time threshold (related to predicted time to LoWC), and alerting distance threshold (related to predicted Horizontal Miss Distance, or HMD). A set of metrics, such as the percentage of true positive, false positive, and missed alerts, based on signal detection theory and analysis methods utilizing the Receiver Operating Characteristic (ROC) curves were proposed to evaluate the safety and performance of DAA alerting and guidance systems and aid development of DAA system performance standards. The effect of pilot response delay on the performance of DAA systems was evaluated using a DAA alerting and guidance model and a pilot model developed to support this study. A total of 18 fast-time simulations were conducted with nine different DAA alerting threshold settings and two different trajectory prediction methods, using recorded radar traffic from current Visual Flight Rules (VFR) operations, and supplemented with DAA-equipped UAS traffic based on mission profiles modeling future UAS operations.

Results indicate DAA alerting distance threshold has a greater effect on DAA system performance than DAA alerting time threshold or ownship trajectory prediction method. Further analysis on the alert lead time (time in advance of predicted loss of well clear at which a DAA alert is first issued) indicated a strong positive correlation between alert lead time and DAA system performance (i.e. the ability of the UAS pilot to maneuver the unmanned aircraft to remain well clear). While bigger distance thresholds had beneficial effects on alert lead time and missed alert rate, it also generated a higher rate of false alerts. In the design and development of DAA alerting and guidance systems, therefore, the positive and negative effects of false alerts and missed alerts should be carefully considered to achieve acceptable alerting system performance by balancing false and missed alerts.

The results and methodology presented in this study are expected to help stakeholders, policymakers and standards committees define the appropriate setting of DAA system parameter thresholds for UAS that ensure safety while minimizing operational impacts to the NAS and equipage requirements for its users before DAA operational performance standards can be finalized.

I. Introduction

ONE of the most critical challenges to full integration of Unmanned Aircraft Systems (UAS) into the National Airspace System (NAS) is the requirement to "see and avoid" other aircraft, which is an important contributor to today's safe air traffic operations.[1] Lacking an on-board pilot to perform "see and avoid," UAS will require Detect-And-Avoid (DAA) systems to remain "well clear" of other proximate airborne traffic to safely operate in civil airspace. While a number of potential UAS DAA system architectures have been proposed (e.g., ground-based vs. airborne, automated vs. pilot-in-the-loop), all DAA systems would be expected to perform the following basic functions: (1) detect and track proximate airborne aircraft, (2) evaluate the collision hazard of each intruder aircraft by predicting their future trajectories and comparing them against the predicted trajectory of the UAS, (3) prioritize the intruders and (if necessary) alert/declare that action is necessary to avoid a predicted loss of well clear, and (4) determine maneuver guidance to resolve the situation. The UAS DAA system investigated in this memorandum relies on the UAS pilot to assess maneuver guidance provided by the DAA system and to determine appropriate action(s) to remain well clear of other aircraft.

Prior research has assessed UAS pilot ability to maintain "well clear" under a variety of UAS Ground Control Station (GCS) display and maneuver guidance concepts using Human-in-the-Loop (HITL) simulations.[2,3] These studies provided the data to refine the UAS DAA display, guidance and alerting concepts, and to develop UAS pilot response models for use in fast-time simulations and Monte Carlo analyses. While HITL simulations are critical to the development of UAS DAA system performance standards, due to cost, schedule and manpower constraints, they are generally only able to assess the performance of a DAA system under a limited set of operating conditions and system parameters. It is necessary to complement these prior studies with additional research addressing a broader range of operating conditions and system parameters to develop a full understanding of how DAA system attributes affect the performance of DAA systems in the context of routine civil UAS operations in the NAS.

In this effort, a fast-time simulation study was conducted to assess UAS DAA system performance with a large number of encounters and across a broader set of DAA alerting and guidance system parameters than was employed in the aforementioned HITL simulations. In this study, encounters between UAS and other aircraft are the result of simulated UAS operations interacting with recorded VFR traffic in a NAS-wide simulation. Eighteen UAS mission profiles developed under prior work were used in this study to simulate a variety of UAS aircraft conducting an array of possible future UAS missions, including: point-to-point transport, regional mapping/monitoring, and patrol.[4] Conventional, manned aircraft traffic operating under Visual Flight Rules (VFR) was based on track recordings of radar facilities from across the continental United States NAS. Ultimately, each simulation included tens of thousands of DAA-equipped UAS operations interacting with tens of thousands of conventional VFR operations. The resulting set of encounters between UAS and VFR aircraft were used to investigate the relationships between UAS DAA system performance, alerting parameters, pilot response delay, and trajectory prediction methods.

A UAS DAA system alerting and guidance model was developed as part of this effort and includes a simple pilot response model based on prior HITL simulation. The following attributes of the DAA system were controlled as independent variables in the experiment: 1) UAS trajectory prediction method (state-based vs. intent-based), 2) alert time threshold (related to predicted time to LoWC), and 3) alert distance threshold (related to predicted Horizontal Miss Distance, or HMD). Further, the alert lead time (time prior to predicted loss of well clear that an encounter met the alerting criteria and was communicated to the pilot) was also investigated to understand its relationship to the ability of the UAS pilot to respond to an alert and maneuver to remain well clear. While metrics traditionally employed in alerting systems (e.g. missed alert rate, false alert rate, etc.) are important to understanding system performance tradeoffs, they provide little insight into selection of appropriate system parameters to achieve desired DAA system performance characteristics.

This research proposes several potential metrics and methods for systematically evaluating the performance of a DAA system with respect to alerting and the ability of the pilot using the DAA system to remain well clear. This study not only investigates the trade-offs and sensitivities between DAA system attributes, but additionally provides metrics in terms of predictability and resolution ability to more directly address effective system parameter selection. Understanding alerting system parameters and their impact on safety and performance is essential for establishing the requirements and associated standards for DAA systems. Therefore, the purpose of the present research is to quantify the effectiveness and performance of DAA alerting and guidance systems to support the Minimum Operational Performance Standards (MOPS) for DAA systems to enable safe operations of UAS in civil airspace. The results and methodology are expected to help stakeholders, policymakers and standards committees define the appropriate setting of DAA system parameter thresholds for UAS that ensure safety while minimizing operational impacts to the NAS and equipage requirements for its users before DAA operational performance standards can be finalized.

To provide the context for understanding the basis of this work, the following section provides a brief background of prior research. Section III describes DAA alerting and guidance systems, the definition of UAS well clear, and DAA alerting criteria modeled in this effort. To address the need for metrics leading to DAA system parameter selection, Section IV proposes a set of performance metrics and analysis methods for evaluating the performance of DAA alerting and guidance systems. Section V describes the simulation models and platform including traffic scenarios used to conduct this research and details the simulation experiment design. Section VI discusses simulation results, and Section VII concludes with a summary.

II. Background

In the United States, RTCA Special Committee 228 (SC-228), a consortium of government, industry and academia, is currently working toward establishing Minimum Operational Performance Standards (MOPS) for DAA systems equipment and Command and Control (C2) Data Link systems to support civil UAS operations in transition airspace from/to Class A airspace under Instrument Flight Rules (IFR).[5] Although some concepts for future DAA systems have been researched for UAS,[6] a DAA system for use on unmanned aircraft has not yet been certified or implemented. Significant design, evaluation, verification and validation efforts are required before final MOPS for DAA systems can be developed. NASA is conducting research to evaluate and quantify the operational performance for DAA systems and algorithms for supporting MOPS development through fast-time simulation and HITL simulation experiments.[7,8]

The UAS DAA alerting and guidance subsystems are intended to assist the UAS pilot in identifying nearby aircraft representing potential collision hazards and to provide the UAS pilot with guidance to select an appropriate maneuver to remain well clear of the threat aircraft, respectively. DAA systems designed with such “suggestive” guidance for the UAS pilot are typically composed of four subsystems: 1) a surveillance subsystem, 2) an alerting subsystem, 3) a maneuver guidance subsystem, and 4) a traffic display subsystem. The surveillance subsystem detects and tracks proximate intruder aircraft with on-board sensors and a tracker (not necessarily on-board the aircraft). After processing the surveillance track data (including prioritizing intruder aircraft), an alerting subsystem evaluates tracks to assess the risk that “well-clear” separation will be lost and alerts the pilot accordingly. If a threat is identified, a guidance subsystem determines an appropriate response and provides maneuver guidance to the pilot through a traffic display subsystem. A traffic display subsystem at the ground control station provides pilots with visual traffic information and aids them in selecting and executing an avoidance maneuver. This study focuses on evaluating the performance of DAA alerting and guidance subsystems, and Section III provides more information about the alerting and guidance subsystems.

The performance of DAA systems can be affected by the volume of the alert zone which is defined by alerting subsystem parameters such as alert criteria and thresholds. Larger alert zones generally lead to earlier alerts (i.e., alerts are generated further in advance of predicted loss of well clear). While earlier alerts may provide the UAS pilot more time to assess maneuver guidance and coordinate a maneuver with ATC, a larger alert zone also leads to an increase in the number of false alerts. An excessive number of false alerts can be a nuisance to UAS pilots and ATC due to required coordination of otherwise unnecessary UAS maneuvers and may impact air traffic controller workload, and thus their ability to provide separation service to other IFR aircraft. On the other hand, if the alert zone is too small, which creates a higher rate of missed alerts, there might not be sufficient space or time for a UAS pilot to determine and command a maneuver to avoid a predicted conflict (i.e., a loss of well clear) even though it might reduce false/nuisance alerts. Balancing false and missed alerts to achieve acceptable DAA system performance is a key design challenge for DAA systems builders. More information about the chosen analysis methodology and a set of proposed DAA system performance metrics are described in Section IV.

The alerting efficacy of a DAA system is sensitive to the encounter geometry between UAS and potential threat aircraft at the time of alerts. In deciding on appropriate alerting criteria, the relative range and bearing angle between aircraft at the time of alerts should also be considered. To investigate the relationship between encounter geometry and alerting thresholds, simulations were conducted without imposing sensor field-of-regard constraints on tracks used to evaluate whether or not alerting criteria were met. Then, the proportion of alerts was determined at which both ownship and intruder aircraft were within a specified minimum surveillance volume defined by a detection range, horizontal and vertical fields of regard. If only small percent of threat aircraft, given a surveillance volume, can be detected with a selected alerting criteria, the alerting criteria or the required surveillance volume should be re-evaluated and adjusted. Therefore, the alerting criteria must also be based in part on the encounter characteristics. However, the encounter characteristics at the time of alerts that UAS are likely to have with other aircraft, particularly with VFR aircraft in transition airspace, are not well understood yet. Prior studies investigating DAA systems with Monte Carlo simulations have relied on encounter models based on the interactions between VFR aircraft operating in the NAS, implicitly assuming UAS operations in the NAS will closely resemble current VFR operations.[9,10] Therefore, one of the goals in this research is to explore the encounter characteristics between aircraft, such as relative horizontal range and bearing angle, when DAA alerts are issued. Analysis of UAS-VFR encounters derived from the mission-based UAS operations in this paper complement prior encounter-model based studies and serve to reduce risk associated with assumptions about the character of future UAS operations. The results are presented in Section VI.A.

The alerting subsystem parameters and performance requirements are selected to achieve a desired level of safety and to satisfy a certain level of operational performance (e.g., an acceptable number of false alerts and missed alerts). This level of safety is, broadly speaking, dependent upon two important variables: 1) the alert rate at which a UAS encounters threat aircraft that are projected to lose “well clear,” and 2) the effectiveness of a DAA system in mitigating those encounters. In the safety-critical domain of aviation, reducing missed alerts is generally more important than reducing false/nuisance alerts because of the very high cost of a missed alert resulting in a potentially catastrophic consequence (e.g., a collision). Therefore, it is important to consider the cost of missed alerts versus that of false or nuisance alerts when selecting the alerting thresholds for DAA systems. Defining the alerting threshold or criteria improperly could result in operational impacts to the NAS or unreasonable sensor requirements. Therefore, the challenge is to identify acceptable alerting thresholds for UAS DAA systems that ensure safety while minimizing operational impacts to the NAS. Simulation results are then assessed by investigating the relationship between the rates of false alerts and missed alerts in Section VI.B.

For DAA systems based on "suggestive" guidance (as suggested by SC-228), the UAS pilot makes the final determination of the resolution maneuver to execute to avoid a predicted loss of safe separation from other nearby aircraft or hazards.[11] To remain well clear of threat aircraft, the pilot must have adequate time to assess the threat, evaluate maneuver options, coordinate the selected maneuver with ATC, and initiate a maneuver to mitigate the threat.[1] Thus, an important feature of a DAA alerting and guidance system is the alert lead time provided to the pilot when a threat to well clear is identified. This study examines how the alert lead time is affected by the setting of DAA system parameter thresholds and how the alert lead time and pilot response delay affect the performance of DAA systems. To model the time delay associated with these pilot actions and cognitive processes, a pilot response delay model was developed for use in this fast-time simulation experiment, based on results from prior HITL studies.[3] The simulation results about DAA guidance performance are presented in Section VI.C.

III. Overview of a DAA Alerting and Guidance System

Pilots onboard aircraft flying under VFR are required to remain well clear of other aircraft by complying with the particular regulatory rules addressing right of way, to remain "well clear", and operating not so close to other aircraft (Title 14 Code of Federal Regulations (14 CFR), Part 91, §91.111, §91.113, and §91.181). In the absence of an onboard pilot, a UAS is required to be equipped with a system to provide the UAS pilot a means of compliance with these rules.

The FAA-sponsored Sense-and-Avoid (SAA) Workshop[1] defined a SAA system as "the capability of a UAS to remain well clear from and avoid collisions with other airborne traffic." To fulfill the regulatory requirement to "see and avoid," a SAA system is comprised of a Detect-and-Avoid (DAA) system and a Collision Avoidance (CA) system to provide two critical services for UAS to maintain appropriate separation from other aircraft: 1) keep the aircraft "well clear" of other traffic and 2) avoid near-midair collisions (NMAC) with other aircraft within a relatively short time horizon. RTCA SC-228 defines DAA as a system function that enables the unmanned aircraft to maneuver within a sufficient timeframe to remain well clear of other airborne traffic.

There are three main sub-functions of a DAA system that may significantly affect its performance. They are: 1) the surveillance function to detect and track intruder aircraft; 2) the threat alerting function to evaluate the tracks and declare that action is needed to prevent a threat aircraft from causing a well-clear violation; and 3) the guidance function to aid the UAS pilot in determining a maneuver to resolve a predicted well-clear violation. The DAA surveillance system provides a means for the UAS pilot to electronically "see" (detect and track) both cooperative (i.e., transponder-equipped) and non-cooperative aircraft. The DAA alerting and guidance system provides a means: to alert and aid the

UAS pilot in prioritizing potential traffic conflicts (i.e., a loss of well clear) and to assist in deciding upon and performing a well-clear maneuver.

DAA system performance relies on a combination of surveillance sensors to collect data on the state of intruder aircraft and a set of algorithms that trigger an alert for the UAS pilot at the ground control station and support the pilot in determining an appropriate guidance maneuver to avoid a loss of well clear. Therefore, the ability of a DAA system to mitigate a risk of losing well clear with other intruder aircraft depends upon important independent factors such as DAA look-ahead time (which is limited by surveillance range), the definition of "well clear," trajectory prediction methods, and DAA alerting thresholds. Tradeoffs between the DAA system design parameters and performance metrics should be investigated to develop MOPS for UAS DAA systems. For example, it will be important to explore which of the alert declaration times are excessive and lead to nuisance alerts and which of the alert declaration times are short and provide insufficient time for pilots to coordinate maneuvers with air traffic controllers (ATC) and execute the maneuvers. In a previous study,[12] the encounter characteristics and time to well-clear violation at which aircraft are detected were investigated with a set of different surveillance volumes in order to identify minimum surveillance sensor requirements for detecting a given percentage of intruding aircraft. However, the effects of DAA system parameters such as alerting thresholds and pilot response delay on the overall performance and effectiveness of DAA systems were not investigated.

Air traffic controllers do not have primary responsibility for separation between aircraft flying under IFR and aircraft flying under VFR in Class E and transition airspace; ATC simply provides traffic advisory and safety alert services to the aircraft on a workload permitting basis. Therefore, UAS flying under IFR should be able and equipped to initiate a maneuver to remain well clear of proximate VFR aircraft. As specified by current regulations that apply to manned aircraft, UAS pilots may still request trajectory changes to remain well clear from other aircraft.[9] Such requests do not require a legal loss of separation (e.g., 5nmi horizontally and 1000ft vertically in enroute airspace) to have occurred. They only depend on the definition of well clear or the existence of pilot-identified situations like severe weather encounters or emergencies. The following section describes a proposed quantitative definition of well clear by RTCA SC-228 and important parameters that may affect the performance of DAA systems.

A. UAS Well-Clear Definition

The definition of UAS well clear in this section is used to support DAA performance evaluation. In order to develop DAA alerting and guidance systems to predict potential violations of well clear and perform maneuvers to remain well clear of other aircraft, the term "well clear" needs to be defined quantitatively (unambiguous and implementable definition) to provide a means to evaluate system performance objectively.

"Well clear" is defined as a state and trajectory relative to another aircraft that would not normally cause the pilot of either aircraft to initiate a collision avoidance (CA) maneuver.[1] Therefore, remaining well clear refers to maintaining airborne separation minima as like distance-based ATC separation standards. Performing DAA functions correctly means remaining an appropriate distance and/or time from other aircraft by maintaining the well clear separation criteria. Failing to do so is called a *loss of well clear* (LoWC). The well clear separation criteria depends upon many factors, including the relative encounter geometry between aircraft and the performance characteristics of each aircraft. Therefore, it is necessary to define an explicit and quantitative definition of well clear so that a UAS will be able to detect and avoid other aircraft within a sufficient timeframe to remain well clear from intruder aircraft.

At the recent Sense-and-Avoid Science and Research Panel (SARP) workshop, several definitions of "well clear" were investigated. The effects of different well-clear definitions on UAS detect-and-avoid system operations were investigated in a previous study.[13] In the present study, a definition of well clear recommended by RTCA SC-228 is used. It was proposed based on the unmitigated risk of collision after crossing of the well-clear separation boundary from a set of random encounters between VFR aircraft under 18,000 ft.[9] "Modified tau," as defined in Eq. (1), is used, similar to the TCAS II alerting definition, in order to assure adequate separation because the previous parameter (i.e., range tau) did not give sufficient alerting time to avoid a LoWC, or even an NMAC, when the intruder performed a sudden acceleration that increased the closure rate (e.g., a turn).[14,15] To provide protection in encounters with very slow rates of closure, a new parameter, "distance modification" (DMOD), was added to the traditional range tau to provide a minimum range at which to alert regardless of the calculated value of range tau.

$$\tau_{\text{mod}} = -\frac{(r_{xy}^2 - DMOD^2)}{r_{xy}\dot{r}_{xy}} \quad for\ r_{xy} \geq DMOD$$

$$= \quad 0 \quad for\ r_{xy} < DMOD \tag{1}$$

where r_{xy} = horizontal range and $\dot{r}_{xy}$ = horizontal range rate.

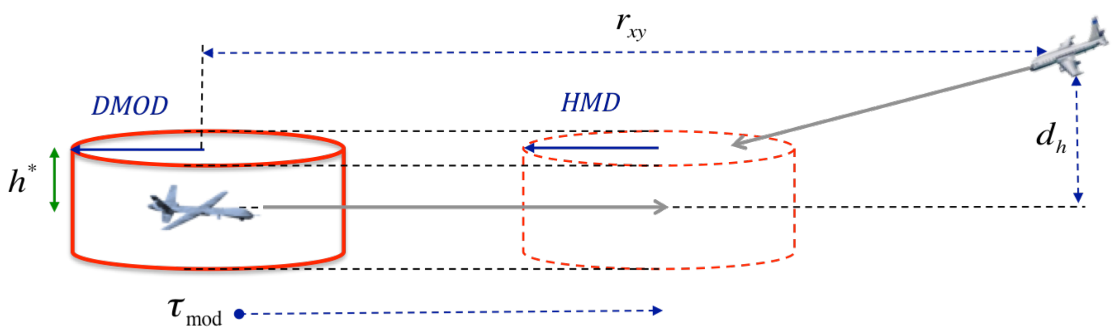


Figure 1. Schematic of well-clear definition.

A loss of well clear generally occurs when two aircraft are projected to be within a certain horizontal and vertical distance from each other and the time to this event is less than a particular time threshold. To calculate the predicted horizontal range at the time of closest point of approach (i.e., horizontal miss distance), dead reckoning is used to predict the intruder aircraft's future positions. The following proposed definition of well clear is taken from a recent RTCA SC-228 workshop. Eq. (2) shows a horizontal criterion and a vertical criterion. Both criteria must be satisfied for an encounter to be considered a well-clear violation. SC-228 established the thresholds for well clear as given in Table 1.[16] A loss of UAS Well Clear occurs when

$$[0 \leq \tau_{\text{mod}} \leq \tau^*_{\text{mod}}\ and\ HMD \leq HMD^*]\ and\ [-h^* \leq d_h \leq h^*] \tag{2}$$

where

τ_{mod} = Modified Tau (sec)
τ^*_{mod} = Modified Tau Threshold(sec)
HMD = $Horizontal\ Miss\ Distance\ at\ Closest\ Point\ of\ Approach\ (CPA)$
HMD^* = $Horizontal\ Miss\ Distance\ Threshold$
d_h = $Current\ vertical\ separation\ between\ two\ aircraft\ (ft)$
h^* = $Vertical\ Separation\ Threshold$

Table 1. Parameters and threshold values for defining UAS Well Clear.

Parameter	τ^*_{mod} *(sec)*	*DMOD (ft)*	*HMD* (ft)*	h^* *(ft)*
Value	35 sec	4000 ft	4000 ft	450 ft

B. DAA Trajectory Prediction Method

The DAA track prediction function takes the current state data for the ownship and track data for all intruders at a common time of applicability and extrapolates the states and tracks into the future. For ownship and intruder track prediction, the well-known dead-reckoning (DR) based prediction method or the flight-plan (FP) based prediction method can be used. In the DR prediction method, each trajectory prediction is extrapolated from an aircraft's current position assuming constant horizontal and vertical velocities based upon the current estimated aircraft state. In the FP-based prediction method, each trajectory prediction is developed from the aircraft's flight plan (intent) information, rather than extrapolating the aircraft's state information. In this study, the intruder trajectory is generated based on the DR prediction method because the intruder's flight plan information is not typically available to ownship aircraft. However, both DR and FP trajectory prediction methods for ownship are investigated to assess the impact of trajectory prediction methods on the DAA alerting performance metrics. It is hypothesized that the trajectory uncertainty stemming from the lack of intent information for VFR intruder aircraft (i.e., DR trajectory prediction) will lead to more frequent false/nuisance alerts. Conversely, it is hypothesized that the FP-based prediction method will lead to fewer nuisance alerts for intruders along the ownship's trajectory prior to a planned turn and will lead to longer alert lead times for intruders that are *not* on the ownship's current trajectory but *are* projected to encounter its planned trajectory.

C. DAA Alerting Thresholds

A DAA alerting system must alert traffic to the UAS pilot that is projected to cross the UAS well-clear volume defined in the previous section within a specified time threshold. In order to give an alert on a predicted loss of well clear with an intruder aircraft to the UAS pilot within a sufficient timeframe, alerting parameters and threshold values for each parameter should be defined and investigated. The DAA alerting thresholds define those conditions at which the alerting system declares that an action is needed to preclude a threat aircraft from causing a loss of well clear. At the point at which the system issues an alert, the pilot must focus his/her attention on the potential threat aircraft to see if an action is necessary. If an action is necessary, the pilot must determine a maneuver based on his/her judgment with the support of the DAA guidance system and start coordinating with ATC. After a response delay from a DAA alert, the pilot will likely determine a maneuver and command a resolution maneuver to the unmanned aircraft. Therefore, the DAA alerting threshold should be provided with sufficient time for the pilot to assess the situation, determine a maneuver, and coordinate a maneuver with ATC.

In a DAA system, the surveillance system component processes the data received from the sensors and generates tracks for each detected intruder aircraft. After processing track information, the DAA alerting function produces and evaluates the future trajectory of each detected intruder aircraft to predict whether there will be a loss of well clear on the generated future trajectories of ownship and intruder aircraft and how long it will take to reach the point at which a loss of well clear is predicted.

Each DAA alert involves a specified alerting threshold. The DAA thresholds can be considered as an alerting zone, which can be defined with time- and distance-based criteria like the definition of well clear. Therefore, one of the important alerting parameters is the time at which the alerting system should issue an alert. The alert must be presented before the intruder aircraft penetrates the LoWC boundary specified in the previous section. In this study, the Estimated Time to LoWC (ETL) is defined as a time-based DAA alerting parameter. The ETL depends on the size of the LoWC boundary defined by variable time-based (τ_{mod}) and distance-based parameters (*DMOD*, *HMD*, d_h) since it calculates the time to LoWC. The distance-based parameters are also important in defining alerting criteria. In the following, it is assumed that *HMD** = *DMOD* in all cases because if the *HMD* threshold is different from *DMOD*, then alerts may oscillate on and off with an un-accelerating ownship and intruder, which is an undesired behavior.

The DAA alert is issued when an intruder is predicted to be within the following alert threshold at any point in time within a specified alerting time threshold (ETL^*). The threshold values of the alerting parameters define the triggering criteria for initiating DAA alerts, and these alerting thresholds are used to define the trade space for when alerts are and are not to be generated. The definition of the alerting thresholds and the variable parameters (τ^*_{mod}, $DMOD$, HMD^*, and h^*) are specified in Eq (3).

$$[0 \leq \tau_{mod} \leq \tau^*_{mod}]\ .and.\ [HMD \leq HMD^*]\ .and.\ [-h^* \leq d_h \leq h^*] \text{ at } t_f \quad (3)$$

where t_f is a future point in time within ETL^*.

All three conditions must be true at the same point in the trajectory prediction, and the alerting time threshold (i.e., ETL^*) must also be true to declare an alert. For example, if the intruder and ownship are predicted to be within the spatial and temporal volume of well clear (specified in Eq (2) for UAS Well-Clear definition: τ^*_{mod} = 35 sec, $DMOD$ = 4000 ft, HMD^* = 4000 ft, and h^*=450 ft) within the *next 55 seconds*, a DAA alert will be issued. By varying these alerting parameters, the size of the alerting zone can be adjusted to meet the performance and safety requirements for DAA alerting and guidance systems.

Figure 2 shows a schematic of DAA alerting logic. The intruder trajectory is generated based on a dead-reckoning prediction method, and the ownship trajectory is generated using either a DR-based prediction method or a FP-based prediction method, depending on the availability of the ownship's flight plan. The intruder trajectory is compared with the trajectory of the unmanned ownship aircraft to evaluate if there is a potential LoWC at each future time step in a pair-wise comparison manner. A DAA alert is issued if a LoWC is predicted to occur within the specified alerting time threshold. However, due to the inherent uncertainty of the intended flight trajectory of the intruder, the predicted LoWC may or may not occur in the future, even without a conflict resolution maneuver.

The performance of a DAA system will be dependent upon how DAA alerting time and distance thresholds are defined. In general, using large DAA threshold values to avoid a well-clear violation with sufficient time might cause a large number of nuisance alerts, resulting in a large number of unnecessary maneuvers of unmanned aircraft and corresponding disruptions to ATC to coordinate the resolution maneuvers. On the other hand, small DAA alerting threshold values might reduce nuisance alerts but might not be sufficient to avoid LoWC. Due to the uncertainty inherent in the trajectory intent information of intruder aircraft, the DMOD, HMD^*, and h^* values play an important role in the safety and performance of DAA systems. While the minimum alerting thresholds could also differ based on sensor or aircraft performance, this study focuses on DAA alerting distance and time thresholds.

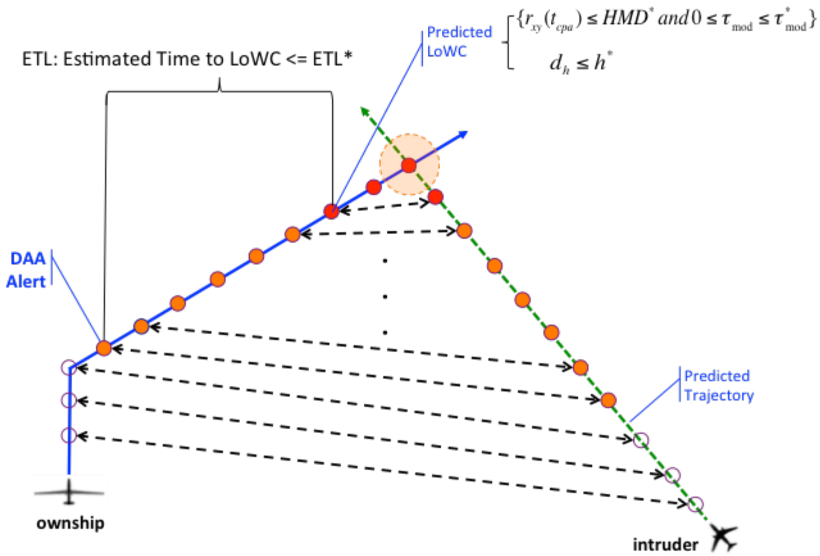


Figure 2. Schematic of DAA alerting thresholds.

RTCA SC-228 is currently defining two different types of DAA alerts (i.e., corrective alert and warning alert) based on the estimated time to LoWC and evaluating candidate DAA alerting threshold values as shown in Table 2.

Table 2. DAA Alert Summary.

		Corrective Alert	Warning Alert
Alert Level		Caution	Warning
Must Alert Threshold	Within Time	55 sec	25 sec
	τ^*_{mod}	35 sec	35 sec
	DMOD and HMD*	0.66 nm	0.66 nm
	h*	450 ft	450 ft
Must Not Alert Threshold	More than time	75 sec	35 sec
	τ^*_{mod}	35 sec	35 sec
	DMOD and HMD*	1.5 nm	1.5 nm
	h*	450 ft	450 ft

The DAA *corrective alert* is intended to be provided in sufficient time for the UAS pilot to assess the situation and determine an appropriate action, to start coordination with ATC, and to command/execute a maneuver to remain well clear from threat aircraft. The point at which a corrective alert occurs defines the DAA threshold. On the other hand, the DAA *warning alert* is intended to inform the pilot that immediate action is required to remain well clear. The warning alert necessitates immediate pilot awareness and a prompt ownship maneuver. The DAA corrective alert and warning alert will be triggered based on the threshold values in Table 2. The time threshold values specified in the SC-228 draft MOPS are based on the minimum time for a pilot to respond to an alert (approximately 15 sec), coordinate with ATC (approximately 10 sec), and maneuver to remain well clear (approximately 30 sec). If the "Must Not Alert" criteria are met, the DAA alerting system must not issue any alert to the pilot. In this study, a set of alerting threshold values were selected between the “Must Alert” and “Must Not Alert” threshold values to conduct trade-off and sensitivity analysis of these threshold values on the performance metrics proposed in the next section, Section IV.

IV. Performance Metrics and Trade-off Analysis Method

The overall performance of a DAA alerting and guidance system can be assessed in terms of its ability to predict/declare threat aircraft accurately within a sufficient timeframe for UAS pilot to respond, coordinate with ATC, and initiate a maneuver to successfully avoid projected LoWC. This section outlines the classification of DAA alerts and presents a list of metrics to evaluate the performance of DAA alerting and guidance systems.

A. Categorization of DAA Alerts

DAA alerting performance can be considered as a two-class prediction problem (binary classification) in which the outcomes are either positive (i.e., it is predicted that there will be a loss of well clear within a specified look-ahead time) or negative (i.e., it is predicted that there will be no loss of well clear within the look-ahead time). The four outcomes can be formulated in a 2x2 confusion matrix as in Table 3. Therefore, a DAA alert in this study can be classified into four possible alerts: true positive, false negative, false positive, and true negative. A true positive (referred to as a *true alert* in this study) occurs when the alerting system correctly predicts that, without intervention by the pilot and/or controller) there will be a LoWC within a look-ahead time. A false negative (referred to as a *missed alert* in this study) occurs when the alerting system predicts that there will not be a LoWC, when in reality, without mitigation by the pilot/controller, a LoWC will occur. A false positive (referred to as a *false* or *nuisance alert* in this study) occurs when the alerting system incorrectly predicts that there will be a LoWC. A true negative (referred to as a *correct rejection* in this study) occurs when the alerting system correctly predicts that there will not be a LoWC. Depending on the estimated time to LoWC at the time of a DAA alert, a level of “alert urgency”— on time or *delayed* —is assigned to further categorize the alerting results.

Table 3. DAA alert confusion matrix.

		Unmitigated True Condition		
		LoWC exists (Positive)	**No LoWC exists (Negative)**	
DAA System Prediction Response	**LoWC will occur: Alert (Positive)**	True Positive (TP)	False Positive (FP)	Total Number of Alerts (TP + FP)
	LoWC will not occurs: No Alert (Negative)	False Negative (FN)	True Negative (TN)	Total Number of No Alert Events (TN+FN)
		Total Number of Positive LoWC Events (TP+FN)	Total Number of Negative LoWC Events (FP+TN)	Total Number of Intruding Events (TP+FP+FN+TN)

B. Performance Metrics for DAA Alerting and Guidance Systems

This section lists and describes the performance metrics used to evaluate DAA alerting and guidance systems in this study. The effects of independent factors (e.g., different alerting thresholds) on the safety (in terms of number of LoWC) and performance metrics of a DAA system are evaluated, as shown in Tables 4 and 5.

It is important to alert the UAS pilot to any potential LoWC early enough that s/he can successfully avoid losing well clear. For example, even a true positive alert is not useful if it is presented with insufficient time to avoid LoWC. Therefore, when measuring the performance of DAA alerting and avoidance systems, it is necessary to consider whether or not a maneuver is executed prior to a predicted LoWC, and the predicted LoWC is successfully avoided.

Operational metrics such as the alert rate are used to measure how disruptive the system is to normal operations. Additional metrics such as the proportion of delayed alerts and the proportion of maneuvers triggered by false alerts are also proposed and measured to evaluate the performance of DAA alerting and guidance systems in this study.

Table 4. Performance metrics for DAA alerting systems.

Performance Metrics	Description
P(True positive alerts | All issued alerts)	Proportion of true positive alerts to all alerts (Positive Predictive Value) = $\frac{TP}{TP+FP}$
P(False positive alerts | All issued alerts)	Proportion of false positive alerts to all alerts (False Discovery Rate) = $\frac{FP}{TP+FP}$
P(Alert was issued | LoWC exists)	Proportion of true positive alerts to all positive condition cases (True Positive Rate) = $\frac{TP}{TP+FN}$
P(Alert was issued | No LoWC exists)	Proportion of false positive alerts to all negative condition cases (False Positive Rate) = $\frac{FP}{FP+TN}$
P(No alert was issued | LoWC exists)	Proportion of false negative alerts to all positive condition cases (Missed Alert Rate) = $\frac{FN}{TP+FN}$
Alert lead time until LoWC	Average time until LoWC at which a DAA alert is first issued (specifically for true positive alerts)

Table 5. Performance metrics for DAA guidance systems.

Performance Metrics	Sub-Metrics	Description
DAA Success Rate = P(No LoWC occurs | Alert was issued)		Proportion of alerts that eventually resulted in no LoWC among all alerts (with/without a maneuver) = $\frac{Number\ of\ cases\ that\ resulted\ in\ no\ LoWC}{Total\ number\ of\ alerts}$
	Resolution Maneuver Success Rate = P(Successful Resolution | Resolution was issued)	Proportion of resolutions that avoided LoWC among all commanded resolutions = $\frac{Number\ of\ successful\ resolutions\ that\ avoided\ LoWC}{Total\ number\ of\ commanded\ resolutions}$
DAA Failure Rate = P(LoWC occurs | Alert was issued)		Proportion of alerts that eventually failed to avoid LoWC among all alerts (with/without a maneuver) = $\frac{Number\ of\ cases\ that\ resulted\ in\ LoWC}{Total\ number\ of\ alerts}$
	Resolution Maneuver Failure Rate = P(Failed Resolution | Resolution was issued)	Proportion of resolutions that failed to avoid LoWC among all commanded resolutions = $\frac{Number\ of\ resolutions\ that\ failed\ to\ avoid\ LoWC}{Total\ number\ of\ commanded\ resolutions}$
Missed Resolution Rate = P(No resolution was executed | Alert was issued)		Proportion of alerts that a resolution maneuver was not commanded among all alerts issued (due to pilot response time or no resolution found given situation or false alert) = $\frac{Number\ of\ cases\ where\ resolution\ was\ not\ executed}{Total\ number\ of\ alerts}$
Unnecessary Resolution Rate = P(Unnecessary maneuvers | All issued resolutions)		Proportion of unnecessary resolutions due to false positive alerts among all issued resolutions = $\frac{Number\ of\ resolutions\ triggered\ by\ false\ positive\ alerts}{Total\ number\ of\ commanded\ resolutions}$
Time until actual LoWC at resolution execution times		Average time until actual LoWC at the time of resolution execution after pilot response delay
P(Induced LoWC | All Actual LoWC)		Proportion of LoWC induced by false alert-triggered resolutions among total number of actual LoWC = $\frac{Number\ of\ LoWC\ induced\ by\ false\ positive\ alerts}{Total\ number\ of\ actual\ LoWC}$

C. Analysis of Trade-off Between Alerting Threshold Parameters

Alerting thresholds define the size of the alerting zone and thus affect the performance of DAA alerting systems. For example, if the alerting zone is too large, alerts will be issued much earlier before LoWC and an excessive number of unnecessary alerts may be generated. On the other hand, if the alerting zone is too small, there may not be sufficient space or time for the UAS pilot to determine and command a maneuver to avoid the predicted LoWC. It is not trivial to measure the sensitivity between alerting system parameters in a systematic way.

This study uses a concept of Signal Detection Theory (SDT) traditionally used for signal detection problems and diagnostic decision-making problems in the presence of uncertainty.[17] The SDT concept has also been used to evaluate alerting thresholds for TCAS systems to balance the need for timely detection, a very low rate of false negative alerts (missed alerts), and reduction of false positive alerts (false/nuisance alerts).[18] The performance trade-off for alerting or diagnostic systems can be visualized and measured using a Receiver Operating Characteristic (ROC)[19] or System Operating Characteristic (SOC) curve, which is a plot of the True Positive Rate (TPR) against the False Positive Rate (FPR) for each alerting threshold setting as shown in Fig.3.

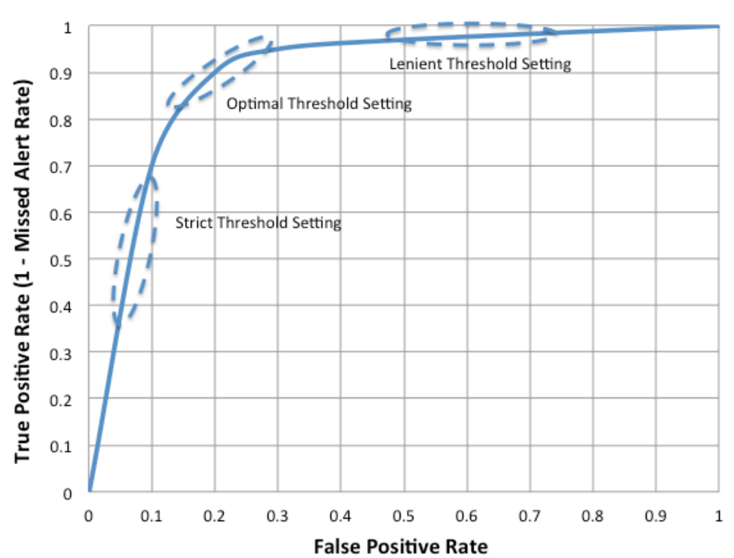


Figure 3. Schematic of Receiver Operating Characteristic (ROC) curve.

If the alerting thresholds are set to be strict, then the FPR can be reduced, but the TPR will decrease as well. Conversely, if the alerting threshold is set too lenient (or conservative), then the TPR can be increased, but the false-positive rate will increase as well. Therefore, the typical optimal alerting threshold setting will be at the upper left corner of the ROC curve, achieving a low FPR and a high TPR. In the aviation application domain of alerting systems, it is common for an allowable missed alert rate (1-TPR) to be set (often on the order of 10^{-3} to 10^{-9}) as a measurement of safety performance standard while verifying that the FPR is not “excessive” given its impact on day-to-day operations as well as its cumulative effects on pilot trust and nonconformance.[20]

This study proposes and utilizes the ROC curve and a measure of weighted harmonic mean of true-positive rate and positive predictive value as a method to objectively measure the performance of DAA alerting systems in an efficient manner. In addition to the proportions of true-positive alerts, false-positive alerts, missed alerts, and late alerts described in this section, several other measures can be derived from those conditional probabilities, such as the accuracy of the detection system and positive predictive value. Such measures can be used to evaluate the effectiveness of different alerting/detection algorithms. This can be examined by combining signal detection theory and Bayesian statistics.[21]

V. Experiment Methodology

A. Simulation Platform

For this study, the Airspace Concept Evaluation System (ACES) fast-time simulation tool developed at NASA was used in evaluating the performance of DAA alerting and guidance system. ACES is a fast-time agent-based simulation tool that has been used to evaluate concepts of operation ranging from applications like traffic flow management and separation management to surface operations over the entire NAS.[22] It provides a capability to simulate NAS-wide, gate-to-gate air traffic operations at local, regional, and national levels with medium-fidelity aircraft flight dynamics models.[23] It simulates flight trajectories using four-degree-of-freedom aircraft models derived from the Base of Aircraft Data (BADA).[24] Currently several UAS models such as Aerosonde Mark 4.7, Shadow RQ-7, Ikhana/Predator B, Reaper MQ-9, and Global Hawk have been implemented and verified in ACES.

ACES also employs a model of a DAA system that provides functions to evaluate potential well-clear violations, to declare the time to take an action, and to initiate a resolution maneuver to avoid predicted LoWC. The model was developed based on the existing separation assurance algorithm for manned aircraft, Autoresolver algorithm,[25] which itself was modeled with controllers' methods of separating aircraft, and was used in this experiment to simulate the UAS pilot's avoidance maneuvers. A simple pilot model was also developed to simulate the response time of UAS pilots in detecting an alert, deciding a resolution maneuver, coordinating the maneuver with ATC, and executing the maneuver (uploading the resolution maneuver to the unmanned aircraft).

B. Traffic Scenarios and UAS Missions

ACES was used to simulate the actual flight tracks of NAS-wide historical VFR traffic and various proposed UAS mission profiles. Results of the simulation were used to investigate the encounter geometries between UAS and VFR traffic in the Class E transition airspace and the performance for DAA alerting and guidance systems. According to Aviation Accident Statistics, the class E airspace is the most critical region where mid-air collisions are most likely to occur between aircraft under VFR condition. Thus, this study is focused on the encounters between UAS and VFR traffic in Class E transition airspace.

Various non-point-to-point mission profiles of UAS in controlled airspace may create different conflict situations (e.g., encounter geometries) between unmanned and manned aircraft.[26] Existing aircraft encounter models do not incorporate these new UAS performance and mission characteristics.[10] Therefore, to evaluate aircraft encounter characteristics for anticipated Class E and transition operations that include UAS and VFR aircraft, it is necessary to model UAS performing different mission profiles with aerodynamic characteristics of these aircraft in NAS-wide simulations.

For this study, UAS flights conducting 18 different types of missions and historical VFR flights flown in Class E transition airspace across the US were included in ACES simulations. The 18 different UAS missions include wildfire monitoring, air quality monitoring, flood inundation and stream monitoring, air taxi transport, cargo delivery, spill monitoring, wildlife monitoring, law enforcement, aerial imaging and mapping, point source emission monitoring, traffic monitoring, maritime patrol, border patrol, airborne pathogen tracking, and weather data collection missions. The demand and mission profiles were proposed and generated by Intelligent Automation, Inc. based on subject-matter experts' opinions and socio-economical analysis.[4]

The traffic scenario used for this simulation was generated using a nation-wide database of VFR flight paths flown on April 4th, 2012. The database was populated from the historical Air Defense 84th Radar Evaluation Squadron (RADES) radar data. The traffic scenario contained cooperative and non-cooperative VFR flights in Class E airspace over a 24-hour period on the chosen day. No IFR manned aircraft were included in the traffic scenario since air traffic controllers have responsibility for separating IFR aircraft from other IFR (including UAS) aircraft. Instead, this study focused on investigating the encounters and interactions between IFR UAS and cooperative/non-cooperative VFR flights.

In the ACES simulation, the actual VFR flight tracks from that day were played back, and UAS were maneuvered to avoid predicted LoWC against the VFR aircraft using the DAA system model. One of the inputs to ACES was a flight demand set consisting of all of the flights to be simulated with their aircraft type, their departure and arrival airports, their departure times and their flight plans. This input traffic data set created realistic encounters between historical VFR traffic and the proposed UAS mission profiles illustrated in Fig. 4.

A DAA system software model, the Java Architecture for DAA Modeling and Extensibility (JADEM),[27] was developed to simulate the components of DAA systems, including the detect, track, evaluate, prioritize, declare, determine, and command functions. A conflict resolution algorithm, Autoresolver-AD (AD stands for "Adapted for DAA systems") was adapted from the Autoresolver algorithm[25] to simulate pilots' "determine" function to avoid losing well clear. This resolution determine function was integrated with a pilot model described in the next section.

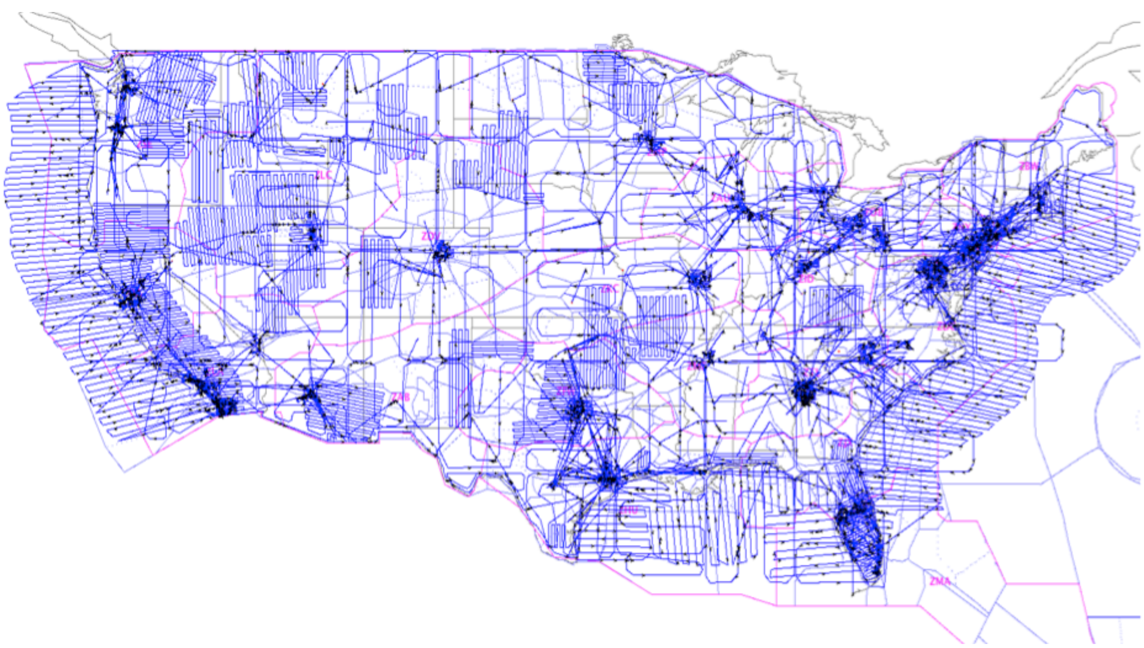


Figure 4. NAS-wide UAS mission profiles (blue lines).

C. Pilot Response Delay Model

The pilot's response time plays a significant role in successfully executing a maneuver to avoid the predicted LoWC before penetrating the well-clear boundary. A simple pilot response model was developed for this study based on human-in-the-loop simulations.[3] Two different types of alerts, corrective alerts and warning alerts, based on the estimated time to LoWC were given to the pilot, and the response time was measured between the time of an alert and the time at which a maneuver was issued to the unmanned aircraft. In the experiment, the pilot response times were classified based on alert urgency into two groups: one for warning alerts that occurred within 25 seconds to LoWC and the other for corrective alerts that occurred between 25 seconds and 75 seconds prior to LoWC. Based on the human-in-the-loop experiments, the mean pilot response times were 12.75 seconds for warning alerts and 20 seconds for corrective alerts, which requires the pilot to coordinate a resolution maneuver with the air traffic controller. Typically, pilots tend to respond quickly when they have little time to LoWC for warning alerts, and their response times for each alert type fit well into a Gamma distribution as shown in Fig. 5

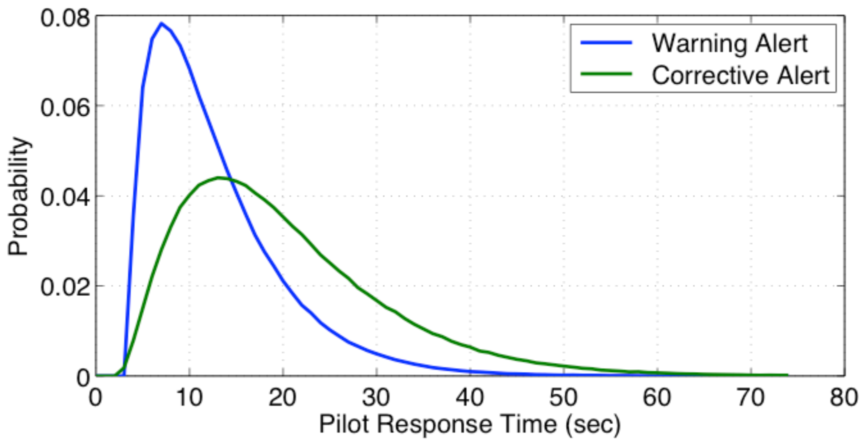


Figure 5. Distribution of pilot response time for each alert type.

In fast-time simulation, a pilot response time is generated for a valid alert based on the predicted time to LoWC to investigate the effect of pilot response delay on how successfully a maneuver can be executed before LoWC occurs and how well predicted loss of well clear can be avoided as a function of different alerting thresholds. In this study, if the estimated time to LoWC upon an alert is longer than 25 sec (i.e., corrective alerts), a pilot response time is sampled from the Gamma distribution with the following parameters: shape = 3.61694, scale = 5.56326. If the estimated time to LoWC is less 25 sec (i.e., warning alerts), a pilot response time is sampled from the Gamma distribution with the following parameters: shape = 3.80955, scale = 3.34685.

D. Experiment Design

The RTCA SC-228 working group suggests that surveillance systems of UAS include an onboard radar specifically to detect non-cooperative intruder aircraft, an active transponder (e.g., Mode A/C or Mode S) to detect transponder equipped cooperative aircraft, and an Automatic Dependent Surveillance-Broadcast (ADS-B) "In" system to receive flight information broadcasts transmitted by aircraft with ADS-B "Out" capability. (ADS-B "Out" will be mandated by 2020 for aircraft flying in certain controlled airspace, including Class A, B, C, around busy airports and above 10,000 feet.) Table 6 shows the values for surveillance sensor system parameters that were used in this study. It is assumed that there is no uncertainty in the state information of intruders detected within a given surveillance volume as a baseline.

Table 6. Parameter values for DAA surveillance sensor system.

Surveillance System Parameters	Onboard Radar	Active Mode A/C or Mode S Transponder	ADS-B Out and In System
Detection Range	8 nmi	14 nmi	20 nmi
Horizontal Field of Regard	±110°	±180°	±180°
Vertical Field of Regard	±15°	±90°	±90°

To begin, the performance of DAA systems as a function of DAA alerting time threshold (i.e., ETL^*) was investigated with perfect generic sensor models, meaning there was no error in the state information of intruder aircraft. The appropriate (or required) settings of ETL will also depend on the detection range of the surveillance sensor systems and pilot's response times.

As shown in Table 7, the reasonable candidates for ETL threshold value (55 sec, 66 sec, and 75 sec) and distance threshold value were selected from the recommended values by RTCA SC-228 as shown in Table 2, and the results of a human-in-the-loop experiment conducted at NASA to evaluate candidate DAA displays and algorithms. Due to inherent uncertainty of intruder flight intent information, the prediction performance of LoWC along the trajectory is affected by the distance-based alerting threshold setting, such as *DMOD*, *HMD**, and h^*. In this study, three different threshold values for *HMD** and *DMOD* (in this study, *HMD* = DMOD)* were chosen, and the vertical separation threshold (h^*) was fixed at the value specified in the definition of well clear in Table 1.

Table 7. DAA alerting system parameters and their threshold values.

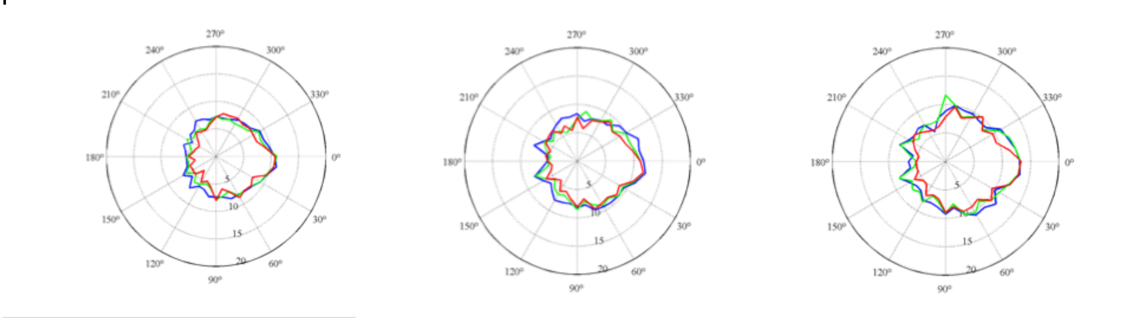
DAA Alerting System Parameters	Threshold Values
Time Threshold: Estimated Time to LoWC (ETL^*)	55, 65, and 75sec
Distance Threshold: Horizontal Miss Distance (HMD^*) (=DMOD)	0.66 nmi, 1 nmi, and 1.5 nmi

VI. Results and Discussion

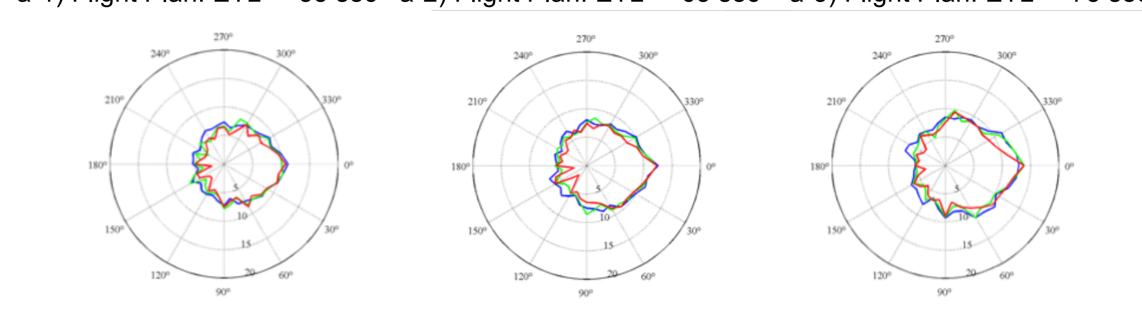
This section presents the results of the fast-time simulation experiments just described. Three key analyses are presented in order to understand the relationship between DAA alerting and guidance system parameters and the associated performance metrics. The first analysis investigates the encounter geometries observed at the time when the DAA system first alerts a potential LoWC condition. The second analysis categorizes the DAA alerts according to the taxonomy presented in Tables 3 and assesses the alerting and guidance performance metrics presented in Table 4 and 5. The third analysis evaluates the utility of the DAA guidance in terms of its timeliness and effectiveness in avoiding LoWC incidents.

A. Analysis of Encounter Geometry at Alerting Times

The goal of this analysis is to understand the encounter characteristics, in terms of relative range and bearing angle to the intruder, that unmanned aircraft are likely to have with cooperative and non-cooperative VFR aircraft in Class E airspace when DAA alerts are first issued. A surveillance system is required to have sufficient detection range and field of regard such that the DAA system has enough look-ahead time prior to LoWC to predict and avoid LoWC.



a-1) Flight Plan: ETL* = 55 sec a-2) Flight Plan: ETL* = 65 sec a-3) Flight Plan: ETL* = 75 sec



b-1) DR: ETL* = 55 sec b-2) DR: ETL* = 65 sec b-3) DR: ETL* = 75 sec

Figure 6. Relative range and bearing angle for all alerts with different DAA threshold settings and trajectory prediction methods: a) Flight Plan prediction, b) Dead Reckoning prediction; Red: 0.66 nmi, Green: 1.0 nmi, Blue: 1.5 nmi.

Figure 6 depicts the encounter geometries observed in terms of relative range and bearing angle to the intruders at the time when each DAA alert was first issued. The plots reflect three different DAA alerting threshold settings. With the maximum alerting time threshold tested, 75 sec to predicted LoWC, 99% of all alerts for the threats were issued within 15 nmi of range. With the 55 sec of alerting time threshold setting, the relative horizontal range of threats at the time of first DAA alerts was shorter (more than 95 % of alerts were occurred within 10 nmi) regardless of distance threshold settings. As expected, the distance to the threats at the time of alerts decreased as the alerting time threshold was decreased. However, the effect of DAA distance threshold settings (HMD* = 0.66 nmi, 1.0 nmi, and 1.5 nmi) on the relative range to the intruders at the time of alert was found to not be significant.

B. Analysis of DAA Alerting Performance

The second analysis explores the distribution of DAA alerting times and performance statistics as a function of DAA distance and time threshold values in order to investigate the effects of different DAA alerting thresholds and the sensitivity of the threshold settings on the performance and safety of DAA systems.

The four numbers in the confusion matrix shown in Table 2 were collected and analyzed. To identify the *unmitigated true condition*, the ownship's flight-plan trajectory without any maneuvers was compared with the intruder's actual flown trajectory. If a LoWC was observed between these two trajectories within a specified look-ahead time (120 sec for this study), then *unmitigated true condition* was set to *True*, otherwise *False*. If an alert is issued and *unmitigated true condition* is true, this is a true positive (TP) case. If alert is issued but *unmitigated true condition* is false, it is a false positive (FP) case. The false negative (FN) and true negative (TN) cases were defined similarly. In this study, all the intruder aircraft detected within the surveillance volume were considered as population (all encounter cases) to calculate the number of TN cases. The TN was calculated by subtracting all other cases (TP+FP+FN) from population.

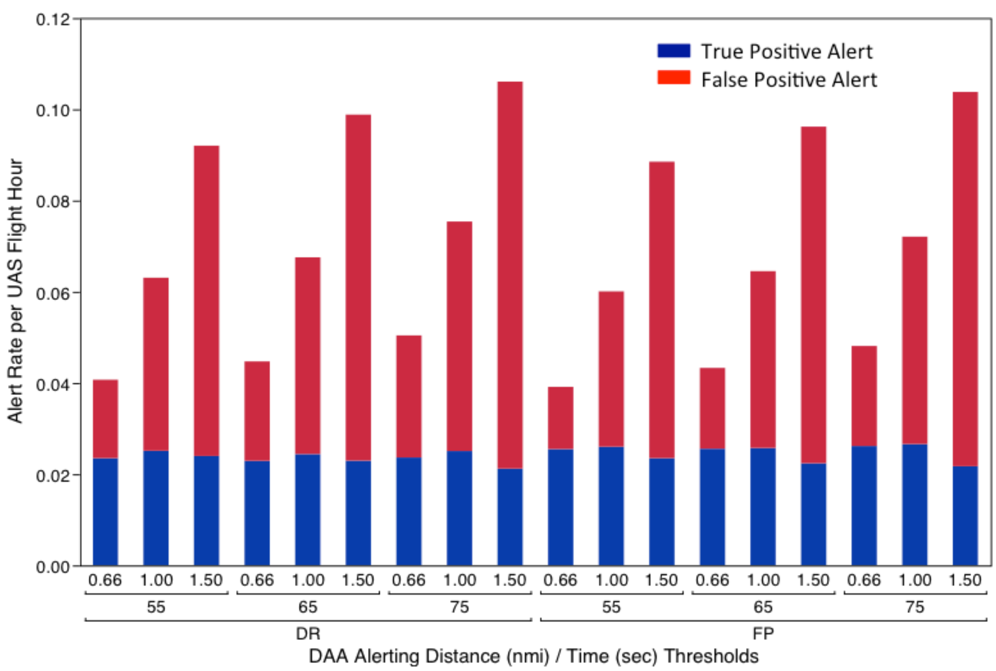


Figure 7. Alert rate per flight hour as a function of different DAA threshold settings.

First, the alert rate per UAS flight hour was analyzed to identify how frequently UAS may disrupt ATC as shown in Fig.7. When the UAS receives a DAA alert, the UAS pilot may initiate coordination with ATC to maneuver to remain well clear from proximate aircraft or the pilot may need to make a maneuver without coordination with ATC if it is an emergency situation. If the pilot is required to coordinate a resolution maneuver with ATC to resolve a predicted LoWC, each DAA alert may cause a disruption to the controller's operations. In the simulation results, DAA alert rate per UAS flight hour was very low; ranging from 0.04 to 0.1 as a function of DAA alerting threshold settings. It means that UAS got one DAA alert every 10 to 25 hours based on the DAA alerting threshold settings. This result implies that the frequency with which UAS pilots may be expected to disrupt ATC to coordinate a maneuver responding to a DAA alert may be acceptably low. The alerting distance threshold has a stronger effect on the alert rate: the alert rate increases sharply as the distance threshold increases. However, it appears that the time threshold and trajectory prediction method have little effect on the alert rate, even though it was expected that the alert rate may decrease if the FP trajectory prediction method is used since it may predict potential LoWC more accurately. Interestingly, the true positive alert rate per UAS flight hour is constant across DAA alerting distance and time threshold settings, while higher rate of false positive alerts were observed for larger distance thresholds. Therefore, it is important to note that there is a negative effect of increasing alerting distance threshold because it creates a much higher rate of false positive alerts with relatively constant rate of true positive alerts.

To examine how the alerting threshold settings affect the alert lead time, DAA alerts were categorized into three different types based on the lead time prior to LoWC at the time of alert: On-time alerts, Warning alerts, and Delayed alerts. On-time alerts were those triggered within 10 seconds after the specified DAA alerting time threshold. Warning alerts were those triggered within 25 seconds prior to LoWC. Delayed alerts were those triggered between 10 seconds after the specified alerting time threshold and before 25 seconds prior to LoWC. Figure 8 shows that increasing the alerting distance threshold correlated with a reduced proportion of warning alerts, which may increase a risk of losing well clear by providing a relatively short period of time to pilots prior to LoWC. The alerting time threshold had relatively little effect on the alerting time; the proportion of delayed alerts was higher, while the proportion of on-time alerts was lower as the alerting time threshold was increased. Therefore, it is important to note that a longer alerting time threshold does not guarantee a longer alert lead time (i.e., longer remaining time to LoWC at the time of alerts) to pilots. On the other hand, the trajectory prediction method did appear to have an effect on the proportion of on-time alerts; the FP-based trajectory prediction method generated more on-time alerts than the DR-based trajectory prediction method.

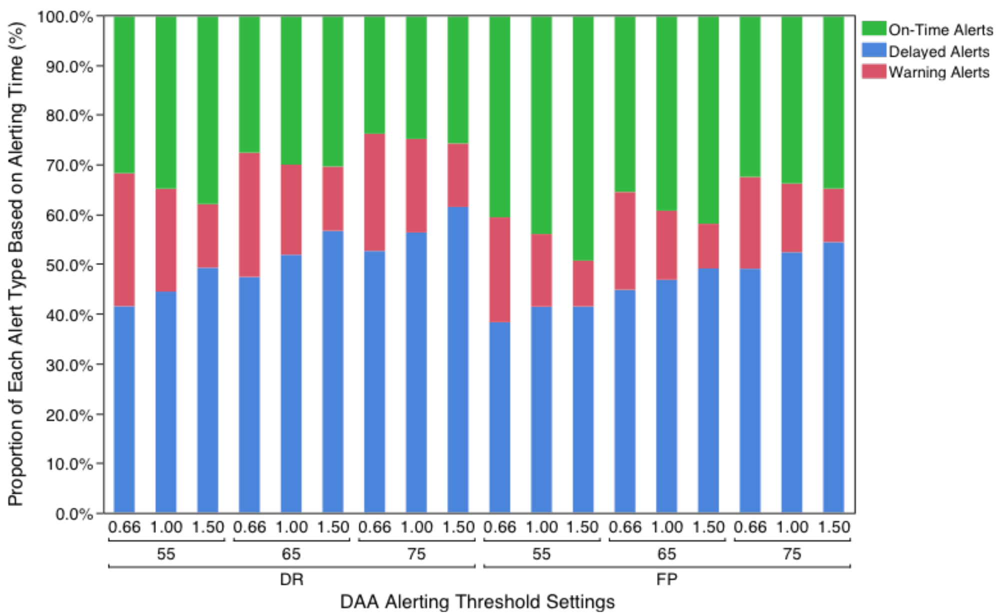


Figure 8. Proportion of each alert type based on alerting time.

Figure 9 shows the proportion of true positive alerts among all alerts as a function of the time threshold (ETL*) and distance threshold (HMD* and DMOD) settings. This probability (i.e., *positive predictive value* as shown in Table 3) represents a *precision* of alerting system in the SDT, which shows how accurately given alerts predict actual LoWC event (i.e., proportion of true positive alerts to all issued alerts). It was found that the distance-based DAA alerting threshold had a significant effect on the precision of the DAA alerting system. For both the FP and DR trajectory prediction methods, the *positive predictive value* decreased significantly from 60% with the distance threshold of 0.66 nmi (no buffer on LoWC boundary) to 20% with the largest distance threshold of 1.5 nmi because the number of false positive alerts increased significantly as the distance threshold increased. Based on this plot, the smaller distance and time thresholds can improve the precision of the alerting system. However, the precision measurement, *positive predictive value*, does not reflect how accurately the alerting system actually detects or misses given true LoWC events. Therefore, the true positive rate or missed alert rate should be also considered to measure the overall performance of the alerting system.

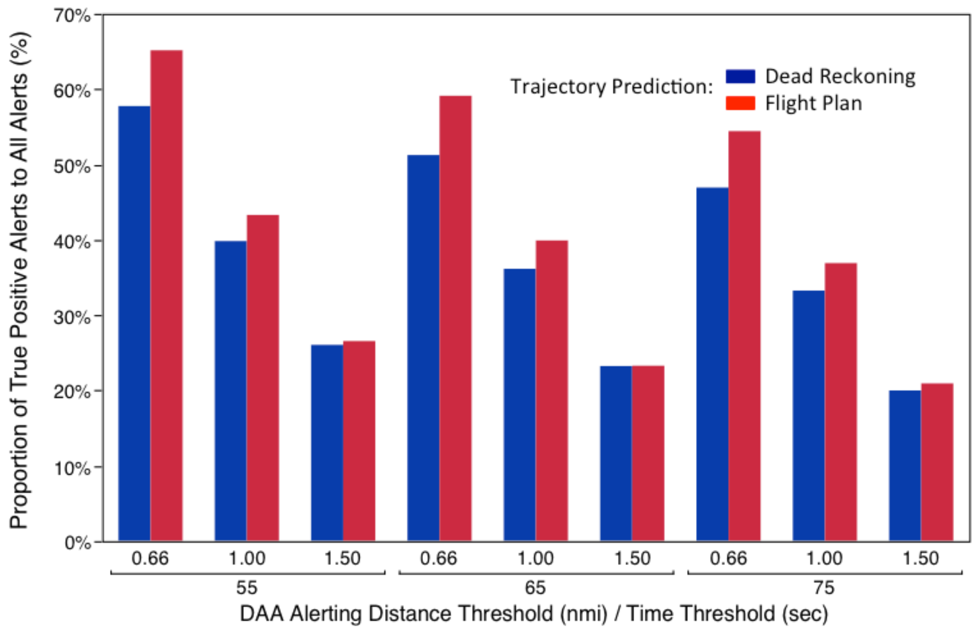


Figure 9. Proportion of true positive alerts to all issued alerts as a function of different DAA threshold settings.

There is also a difference between DR and FP trajectory prediction methods on the precision of the DAA alerting system. The effect of the alerting time threshold on the precision is relatively smaller than that of the alerting distance threshold because the uncertainty of the predicted future trajectory decreases as the time to LoWC at DAA alerts approaches to actual LoWC. If the remaining time to LoWC at DAA alert is short, there is less chance for the threat aircraft to change its flight trajectory. Similarly, as expected, the proportion of false positive alerts to all issued alerts increases as the time to LoWC at alerts gets longer due to greater trajectory prediction uncertainty when a DAA system predicts a potential LoWC further in advance. Thus, if the alerting time threshold is set to a much smaller or larger value, then the effect of the time threshold will be increased.

One of the factors affecting the performance of the alerting system is the alert lead times until actual LoWC at the time of alerts as described in previous sections. Figure 10 shows the average time between the DAA alert and the actual LoWC as a function of DAA alerting threshold settings. The distance threshold settings had a noticeable effect, but the time threshold settings had little effect on the actual time to LoWC. The average lead time to actual LoWC increased by 20 seconds as the distance threshold (HMD* and DMOD) was increased from 0.66 nmi to 1.5 nmi. The FP-based trajectory prediction method provides more alerting lead time (about 7 seconds) than the DR prediction method, although the effect was relatively small.

Figure 11 shows the proportion of false negative (missed alert rate), which represents the cases where an alert was not issued until LoWC occurred. It can be observed that the alerting distance threshold setting had a significant effect on the missed alert rate. The missed alert rate was significantly lower even with 50% increase of the distance threshold value. However, the effect of the distance threshold remains constant even with the larger value of the distance threshold. When there was no buffer on LoWC boundary (HMD* and DMOD = 0.66 nmi), the proportion of missed alerts was significantly less with flight-plan based trajectory prediction, but there was little effect of trajectory prediction method when the alerting distance threshold value was larger than 1.0 nmi.

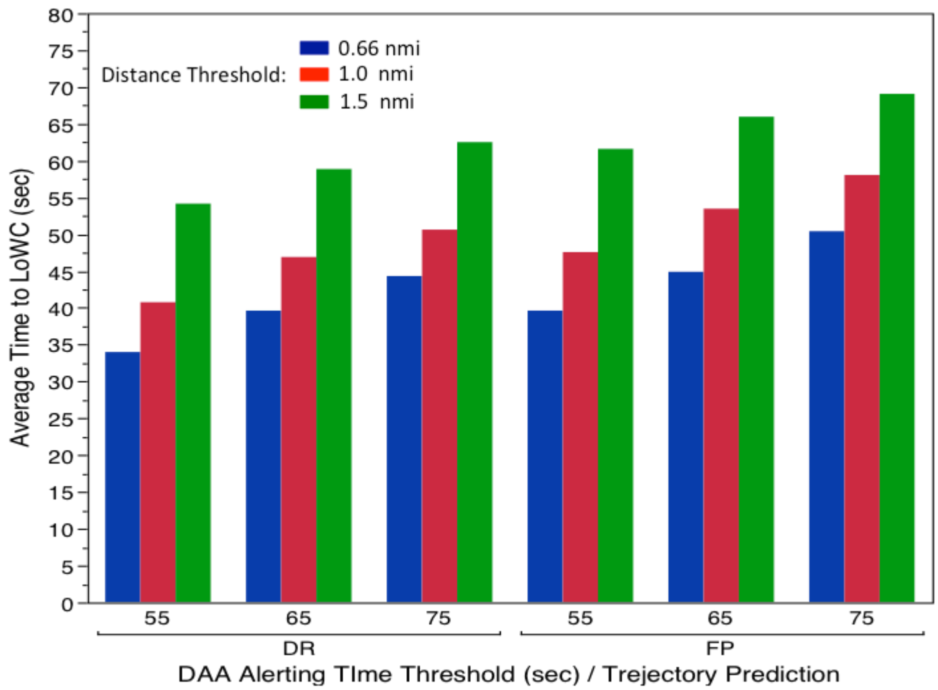


Figure 10. Average time to LoWC as a function of different DAA alerting thresholds (for true positive alerts).

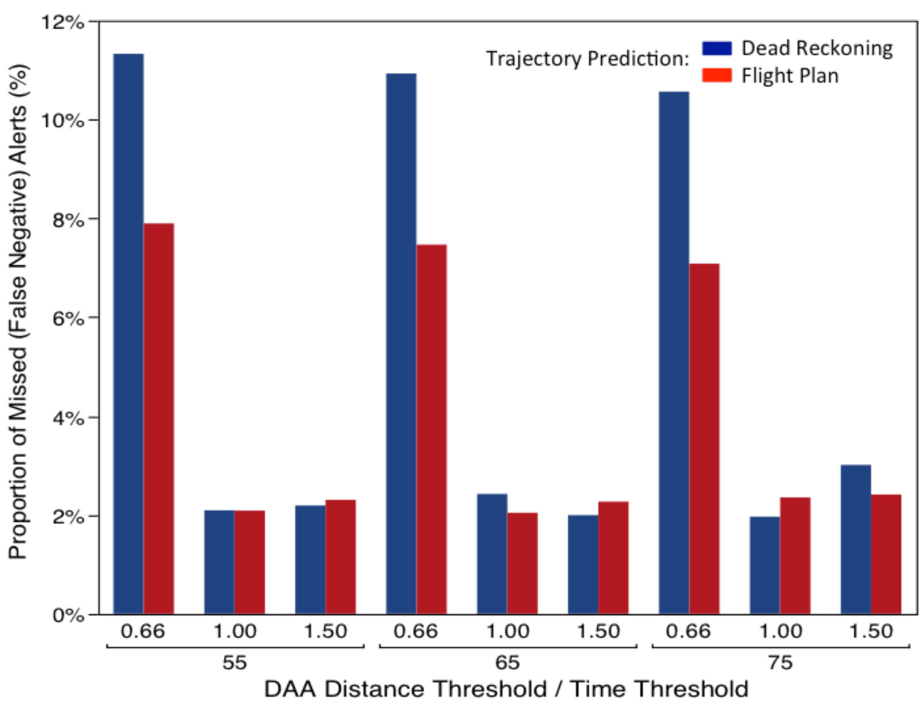


Figure 11. Proportion of false negative alerts to all positive condition cases (i.e., missed alert rate).

The ROC curve was created based on 9 different combinations of alerting threshold parameters for each trajectory prediction method as in Fig.12. All the data points were located in the upper left corner of the ROC curve, which indicates that the alerting system performs promisingly since the TPR is close to 1 and the FPR is close to 0. The different colors represent different alerting distance threshold settings (HMD* = 0.66, 1.0, and 1.5 nmi) and the different shapes indicate different alerting time threshold settings (Predicted time to LoWC = 55, 65, and 75 sec). There were no noteworthy differences between the two prediction methods and between the time thresholds. However, the alerting distance threshold settings had a significant effect on the TPR. When the alerting distance threshold was set to 0.66 nmi, the TPR is below 0.9; however, it went up to 0.98 when the threshold was set to 1.0 nmi (roughly 50% of increase of HMD*), while the FPR was increased by only 0.005. Interestingly, when the alerting distance threshold was increased by more than 100%, the effect became worse than the 50%-increased distance threshold since there was no difference in the TPR, but the FPR was increased. This ROC analysis found that the alerting distance parameters such as HMD* and DMOD is a key parameter that can improve the overall DAA system's alerting performance among the three parameters (trajectory prediction method, alerting distance parameter, and time parameter) investigated in this study. With a slightly conservative threshold of the alerting system, there might be less missed alerts at the expense of increasing false alerts. Among three distance settings (i.e., 0.66, 1.0 and 1.5 nmi), the best value of the threshold was 1.0 nmi providing both lower FPR and higher TPR than other distance threshold setting.

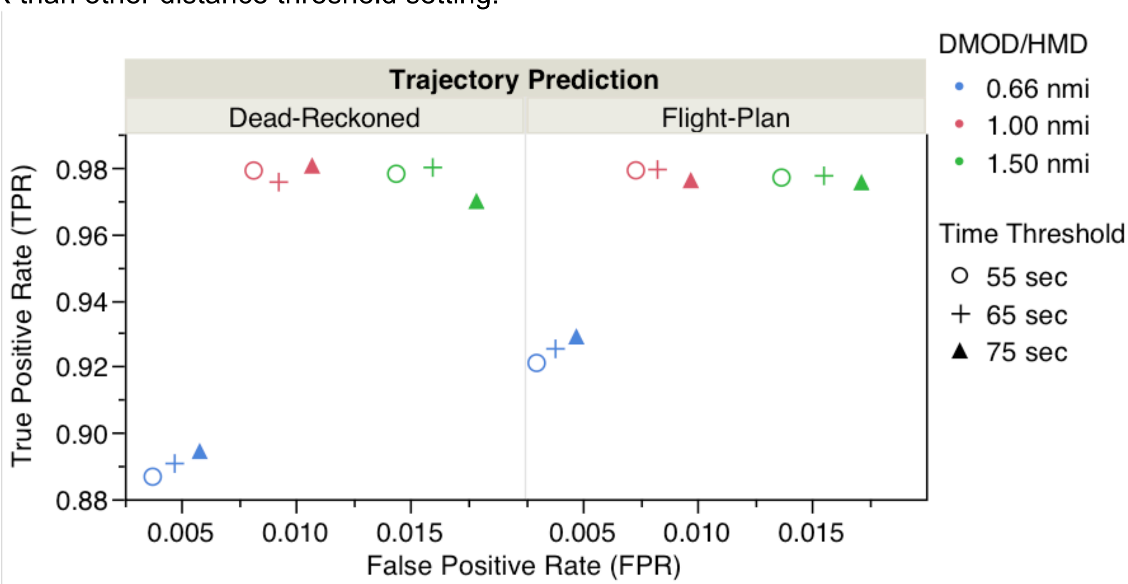


Figure 12. Receiver Operating Characteristic (ROC) plots with different alerting threshold settings.

However, it is important to note that the FPR was extremely low (lower than 0.02) while the TPR was relatively high (higher than 0.85) on every DAA alerting threshold settings. In this study, all pairs of UAS ownship aircraft and intruder VFR aircraft detected by the surveillance volume of ownship aircraft were considered as total number of cases to be evaluated. The total number of pairs that were evaluated for each alerting threshold setting was about 270,000, which means 10 intruders were detected within the surveillance volume on average during the flight of each UAS. It was shown that total number of true positive condition cases was less than 1% of total true negative condition cases since the LoWC occurs extremely rarely as shown in Fig. 7. This means that a large portion of intruder aircraft detected by UAS surveillance volume are not potential threats that may cause a loss of well clear. Therefore, it was difficult to distinguish the performance of alerting thresholds based on very low rate of false alerts.

For those cases where the number of true positive conditions is much smaller than the number of true negative conditions, the better prediction performance could be calculated by removing the effect of true negative cases.[28] One of metrics widely used in this case is F_β Score (also known as F-Measure).[29] This metric is the weighted harmonic mean of true positive rate and positive predictive value, and a higher score represent a better performance. If β is 1, it's the balanced harmonic mean, that is, the true positive rate and positive predictive value have the equal weight. However, generally one has more weight over the other and different weight rates are used for different prediction systems based on its characteristics. For the DAA's alerting system, true positive (true alert) and false negative (missed alert) are much more important than false positive (false/nuisance alert). Therefore, β was set to 5 for the experiments in this study under the assumption that true positive and false negative are at least 5 times more important than false positive. The F_β Score is defined as

$$F_\beta = (1+\beta^2)\cdot\frac{positive\ predictive\ value\cdot true\ positive\ rate}{\beta^2\cdot positive\ predictive\ value\ +\ true\ positive\ rate}$$

$$= \frac{(1+\beta^2)\cdot true\ positive}{(1+\beta^2)\cdot true\ positive\ +\ \beta^2\cdot false\ negative\ +\ false\ positive}, \qquad (5)$$

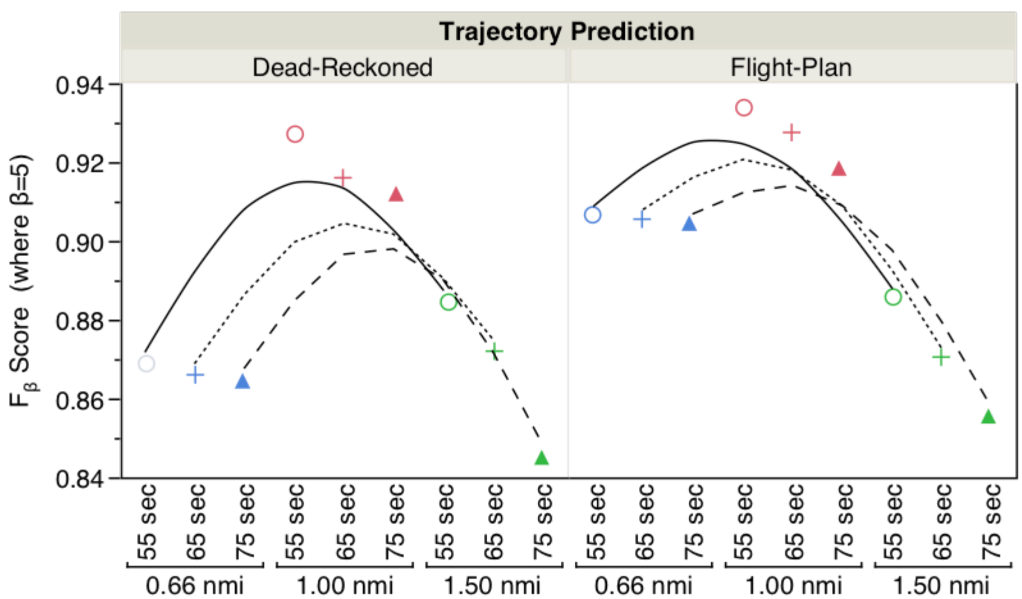


Figure 13. F_β Score analysis: The β value represents the weight on true positive (true alert) and false negative (missed alert) over false positive (false/nuisance alert). Here, β is set to 5, which means that true alert/missed alert has 5 times more weights than false alert to measure the alerting performance.

Figure 13 illustrates the F_β Scores for the 18 different parameter settings. Each curve in Fig. 13 is a cubic spline that smooths the changes in F-Score as the alerting distance threshold increases for each alerting time threshold setting. This figure shows that the alerting distance threshold made significant effects on the scores, while the other two parameters do not give big impacts on the scores. Even though the trajectory prediction method made an effect when the distance threshold is set to 0.66 nmi and the time threshold did when the distance threshold is set to 1.5 nmi, they are specific cases. The main general trend is that the score is increasing when the distance threshold increases to 1.0 nmi but it is decreasing when the distance threshold increases further. When the distance threshold increased to 1.0 nmi, true positive significantly increased and false negative decreased accordingly. Therefore, there was a big jump for the F_β Score. When the distance threshold increased further, false positive increased rapidly but there was no noteworthy changes in true positive and false negative. This led the score to go down again. Based on this result, 1.0 nmi is the best value for the distance threshold among three values tested in the experiments.

C. Analysis of DAA Guidance Performance

As described, the DAA alert should be given with sufficient timeframe in order for UAS pilot to aware situation, determine a maneuver to avoid the predicted LoWC, coordinate the maneuver with ATC, and command the maneuver to unmanned aircraft via communication links. If the pilot takes a long time to perform the series of actions, the unmanned aircraft may not be able to avoid the predicted LoWC even though DAA alerts were given on time. Therefore, this study investigates the effect of UAS pilot response delay on the performance of DAA guidance systems. For example, the proportion of LoWC that cannot be resolved when there is a pilot response delay after DAA alerts is measured to see the impact of pilot delay.

Figure 14 shows the proportion of successful resolutions, failed resolutions, and missed resolution as a function of alert times (given all true positive alerts). "Missed resolution" means just a case where a loss of well clear defined by the alerting logic was already violated at the time of maneuver after a pilot delay, thus any resolution maneuver could not be executed. "Failed resolution" means that a resolution maneuver was executed, but failed to avoid actual loss of well clear and "Successful resolution" means that a resolution maneuver was executed and successfully avoided LoWC.

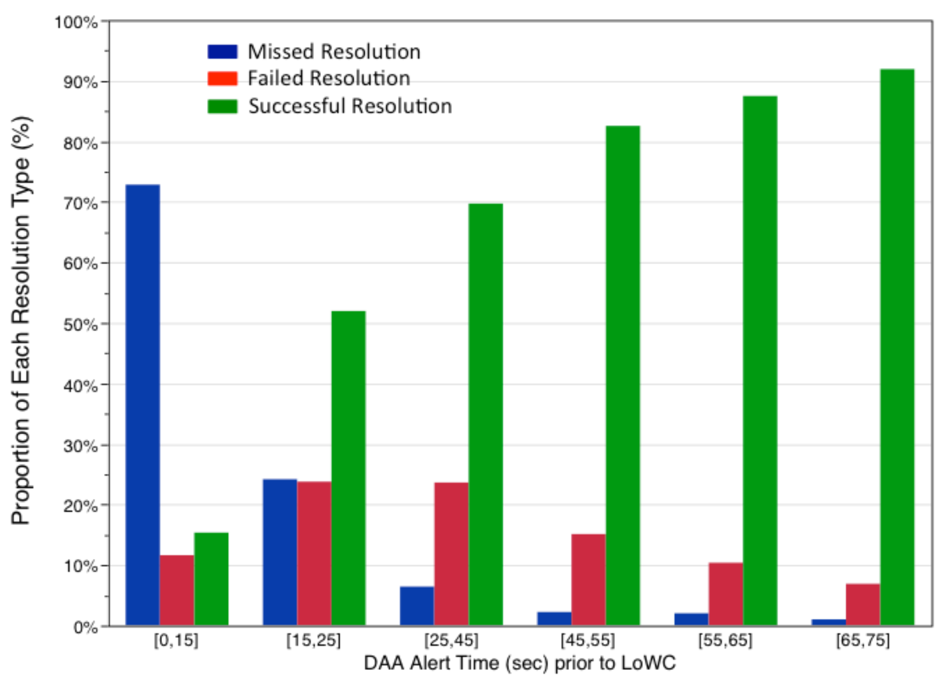


Figure 14. Proportion of successful resolutions, failed resolutions, and missed resolutions to all true positive alerts as a function of DAA alert times.

As alert lead time gets shorter, the proportion of successful resolutions decreases and the proportion of failed resolutions which eventually resulted in LoWC increases as expected. When the remaining time to LoWC at DAA alerts was smaller than 15 seconds, the successful resolution rate dropped noticeably (below 15%) and the missed resolution rate, in which a resolution maneuver could not be executed due to pilot response delay, increased significantly (went up to more than 70%) resulting in LoWC eventually. Therefore, minimum or average alert lead time prior to LoWC should be specified as a requirement in the MOPS. If a DAA alerting system is required to avoid more than 70% of LoWC, the minimum time should be longer than 45 seconds and at least 65 seconds for resolving more than 90% of LoWC given true positive alerts. However, the true positive rate and the false positive rate should also be considered in evaluating the required or desirable DAA alerting threshold settings as described in previous sections.

UAS pilots take time to respond to DAA alerts as described earlier. The pilot may not be able to command/execute a resolution maneuver before penetrating LoWC boundary and the resolution success rate will be significantly dependent upon when a resolution maneuver is executed. Figure 15 shows the average remaining time to actual loss of well clear at the time of commanding a resolution maneuver after pilot response delay for given true positive alerts. As the alerting distance and time thresholds increase, it provides much longer remaining time to actual loss of well clear after pilot response delay. When FP trajectory prediction method is used, it also provides longer remaining time than DR prediction method is used. Specifically, it appears that the effect of alerting distance threshold is much bigger than the one of alerting time threshold on the mean remaining time at the time of resolution execution. To provide UAS pilot more sufficient time at the time of commanding a maneuver prior to actual loss of well clear, therefore, the alerting distance and time threshold should be set larger.

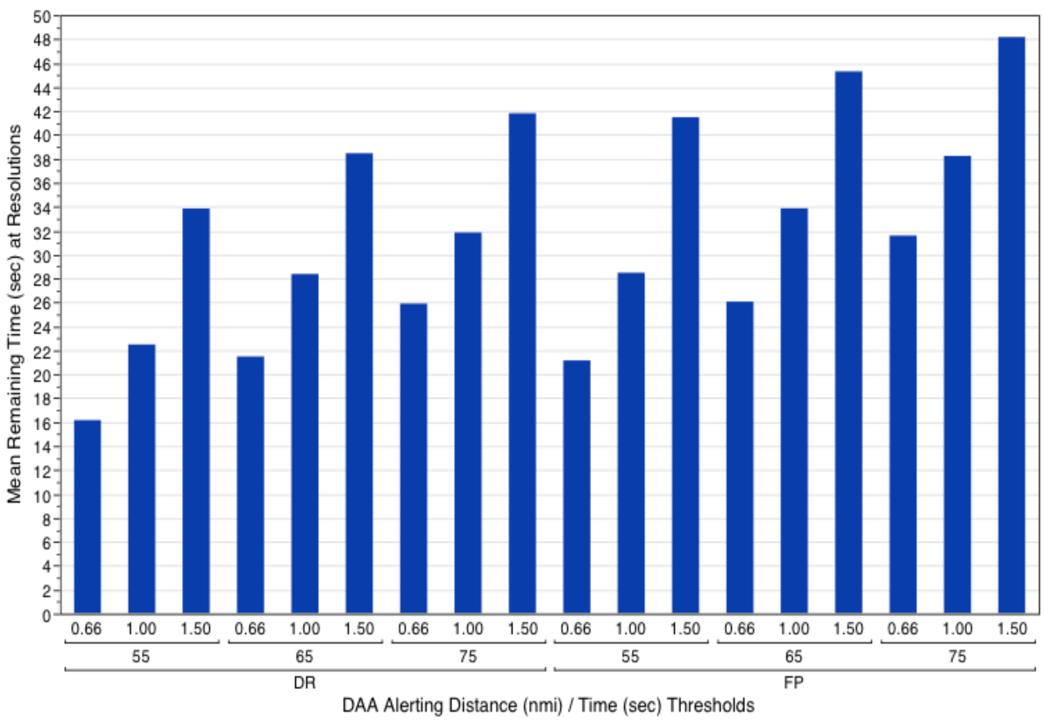


Figure 15. Mean time until actual loss of well clear at the time of resolution execution after pilot response delay as a function of different DAA alerting thresholds.

Based on the remaining time until actual loss of well clear after pilot response delay, a DAA guidance maneuver can be executed or missed. Based on RTCA SC-228 draft MOPS document, UAS pilots requires approximately minimum 15 seconds prior to LoWC to successfully remain well clear without ATC coordination. Therefore, it might be too late to execute a maneuver to remain well clear if the remaining time to actual loss of well clear at the time of resolution execution is less than 15 seconds. The timing of actual resolution maneuvers executed given a DAA alerting threshold setting were examined to see if and when a DAA guidance maneuver was executed as shown in Figure 16.

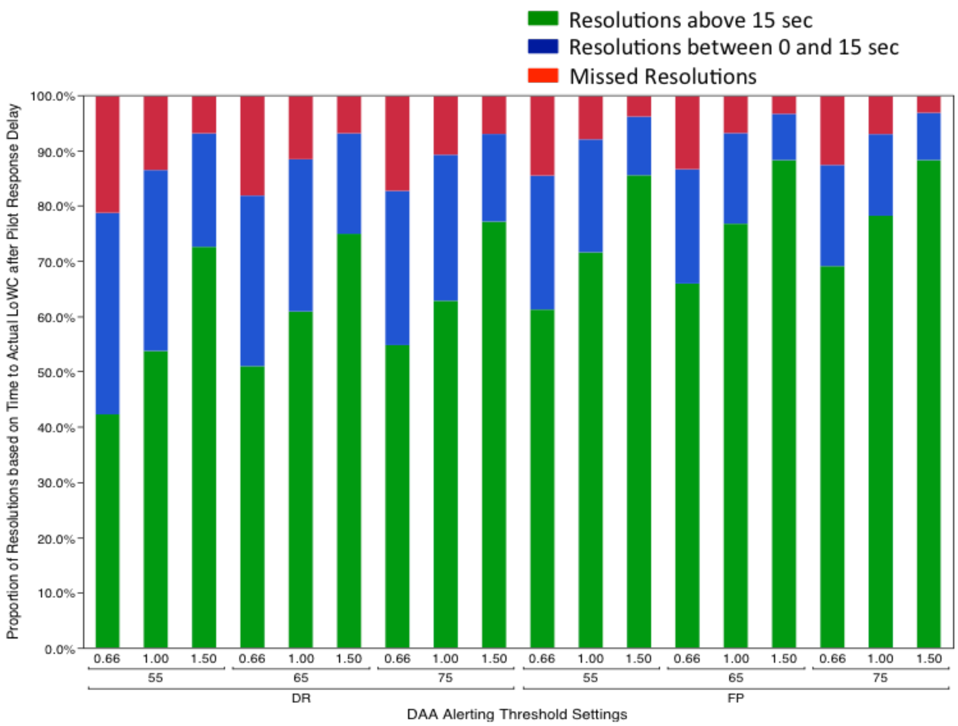


Figure 16. Proportion of resolutions based on the time to actual LoWC at resolution execution times after pilot response delay.

Much smaller percentage of resolutions were executed before 15 seconds prior to actual loss of well clear when the alerting threshold settings were set with smaller distance and time threshold values. For example, only 40% of resolutions were executed before 15 seconds prior to actual loss of well clear when the distance threshold was 0.66 nmi and the time threshold was 55 seconds. There was also the effect of trajectory prediction method on the resolution execution times. With the FP-based trajectory prediction method, a resolution maneuver can be executed much earlier than the DR-based trajectory prediction method. The effect of trajectory prediction method was bigger with smaller alerting distance threshold value. Therefore, a larger alerting distance threshold allows pilots to execute a resolution maneuver much earlier so that the proportion of missed resolution can be reduced.

Figure 17 shows the proportion of successful resolutions, which actually avoided the predicted loss of well clear, as a function of resolution execution times. Interestingly, the success rate is more than 80% when a resolution maneuver is executed at least 15 seconds before LoWC occurs, and the success rate is still greater than 60% even though a resolution maneuver is executed less than 15 seconds before LoWC occurs. Therefore, it would be better if DAA alerting and guidance system will be able to support UAS pilots commanding and executing a resolution maneuver at least 15 seconds before LoWC occurs to increase success resolution rate.

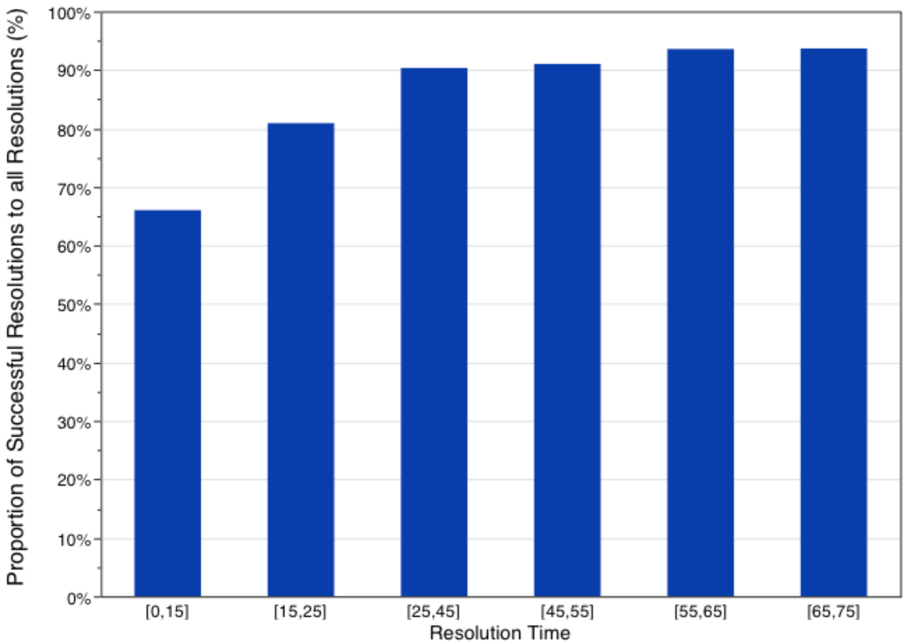


Figure 17. Proportion of successful resolutions as a function of resolution execution times.

However, there are still LoWC that were not avoided even though there is sufficient time to LoWC at the time of resolution execution (e.g., 10% failed resolutions when a resolution maneuver was executed between 65 seconds and 75 seconds before LoWC). A potential reason is that the actual LoWC occurred much earlier than the predicted LoWC due to sudden acceleration of the intruder into the ownship or DAA guidance algorithm could not find a conflict-free resolution maneuver for the look-ahead time period given encounter geometry and aircraft performance. Further analysis is required to find out the reasons in future research.

As mentioned in previous section, false positive alerts may cause unnecessary resolution maneuvers, which means there would not have seen a LoWC even if no action was taken, and also cause interruptions to ATC to coordinate the maneuvers. This will also affect the performance/behavior of pilots such as the pilot's compliance on the DAA alerting system. Previous research that has been conducted regarding the relationships between false positive alerts and operator trust and use of automation indicated that false alerts lead to a distrust, or disuse in the alerting system, resulting in disregarding or responding late to some true positive alerts.[30, 31]

The false positive alerts seem to remain until the pilot determines a resolution because the pilot model executed the maneuver to the unmanned aircraft after the pilot response delay. This means the DAA alerts can last for a while even when they are false positive alerts. Therefore, it will be difficult to discriminate between false positive alerts and true positive alerts at the time of alerts based on the duration of alerting time. Such alerts are more likely to trigger a maneuver even after a pilot delay. Figure 18 shows the proportion of unnecessary resolutions that are triggered by false/nuisance alerts to all resolutions as a function of DAA alerting threshold settings. The resolutions that were executed due to false positive alerts were considered as unnecessary resolutions among all executed resolutions (it is called "false alert-induced resolution") in this study. The proportion of false alert-induced resolutions increases significantly (up to 70% of resolutions) as the alerting distance threshold increases, since false positive alerts increase significantly as the distance threshold increases, but the effect of DAA time threshold and trajectory prediction method is relatively small. The false alert-induced response can be quite disruptive to pilot's tasks and air traffic controllers as a result of carrying out the unnecessary resolution maneuvers. The resolution maneuvers triggered by false alerts can be "acceptable" or actually "unnecessary" based on the effects of the false alert-induced resolutions on the safety in terms of the proximity between aircraft and on the severity of disruption to ATC and UAS pilot tasks.[32] Further research is required to investigate how false alert-induced resolutions affect pilot's trust and compliance and the positive and negative effects of "acceptable" and "unnecessary" false alerts.

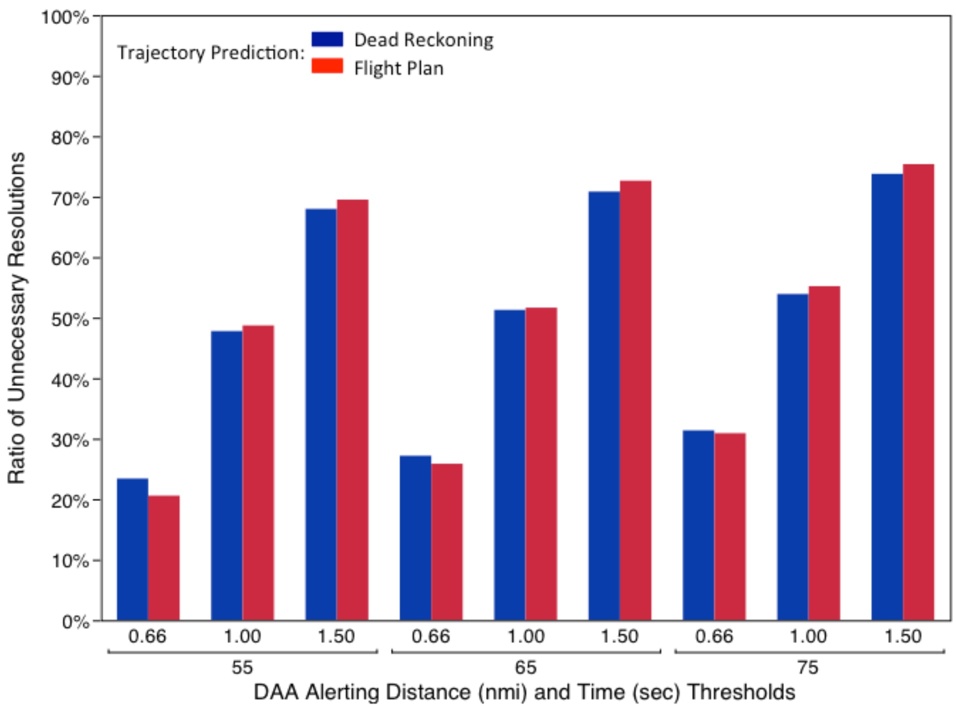


Figure 18. Proportion of unnecessary resolutions triggered by false positive alerts to all executed resolutions.

Figure 19 shows the proportion of LoWC induced by unnecessary resolutions due to false positive alerts to all actual losses of well clear. Among all unnecessary resolutions, the cases where resulted in actual LoWC were counted as the induced LoWC. The induced LoWC increases significantly as the alerting distance threshold increases because there are more false positive alerts with larger distance threshold. It was also found that the number of false positive alerts correlates strongly with the LoWCs induced by resolutions due to false positive alerts. The correlation between the total number of false positive alerts and the number of induced LoWC was 0.93 and statistically significant ($<0.0001^*$). It shows that there is negative effect of false positive alerts in terms of induced LoWC in addition to the effects of false positive alerts on pilot performance and reliance on the alerting system. Therefore, it would be important to reduce the number of unnecessary false positive alerts in setting the appropriate DAA alerting threshold values.

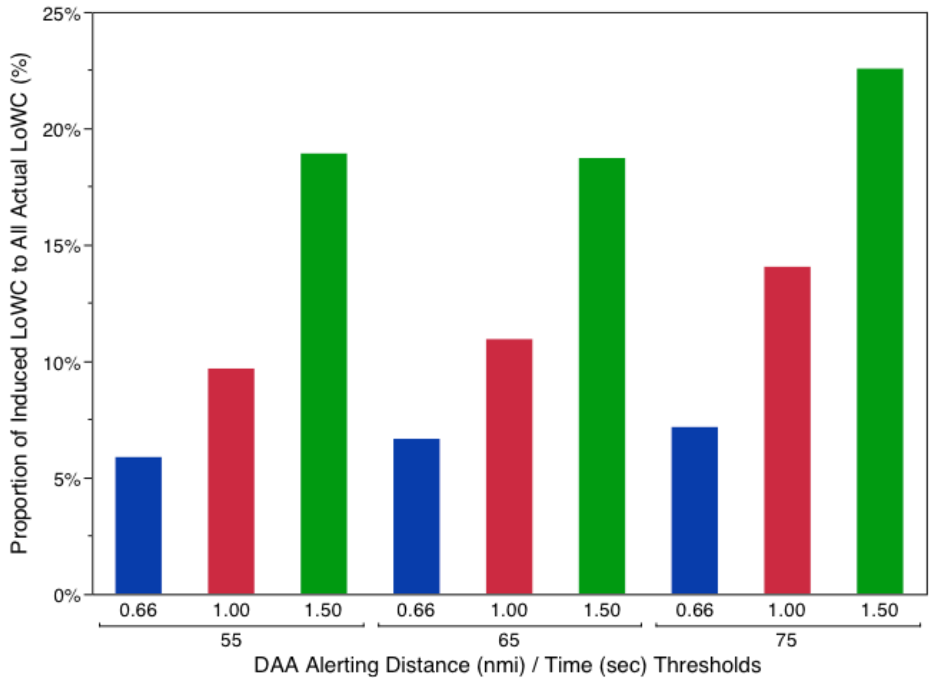


Figure 19. Proportion of induced LoWC to all actual LoWC.

VII. Conclusion

DAA systems are intended to support the remote pilot at the UAS ground control station in keeping his/her aircraft "well clear" of proximate airborne traffic in a manner that preserves the safety of the airspace and the efficiency of the air traffic system. This study investigated the effects of alerting criteria and pilot response delay on the safety and performance of UAS DAA systems in the context of routine civil UAS operations in the National Airspace System (NAS).

The performance of DAA system alerting and guidance functions was assessed with a large number of encounters and a broad set of alerting and guidance system parameters using a fast-time, NAS-wide simulation tool. Three attributes of the DAA system were controlled as independent variables in the study to conduct trade-off analyses: UAS trajectory prediction method (dead-reckoning vs. intent-based), alerting time threshold (related to predicted time to LoWC), and alerting distance threshold (related to predicted Horizontal Miss Distance). Specifically, the overall performance of DAA system alerting and guidance functions was evaluated in terms of its ability to accurately predict potential losses of well clear with sufficient lead time such that the UAS pilot is able to evaluate the encounter threat, determine an effective maneuver, coordinate with ATC and initiate the selected maneuver to successfully avoid the predicted loss of well clear.

To evaluate the accuracy performance of a DAA system alerting function, the positive predictive value—the proportion of true positive alerts to all issued alerts—was measured. This metric was mainly affected by the alerting distance threshold. Results indicated DAA alerting distance threshold had a greater effect on DAA system performance than either DAA alerting time threshold or ownship trajectory prediction method. It showed that increased distance thresholds were correlated with more false positive alerts but also longer alert lead times. The distance threshold settings had a noticeable effect on the average time to actual LoWC from initial DAA alerts.

Another important metric is the proportion of missed alerts (false negative alerts) since it adversely affects safety, potentially leading to a mid-air collision. Results indicated the missed alert rate dropped significantly from ~11 % to ~2 % when the alerting distance threshold increased from 0.66 nmi to 1.0 nmi. However, no significant differences were observed for further increase in the distance threshold. While increased distance thresholds had beneficial effects on alert lead time and missed alert rate, they also resulted in higher false alert rates. In the design and development of DAA systems, therefore, the positive and negative effects of false alerts and missed alerts should be carefully balanced to achieve acceptable alerting system performance.

In an effort to determine desirable alerting parameter settings in a systematic manner, ROC curves showing the trade-offs between missed alert rate and false alert rate were computed for the alerting system parameter sets used in this study, but they did not draw meaningful distinctions between those parameter sets. An F-score metric—a weighted harmonic mean of true positive rate and positive predictive value—was found to be useful in selecting an optimal (or acceptable) set of DAA alerting thresholds. Results indicated that the F-score was sensitive to changes in the alerting distance threshold but was insensitive to changes in the alerting time threshold. Although the F-score could provide a single quantitative number for measuring the DAA alerting performance, it is important to choose an appropriate value for the beta (β) parameter used in calculating the F-score. Therefore, subject-matter experts should be consulted to identify an appropriate beta value, and the trade-off between different beta values should also be investigated in future research.

Analysis on the alert lead time was conducted to evaluate the timeliness of DAA system alerts. As expected, results indicated a strong positive correlation between alert lead time and DAA system performance (i.e., the ability of the UAS pilot to maneuver the unmanned aircraft to remain well clear). When the alerting distance threshold was increased from 0.66 nmi to 1.5 nmi, the average time to actual LoWC was increased by 20 seconds, which suggests that the DAA alerting system will give more lead time to the pilot by increasing the distance threshold at the expense of a higher false alert rate. Varying the alert time threshold parameter had little effect on average alert lead time.

In conclusion, the DAA alerting distance threshold parameter has a key role in reducing missed alerts and increasing alert lead time, as compared to either the alerting time threshold parameter or the ownship trajectory prediction method. While increased distance thresholds have beneficial effects on alert lead time and missed alert rate, they also generate higher false alert rates. The simulation results and analysis methodology presented in this study are expected to help system designers/developers and standards groups evaluate and determine the required or appropriate setting of DAA system parameter thresholds for UAS that ensure safety while minimizing operational impacts to the NAS before DAA operational performance standards can be finalized.

Additional research is needed to determine a methodology for setting alerting system parameters to achieve an optimal (or acceptable) balance between false positive alerts and missed alerts in the design and development of DAA alerting and guidance systems. Future studies should include analysis of induced LoWCs (resulting from false positive alerts) and “missed” resolutions resulting from untimely alerts and/or excessive pilot response delay. Human-in-the-loop studies may be necessary to assess the impact of false and missed alerts on UAS pilot trust and response in the DAA system alerting and guidance. Lastly, future work is warranted to evaluate the effect of surveillance sensor uncertainty on DAA system performance and to determine an effective concept of interoperability between UAS DAA systems and existing collision avoidance systems operating in the NAS (e.g., TCAS II).

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