En Route Detect and Avoid Well Clear in Terminal Area Landing Pattern

Anna C. Trujillo*
NASA Langley Research Center, Hampton, VA, 23681

Devin P. Jack†
Adaptive Aerospace Group, Inc., Hampton, VA, 23681

Dimitrios Tsakpinis ‡
SAIC, Hampton, VA, 23681

A fast time simulation was conducted to test the detect and avoid Well Clear definition designed for en route use when an unmanned aircraft (UA) is approaching the landing pattern of the terminal area. Measures focused on were loss of well clear and alerts intended to help the pilot avoid loss of well clear. Data indicated warning-level alerts will occur outside the typical Class D airspace which may prevent the UA from normal operations in the terminal airspace. Other aircraft on 45º entry could result in "nuisance" alerts which may also prevent the UA from normal operations in the terminal airspace. However, eliminating horizontal proximity (τ_{mod}) has the potential to increase "nuisance" alerts on the 45º entry and downwind legs. Overall, this suggests that a more stringent definition of Well Clear may be advisable in the landing pattern of the terminal area.

I. Nomenclature

d_h	=	vertical separation
$DMOD$	=	distance modification
HMD	=	horizontal miss distance (horizontal separation)
τ_{mod}	=	temporal separation
AGL	=	above ground level
CPA	=	closest point of approach
DAA	=	detect and avoid
DWC	=	DAA well clear
ft	=	feet
KTAS	=	knots true airspeed
kts	=	knots
LoWC	=	loss of well clear
min	=	minute
MOPS	=	minimum operational performance standards
nmi	=	nautical mile(s)
sec or s	=	second(s)
UA	=	unmanned aircraft
UAS	=	unmanned aerial system

*Senior Research Engineer, Crew Systems and Aviation Operations Branch, MS 152.
†Research and Development Engineer, 100 Exploration Way, Suite 330, AIAA Member.
‡NASA Langley UAS in the NAS Contractor Team Lead and Modeling/Simulation Engineer, MS 152.

II. Introduction

The National Aeronautics and Space Administration's (NASA) Unmanned Aerial Systems Integration in the National Airspace System (UAS Integration in the NAS) project is developing detect and avoid (DAA) system performance capabilities and enumerating limitations so that UAS can integrate seamlessly and safely into the current NAS. Work to date has defined DAA well clear (DWC) parameters for UAS operations in the en route environment [1]. These DWC parameters incorporate a horizontal distance and temporal threshold, and vertical distance threshold [2]. From this, RTCA Special Committee 228 (SC-228) developed minimum operational performance standards (MOPS) for DAA to replace see and avoid [1, 3].

These MOPS are only applicable for UA transitioning from terminal airspace to higher altitudes where other means of separation are provided [1]. The effectiveness of en route DWC parameters for a UAS in the terminal area traffic pattern has not been verified and excessive alerts may occur [4]. The terminal area often requires vehicles to be separated by smaller distances than en route, and these typically smaller distances may unnecessarily result in loss of DAA well clear (LoWC) and inadvertent alerts for aircraft behaving appropriately. The research described in this paper begins to detail the effects of using the en route DWC definition in the terminal area. This initial study used fast-time simulation techniques to detail DWC violations between a UAS and intruder aircraft in the standard visual traffic pattern using the en route DWC parameter definitions.

III. Background

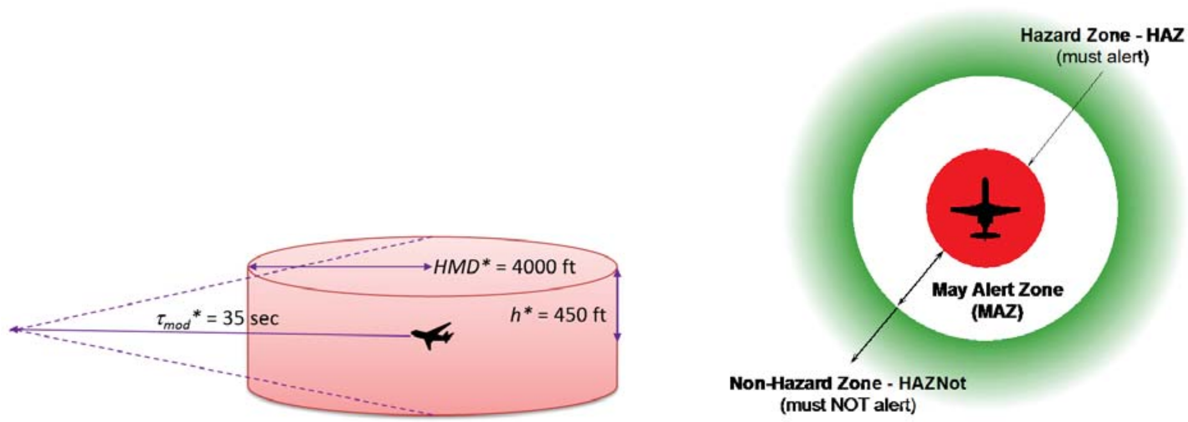
Chapter 14 of the Code of Federal Regulations (14 CFR) Section 91.113 requires that "vigilance shall be maintained by each person operating an aircraft so as to see and avoid other aircraft" and maintain well clear from other aircraft [5]. The definition of well clear was left intentionally vague to allow the pilot in command to determine the appropriate safe separation in any given encounter. Without a pilot on board the aircraft, UAS must compensate by using a DAA system to maintain safe separation. SC-228 has defined a quantitative separation standard for UAS in the en route operational environment, termed DAA well clear or DWC. Using an array of on-board sensors, alerting and guidance algorithms, and a ground control station, the DAA system provides sufficient information for a remote pilot to safely operate the unmanned aircraft (UA).

DWC is a volume maintained around the UA that incorporates vertical and horizontal distance as well as a time component (Fig. 1a) [1, 6]. A DWC violation is defined as

$$\left[0 \le \tau_{mod} \le \tau^*_{mod} \| r_{xy} \le DMOD\right] \text{ and } \left[HMD \le HMD^*\right] \text{ and } \left[-h^* \le d_h \le h^*\right] \qquad (1)$$

where $\tau^*_{mod} = 35$ sec $\doteq$ horizontal proximity, $r_{xy} \doteq$ horizontal range, $DMOD = HMD^* \doteq$ distance modification, $HMD^* = 4000$ ft $\doteq$ horizontal miss distance, $h^* = 450$ ft $\doteq$ vertical separation, and τ_{mod}, HMD and d_h are described in Appendix A on page 9.

In addition to the DWC definition, this fast-time simulation also incorporated en route alerting requirements, specified by DO-365 [1], in the terminal area. For each level of alert, there are associated Hazard Zones and Non-Hazard



(a) DAA Well Clear Volume with En Route Parameter Values **(b) DAA Well Clear Hazard Regions**

Fig. 1 Well Clear Volume and Alerting Zones

Zones defined to provide flexibility in the implementation of an alerting system (Fig. 1b on the preceding page). These zones define where an alert must be issued and where an alert is undesirable, respectively. Alerts are issued by the reference DAA algorithm, DAIDALUS [7], and evaluated against the Hazard/Non-Hazard zones. There were also two alerting thresholds, early and late, which are measured relative to the time the hazard zone is violated. Hazard zone volume and hazard zone alert times are shown in Table 1 [6].

Table 1 DAA Alerting Requirements

Alert Type		Preventive Alert	Corrective Alert	Warning Alert
Hazard Zone	τ^*_{mod} **(sec)**	35	35	35
	$DMOD$ **and** HMD^* **(nmi)**	0.66	0.66	0.66
	h^* **(ft)**	700	450	450
Hazard Zone Alert Times	**Minimum Average Time of Alert (sec)**	55	55	25
	Late Threshold (sec)	20	20	15
	Early Threshold (sec)	75	75	55

There are three alert levels: Preventive, Corrective, and Warning. The preventive is a caution-level alert [8] intended to bring awareness to the pilot of traffic that may become a danger if either the UA or intruder maneuvers vertically. Corrective alerts are caution-level alerts, designed to have the UA pilot recognize traffic, determine an appropriate maneuver, and begin to coordinate with Air Traffic Control (ATC) prior to maneuvering. The warning alert, a warning-level alert [8], is designed for the UA pilot to promptly recognize traffic, determine an appropriate maneuver, and execute the maneuver to maintain DWC. Since preventive alerts do not occur in all encounter geometries (*e.g.*, co-altitude encounters), only corrective and warning alerts are discussed herein.

IV. Experiment Description

A. Objectives

The specific objectives accomplished in this fast-time simulation were (1) exploring effects of alerting performance of the en route DWC definition and associated alerting criteria in Class D/E terminal airspace, in particular, in the landing pattern; and (2) evaluating the en route DWC definition in the terminal area with an assumption of having perfect surveillance of intruder aircraft.

B. Fast-Time Simulation Environment

The fast-time simulation entailed the UA on an instrument approach to an airport with a 3^o glideslope approach with an intruder aircraft in a standard visual approach pattern for landing on the same runway. The simulation was open loop and without a sensor model; therefore, vehicle maneuverability was not considered and no mitigation for sensor uncertainty was needed [9]. UA and intruder aircraft performance characteristics are detailed in Table 2 on the following page. While the UA was always on final approach, the intruder was on one of the legs of a standard visual approach pattern or turning onto one of these legs. The intruder legs were midfield entry, 45^o entry, downwind, and base. The turns were turn to downwind, turn to base, and turn to final. See Fig. 2 and Table 3 on the following page for a description of the legs and turns. Each run consisted of a combination of the UA on final approach and the intruder aircraft on any one of the legs or turning onto a leg.

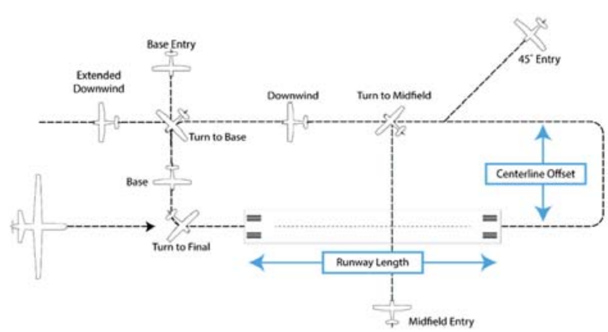


Fig. 2 Straight Legs and Turns in Visual Landing Pattern with UAS on Straight-In Instrument Approach

Table 2 UA and Intruder Aircraft Characteristics

Parameter		Value(s)
UA	Airspeed (kts)	40, 60, 90, 120, 150, 180, 200
	Climb Rate (ft/min)	±500 and ±1000
	Flight Path Angle	3°
	Minimum Approach Altitude (ft)	200
Intruder	Airspeed (kts)	60, 75, 90, 120, 150, 180, 200
	Pattern Altitude (ft AGL)	1000 and 1500
	Climb Rate (ft/min)	±500 and ±1000

Table 3 Legs and Turns Description

Leg or Turn		Description
Straight Leg	45° Entry	45 degree entry into pattern
	Midfield Entry	aircraft flies over the runway at an altitude <1000 ft and descends to join downwind leg of pattern
	Downwind	long level flight path parallel to but in the opposite direction of landing runway
	Extended Downwind	see Downwind
	Base	short descending flight path at right angles to the approach end extended centerline of landing runway
	Final	descending flight path in direction of landing along extended runway centerline from base leg to runway
Turns	Turn to Downwind	turn onto Downwind leg
	Turn to Base	turn onto Base leg
	Turn to Final	turn onto Final leg

V. Data Analysis

Data was analyzed using IBM® SPSS® Statistics Version 24*, SAS/JMP® Version 13, and Mathwork® MATLAB® Version R2017a software. Note that data were filtered to eliminate any runs that began in LoWC or runs that never resulted in a LoWC.

Certain key events occurred in each run. At each event, a common set of metrics was gathered. These events included closest point of approach (CPA), LoWC, near midair collision (NMAC) [10], early and late alert thresholds, and when DAIDALUS alerts were issued.

LoWC occurred when Eq. 1 on page 2 was true with τ^*_{mod}, HMD^*, and h^* values indicated in Table 1 on the preceding page. Early and late alert thresholds are also indicated in Table 1 on the previous page. CPA is the minimum three dimensional range between the two aircraft at any time throughout the encounter.

A. Loss of Well Clear Geometry

LoWC was calculated for all segment encounters, and the most problematic were those with intruder aircraft on 45° entry, downwind, and base. Figure 3 on the following page provides a graphical representation of the key events in the vicinity of the airport environment. In each figure, the runway is displayed at the origin (0,0) and is shown with a 5000 ft runway length. There is a solid black line indicating the UA's constant trajectory. For simplicity, the figure only shows the positions for straight traffic pattern segments, each indicated by a unique color. As can be seen in Fig. 3 on the next page, a LoWC could occur with the UA as far out as 4.5 nmi from the runway threshold.

The horizontal distance between the UA and the intruder aircraft at initial LoWC could be as great at 2 nmi for intruder aircraft on 45° entry (Fig. 4 on the following page). This could result in "nuisance" alerts before the LoWC as described in [11]. These "nuisance" alerts may unnecessarily cause the UA to perform a missed approach even though the intruder aircraft is entering the traffic pattern and is not a threat to the UA. Intruder aircraft on downwind near base

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and on base may be only 0.5 nmi from the UA when there is a LoWC. In these cases, alerting may be appropriate since the intruder aircraft is close to turning on final where the UA is on glideslope, which is recommended in [11].

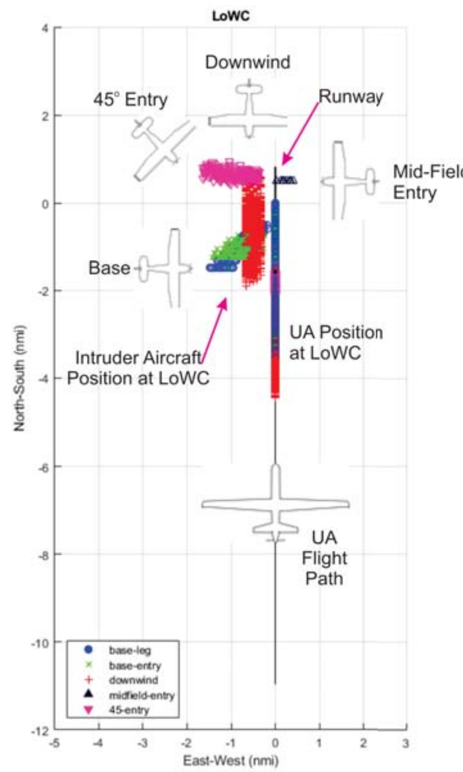


Fig. 3 LoWC Geometry

B. Alerts

1. Alert Geometry by Intruder Leg

A primary concern when applying the en route DWC definition when interacting with the visual traffic pattern is the range at which the UA would receive alerts which would cause a disruption to the UA's intended operation. To identify the relative proximity to the airport at which alerts and LoWC occur, a series of figures presenting the intruder and UA position at key events were developed. Figure 5 on the next page shows aircraft position for each of the specified events. The colored dots in each figure represents the position of the ownship and intruder aircraft when each event occurred. Note that the UA position is always in line with 0 feet East-West (x-axis).

In Fig. 5a and 5b on the following page, the UA may receive Corrective alerts as far out as 8.55 nmi from the runway. Similarly, a Corrective alert may be issued on an intruder aircraft on an extended base more than 4 nmi from the runway centerline. These dimensions are larger than the Class D airspace surrounding an airport environment (typically a 4.4 nmi radius). The Late Corrective alert threshold indicates the positions at which a Corrective alert must be issued. Figure 5b on the next page shows that the Late Corrective alert threshold may be crossed when the UA is nearly 5 nmi from the runway while the UA would still typically be outside of Class D airspace dimensions.

Potentially more imperative within the terminal area, the issuance of the Warning alert is bound between the Early Warning position and the Late Warning position, as shown in Figs.5c and 5d on the following page respectively. From the figure, Warning level alerts may be issued between up to 7.45 nmi and 5.25 nmi; of which both bounds are outside of the Class D airspace. Therefore, warning-level alerts at this distance may prevent the UA from normal operations

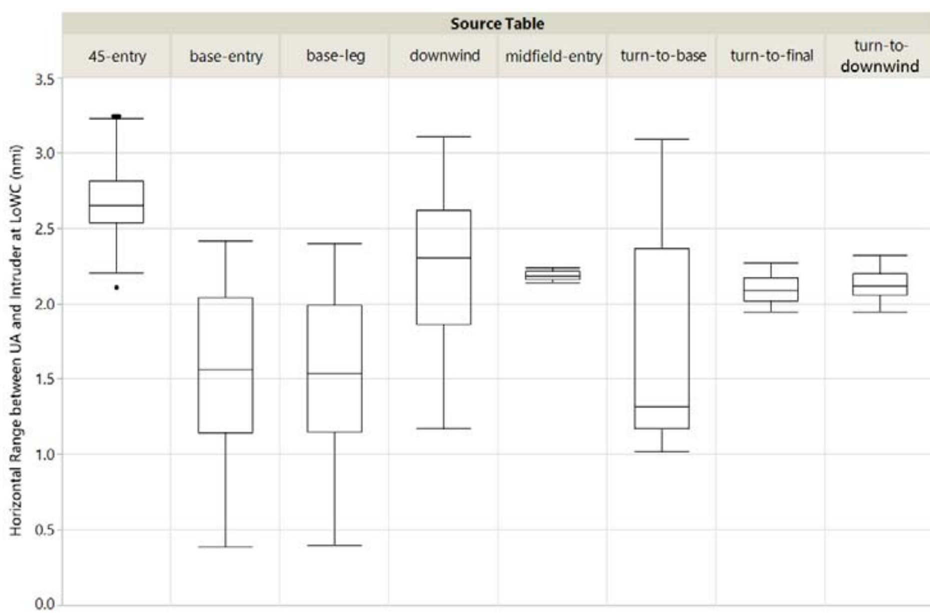
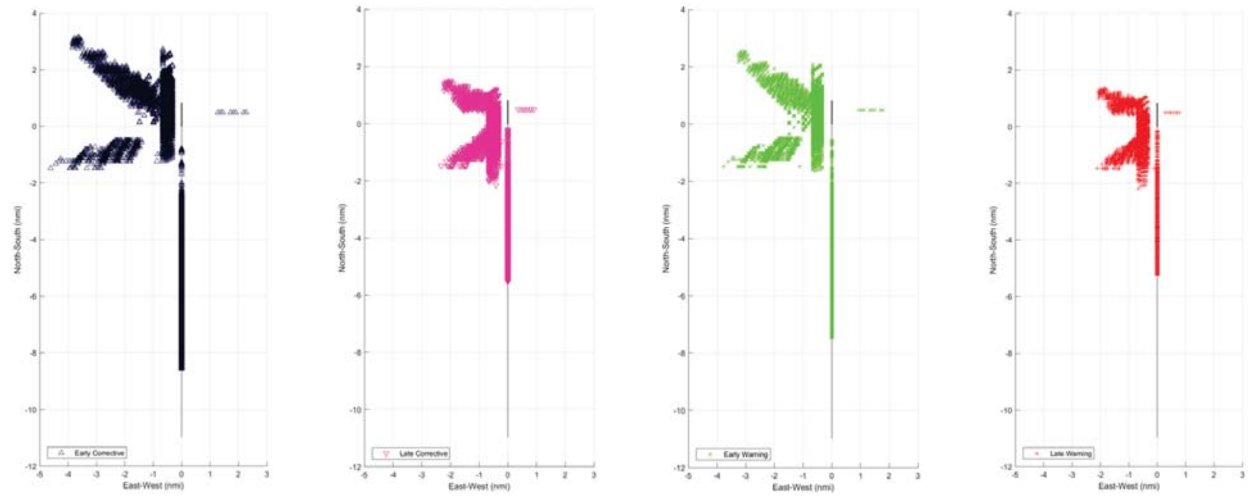


Fig. 4 Horizontal Distance between UA and Intruder Aircraft at Initial LoWC



(a) Early Corrective **(b) Late Corrective** **(c) Early Warning** **(d) Late Warning**

Fig. 5 UA and Intruder Aircraft Position at Alert Event

in the terminal airspace because the DAA system would be constantly recommending path deviations due to aircraft established in the nominal terminal area traffic pattern, which would most likely result in the UA performing a missed approach.

Figure 6 on the next page shows box plots for the UA distance to the runway at each event separated by intruder aircraft traffic pattern segment. This figure gives a better sense of where the UA is positioned when each event occurred, and contains a unique box plot for each combination of event and intruder traffic pattern segment. From the figure, downwind and extended downwind segments resulted in the greatest UA range to runway for each event. As a supplement to Fig. 6 on the following page, Table 4 captures the maximum UA distance to runway for each event and traffic pattern segment.

Table 4 UA Range to Runway

Intruder Leg	Maximum UA Distance to Runway (nmi)				
	Early Corrective	Late Corrective	Early Warning	Late Warning	LoWC
45^o Entry	7.53	3.91	6.43	3.63	2.12
Base Entry	7.50	4.47	6.40	4.19	3.37
Base	7.65	4.65	6.56	4.37	3.55
Downwind	8.55	5.53	7.45	5.25	4.42
Midfield Entry	5.84	2.81	4.74	2.53	1.71

As seen in the Fig. 6 on the following page and Table 4, the downwind segments result in the UA being furthest away from the runway when each event occurred. Many downwind legs are flown within 4000 ft of the runway centerline for many general aviation piston aircraft. These aircraft on downwind are commonly in violation of the HMD component of DWC accounting for the large UA distance to runway.

2. Influence of UA Airspeed on Alerts

Focusing on the downwind segment as the encounter that resulted in the furthest UA range to the threshold at each event, Fig. 7 on the following page shows the influence of UA airspeed for each event. The figure shows the maximum UA range to the runway threshold in nmi at each event as a function of the UA airspeed. The maximum distance to the runway at an alert event is shown in Table 4 and these maximum distances occurred with the UA flying at 200 KTAS, which is the maximum speed allowed in the terminal airspace [12].

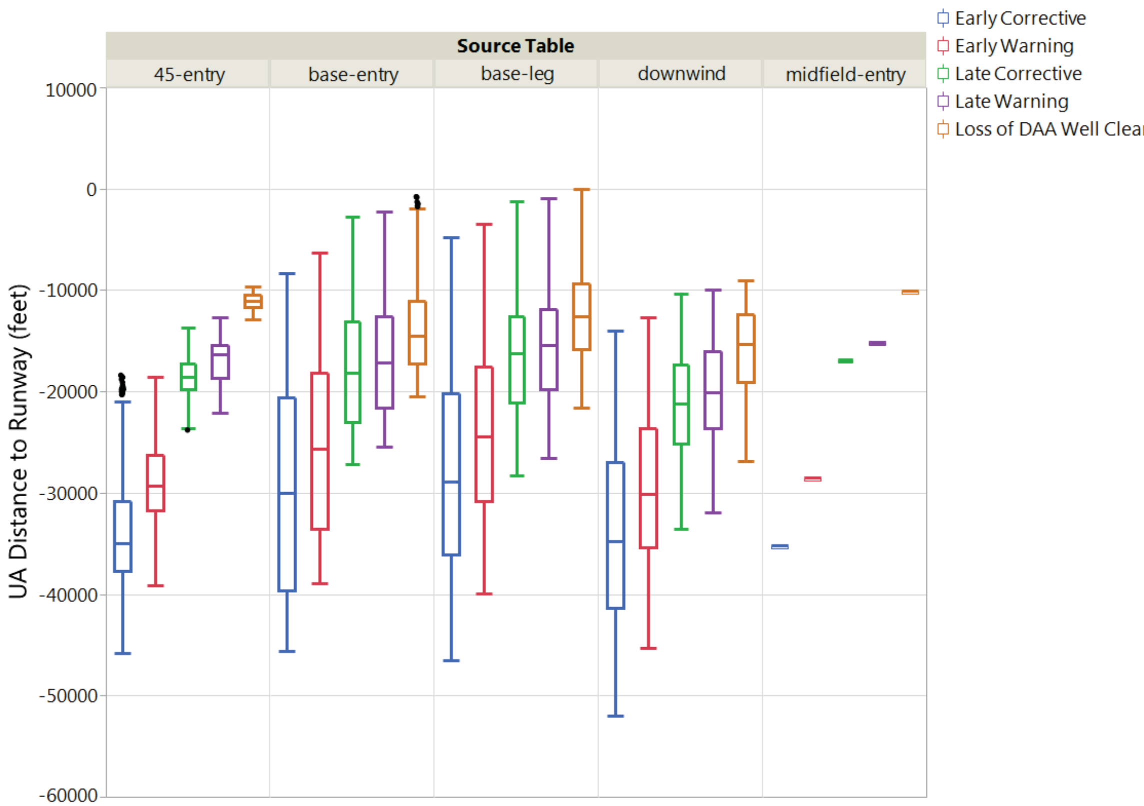


Fig. 6 UA Range to Runway at Alert Event

Within the operational speed range enabled by DO-365 [1], to avoid LoWC outside of 4 nmi with aircraft in the immediate airport traffic pattern, UA operations must be limited to 150 KTAS. However, Corrective and Warning alerts may occur between 5 nmi to 7.5 nmi from the runway (outside the typical Class D airspace) when the UA speed is 150 KTAS.

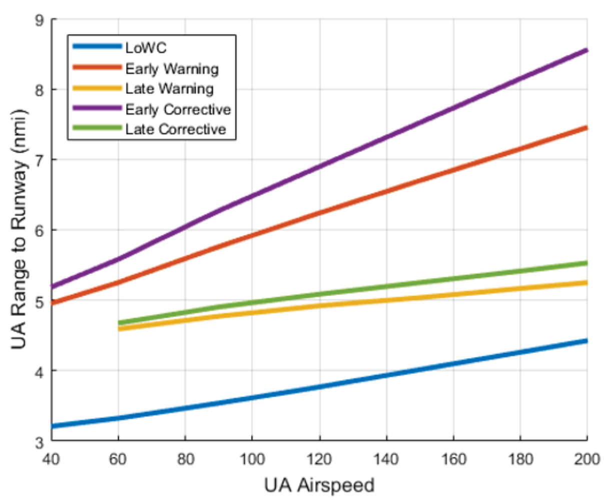
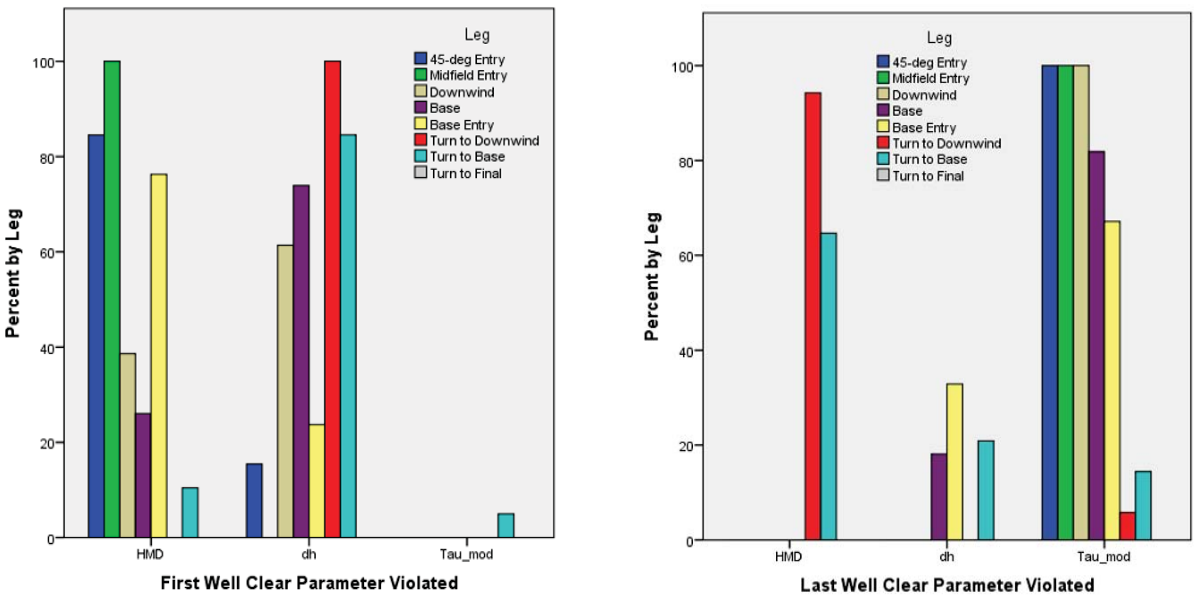


Fig. 7 UA Range to Runway for Downwind Segment as a Function of Airspeed and Event

C. First and Last Well Clear Parameter Violated

The first and last DWC parameter (τ^*_{mod}, HMD^*, and h^*) to be violated was found (Fig. 8 on the following page). As can be seen in Fig. 8a on the next page, d_h, vertical separation, was typically the first DWC parameter to be exceeded when the intruder was near the runway threshold (*i.e.*, departures, turn to base, and base) and for turn to downwind. The compressed altitude ranges, especially near the runway threshold, between aircraft in the visual landing pattern most likely account for this. Horizontal miss distance, HMD, was the first DWC parameter violated for the entries (*i.e.*, 45°, midfield, and base entries). In these cases, the intruding aircraft is descending to enter the traffic pattern while still fairly high relative to the UA but the lateral distance between the vehicles is decreasing, especially for high closure rates.

The last DWC parameter exceeded was typically τ_{mod}, horizontal proximity, for the straight legs and HMD, horizontal miss distance, for turn to downwind and base (Fig. 8b on the following page). The close proximity of aircraft



(a) First Well Clear Parameter Violated **(b) Last Well Clear Parameter Violated**

Fig. 8 Well Clear Parameter Violation by Leg

in a visual traffic pattern, as compared to en route, accounts for the time variable of DWC, τ_{mod}, being the last to be exceeded for the straight legs. For turns, the horizontal component of DWC, HMD, was finally exceeded because the time component, τ_{mod}, most likely was exceeded once the intruder's straight track projection intersected the UA's glideslope, which was early in the turn initiation.

In general, the farther away the intruder was to runway threshold, the larger the differences in time between the first and last DWC parameter violated (Fig. 9 on the next page). With the consideration of where alerting may become a "nuisance" and where it may be appropriate [11], eliminating τ_{mod} has the potential to increase "nuisance" alerts on the 45^{o} entry and downwind legs.

VI. Conclusion

A fast-time simulation was conducted to test the effects of the en route DWC definition in the terminal area for a UA on final approach and an intruder aircraft in the visual landing or taking off flight pattern. The measures focused on were Corrective and Warning alert thresholds, LoWC, and the associated geometries between the UA and intruder aircraft when these events occurred.

The geometry of the UA and intruder aircraft to the runway indicates that the Early Corrective alert threshold may be crossed while the UA is 8.55 nmi from the runway and Warning level alerts may be issued as far away as 7.5 nmi from the runway. Furthermore, to avoid LoWC outside of 4 nmi with aircraft in the immediate airport traffic pattern, UA operations must be limited to 150 KTAS. However, Corrective and Warning alerts may still occur between 5 nmi to 7.5 nmi from the runway at this UA speed, which are outside the typical Class D airspace. Warning-level alerts at this distance may prevent the UA from normal operations in the terminal airspace because the DAA system would be constantly recommending path deviations due to aircraft established in the nominal terminal area traffic pattern.

LoWC was calculated for all segment encounters and the most problematic were those intruder aircraft on 45^{o} entry, downwind, and base. For intruder aircraft on 45^{o} entry, the horizontal distance between the UA and intruder aircraft at initial LoWC could be as great as 2 nmi. These LoWC could result in "nuisance" alerts, which may unnecessarily cause the UA to perform a missed approach even though the intruder aircraft is entering the traffic pattern and is not a threat to the UA. However, intruder aircraft close to turning final may be only 0.5 nmi from the UA when there is a LoWC. In these cases, alerting may be appropriate since the intruder aircraft is closer to the UA which is on final.

Horizontal proximity, τ_{mod}, was typically the last DWC parameter violated for the straight legs and HMD, horizontal miss distance, for turns. With the consideration of where alerting may become a "nuisance" and where it may be

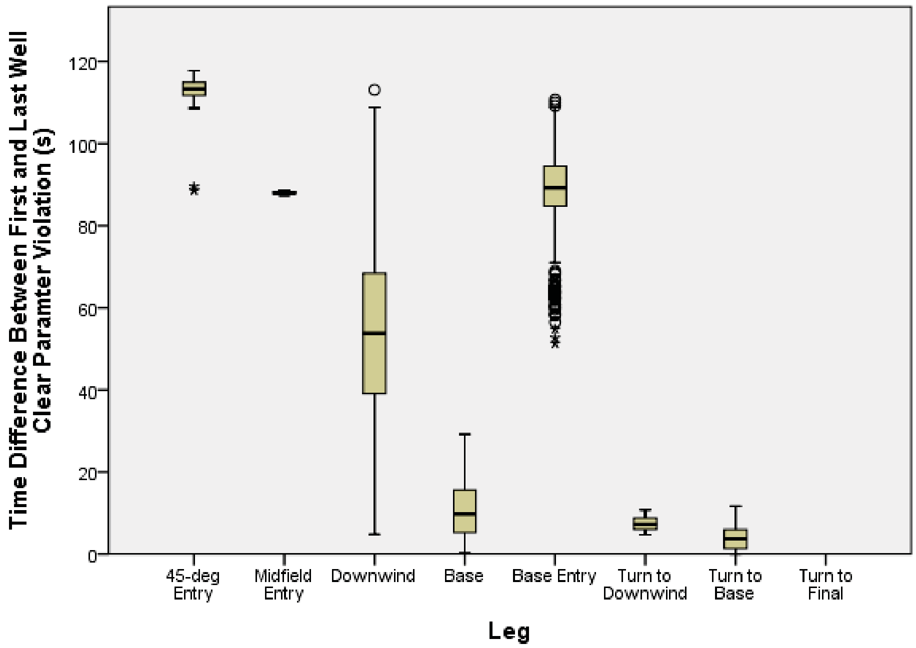


Fig. 9 Well Clear Parameter Violation Time Difference

appropriate [11], eliminating τ_{mod} has the potential to increase "nuisance" alerts on the 45^{o} entry and downwind legs.

Therefore, using the en route DWC definition in the terminal area will incur many LoWC due to the compressed lateral and vertical ranges of aircraft in the landing traffic pattern. These compressed ranges are valid in the terminal area; thus, the UAS pilot may unnecessarily react to essentially "nuisance" alerts that would necessitate the UA operator to determine whether an avoidance maneuver is required [13, 14]. These results suggest that a more stringent definition of DAA Well Clear may be advisable in the terminal area [11, 15], which will hopefully decrease "nuisance" alerts while maintaining a safe distance from appropriately behaving traffic in the terminal area flight pattern.

Appendix A

For computing LoWC, equations for τ_{mod}, HMD, and d_h are

$$\tau_{mod} = \frac{DMOD^2 - r^2}{r\dot{r}} \doteq \text{Modified Tau [time]}$$

$$\begin{aligned} \text{where } DMOD &\approx HMD^* \\ r &= \text{xy-range between vehicles} \\ \dot{r} &= \text{xy-range rate between vehicles} \end{aligned}$$

$$HMD = \sqrt{(d_x + v_x t_{CPA})^2 + \left(d_y + v_y t_{CPA}\right)^2}$$

$$\begin{aligned} \text{where } HMD &= \text{Horizontal Miss Distance} \\ d_{[x,y]} &= \text{distance in the } [x, y] \text{ direction} \\ v_{[x,y]} &= \text{velocity in the } [x, y] \text{ direction} \\ t_{CPA} &= \text{time at closest point of approach} \end{aligned}$$

and

$$
\begin{aligned}
d_h &= \text{abs}\left(h_{AC_2} - h_{AC_1}\right) \\
\text{where } h &= \text{height} \\
AC &= \text{aircraft.}
\end{aligned}
$$

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