Detect and Avoid Alerting Performance with Limited Surveillance Volume for Non-Cooperative Aircraft

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This paper investigates effects of limited surveillance volume on the alerting performance of a Detect and Avoid (DAA) system for unmanned aircraft systems (UAS). The surveillance volume accounts for an airborne sensor capable of detecting non-cooperative aircraft. Independent variables include four candidate DAA Well Clear (DWC) definitions and five surveillance volumes. Open-loop alerting performance metrics are computed from the results of running a reference DAA algorithm on a large number of synthesized encounters. The speed range for the UAS traffic considered is between 40 and 100 kts. Results show that, with a 2.5 nmi sensor range, all four candidate DWCs allow at least an average of 25 seconds warning alert times before a loss of DWC. Cumulative distributions of the intruder's bearing and elevation at the first warning alert suggest that ±10° and ±140°, respectively, are sufficient for alerting $> 95\%$ of the encounters that lead to losses of DWC.

I. Nomenclature

AGL	=	above ground level
C-SWaP	=	cost, size, weight, and power
DAA	=	detect and avoid
DWC	=	DAA Well Clear
D_{mod}	=	distance modification
HMD	=	horizontal miss distance
LoDWC	=	loss of DWC
MOPS	=	minimum operational performance standards
MSL	=	mean sea level
OE	=	operational environment
NMAC	=	near mid-air collision
RADES	=	radar evaluation squadron
SC-228	=	special committee 228
TCAS	=	Traffic Alert and Collision Avoidance System
TSO	=	Technical Standard Order
UAS	=	unmanned aircraft system
VFR	=	visual flight rules
h	=	altitude separation between two aircraft
r	=	range between two aircraft
$\dot{r}$	=	range rate
t	=	time
τ_{mod}	=	modified tau

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II. Introduction

Successful integration of Unmanned Aircraft System (UAS) operations in the National Airspace System (NAS) cannot be realized without adequate Detect and Avoid (DAA) Systems. A DAA system provides surveillance, alerts, and maneuver guidance to keep a UAS "well clear" of other aircraft [1, 2]. In the United States, simulation tests as well as flight tests have provided supporting information for defining a DAA Well Clear [1, 3] (DWC) and requirements for the alerting and maneuver guidance performance [4–8]. Prototype DAA algorithms have also been developed for alerting and maneuver guidance (referred to as guidance in this paper) research [9–11]. These developments enabled the RTCA Special Committee 228 (SC-228) to publish the Minimum Operational Performance Standards (MOPS) for DAA systems [12] and air-to-air radar [13] in 2017. The corresponding Technical Standard Orders (TSO), TSO-C211 and TSO-C212, were published by the Federal Aviation Administration (FAA) in October 2017. These standards, referred to as the Phase 1 MOPS, target UAS operations in non-terminal areas. A DAA system, according to the Phase 1 MOPS, contains surveillance components of Automatic Dependent Surveillance-Broadcast (ADS-B) In, airborne active surveillance, and air-to-air radar that can detect aircraft with or without transponders. Traffic Alert and Collision Avoidance System (TCAS) II [14] is an optional component. Phase 2 work for extending the MOPS to additional UAS categories and operations is underway.

One of the Phase 2 objectives is to define requirements for operations by UAS equipped with low cost, size, weight, and power (low C-SWaP) sensors. These UAS missions are envisioned to fly much slower than 200 kts, the maximum UAS airspeed in the Phase 1 MOPS. For these UAS and their missions, a large and high-power radar, as required by the Phase 1 radar MOPS, is physically infeasible and/or economically impractical. Examples of missions in this category are air quality monitoring, aerial imaging and mapping, and flood inundation mapping [15]. While low C-SWaP sensors are desirable for these missions, they must provide sufficient surveillance volume and accuracy to ensure the DAA system's capability of maintaining safety.

Another Phase 2 objective seeks an alternative DWC for UAS with non-cooperative aircraft, i.e., aircraft without a functioning transponder. The DWC in the Phase 1 work was selected with considerations of interoperability with TCAS-II. To avoid triggering TCAS's resolution advisories during an encounter which leads to DAA maneuvers, the DWC was defined to enclose a vast majority of the TCAS alerting volume [1]. The resulting DWC is deemed very safe but may be unnecessarily large for encounters of UAS with non-cooperative aircraft, which TCAS-II cannot detect and therefore need not be considered. Four candidate DWCs were proposed for additinal analyses following an analysis of encounters representing low C-SWaP UAS operations [16].

As a direct support of SC-228 Phase 2 MOPS work, this paper analyzes the effects of surveillance volume on the DAA's alerting performance. Adequate surveillance volume provides sufficient alerting timelines for UAS operators or pilots to maneuver upon DAA's guidance. Additional surveillance volume may provide marginal benefit to the DAA system's overall performance while raising the required C-SWaP of the sensor to a level too high for the feasibility of many UAS operations. Figure 1 depicts a notional plot of the relationship between the DAA system's performance and surveillance volume. The DAA system's performance can be measured by safety metrics, operational suitability, pilot acceptance, etc. Here, an operational environment (OE), defined by parameters such as airspace, mission type, and speed range, can vary the performance of a DAA system. In addition to identifying an adequate surveillance volume, this paper also analyzes the alerting timeline's sensitivity to a DWC by comparing results across four candidate DWCs for non-cooperative aircraft. Results will inform the SC-228 of the selection of a final DWC as well as recommendations to alerting and surveillance requirements.

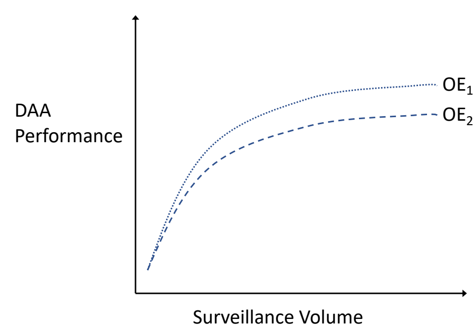


Fig. 1 The DAA performance vs. surveillance volume.

This paper is organized as follows: Section III provides background information about the DWC, alerting, guidance, and operational assumptions. The alerting metrics, encounter set, and the experiment matrix for this work are described in Section IV. For this study, four candidate DWCs and five surveillance volumes serve as independent variables. Section V presents results and discusses variations across DWCs.

III. Background

A. Detect-and-Avoid Well Clear, Alerting, and Guidance

The DAA system aims to keep the UAS "well clear" of other aircraft. The DWC defines, in a quantitative way, the well clear volume around other aircraft the UAS should avoid. Requirements for alerting and guidance are built upon a DWC definition. For reasons stated in Section II, considerations for an alternative DWC for UAS and non-cooperative aircraft were investigated and four candidate DWCs, two primary and two secondary (backup), were proposed for additional analyses [16]. Table 1 lists the four candidate DWCs. The Phase 1 DWC is also listed at the bottom of the table for comparison. Appendix VI defines the parameters, HMD*, $\tau_{mod}{}^{*}$, and h^{*} in detail.

Table 1 Candidate DWCs for non-cooperative aircraft (Phase 1 DWC shown at bottom)

Name	HMD* (ft)	$\tau_{mod}{}^{*}$ (sec)	h^{*} (ft)	Comment
DWC1	2000	15	450	Primary
DWC2	2200	0	450	Primary
DWC3	1500	15	450	Secondary
DWC4	2500	25	450	Secondary
Phase 1	4000	35	450	Phase 1 DWC

DWC2 does not have a time component, τ_{mod}, in its definition. The implication of this is, regardless of closure rate, intruders (usually manned aircraft) must be within 2,200 ft (0.36 nmi) of the UAS horizontally to result in a LoDWC. On the other hand, the τ_{mod} component in DWC1 can cause a LoDWC when the two aircraft are still 1 nmi apart horizontally if the closure rate between the aircraft is high enough. In general, for most closure rates a LoDWC will occur earlier with DWC1 than with DWC2.

The DAA alerting structure consists of three alert types:

1) Preventive: a caution level alert that advises the pilot to maintain the UAS's current altitude in order to avoid conflicts.
2) Corrective: a caution level alert that advises the pilot to coordinate with ATC before maneuvering.
3) Warning: a warning level alert that requires immediate action from the pilot to start maneuvering in order to maintain DWC.

In addition to the three alert types, if the DAA system is equipped with TCAS-II (Equipment Class 2 system only [12]), TCAS alerts may be triggered. The preventive alert is irrelevant for encounters involving non-cooperative aircraft due to the lack of accurate vertical (altitude and vertical speed) surveillance data. The analysis in this paper targets only the corrective and warning alerts. Figure 2 shows the alerting timeline as well as the corresponding guidance.

The guidance include ranges of heading and altitude predicted by the DAA system to have a high likelihood of leading to losses of DWC (LoDWC). There is a corresponding guidance for each alert type. Aircraft performance parameters such as turn, climb, and descent rates can be used for computing the ranges of heading and altitude. The DAA MOPS also defines display requirements for alerts and guidance. Figure 3 shows an example of display of a warning alert and guidance, where AC01 represents the position of an intruder and the triangle at the center of the circle represents the position of the ownship (the unmanned aircraft). The ranges of heading and altitude predicted to lead to conflicts are displayed in bands with a red color specifically for the warning alert.

If the ownship gets too close to the intruder, a LoDWC may become inevitable even with maneuvers. In this situation, the guidance bands display all red for heading and altitude, but at the same time computes "regain well clear" bands to assist the ownship in maneuvering in order to regain well clear effectively. Regain-well-clear is referred to as well clear recovery (WCR) in this paper. The WCR usually takes place earlier than a LoDWC during an encounter.

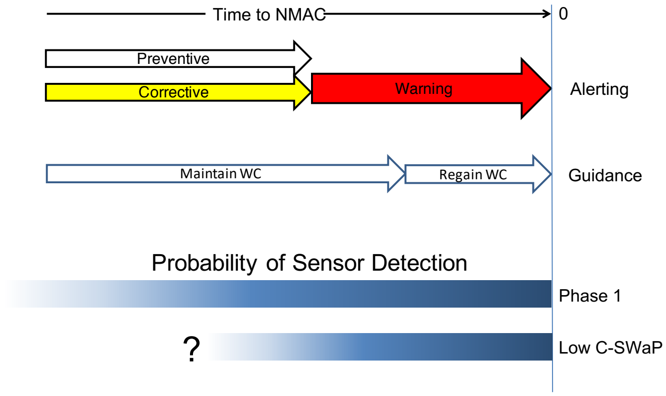


Fig. 2 Alerting timeline and the target detection time provided by the surveillance volume.

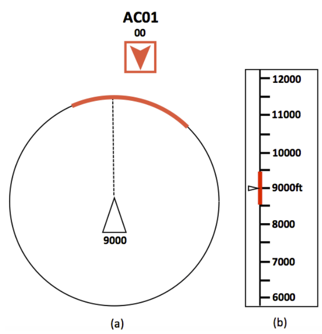


Fig. 3 Display of the Warning alert and guidance (reprinted from MOPS DO-365 of RTCA with permission).

B. Surveillance

The Phase 1 radar, the only sensor that detects non-cooperative aircraft, requires a target declaration volume of 6.7 nmi range,* ±110° bearing, and ±15° elevation. This surveillance volume allows more than enough alerting time for warning alerts in an encounter with the highest possible closure rate (370 kts). For detection of cooperative aircraft, both ADS-B and active surveillance provide even greater detection range (> 15 nmi).

The Phase 2 work seeks to create requirements for low C-SWaP sensors, which are expected to have smaller surveillance volume than that of the Phase 1 radar. Associated with a low C-SWaP sensor are requirements for an alternative DWC as well as alerting and guidance. ADS-B and active surveillance are still required of the DAA system for detection of cooperative aircraft (those with functioning transponders and/or ADSB-out.) The following observations serve to justify lower sensor requirements than the Phase 1 radar while still maintaining operational safety in the airspace:

- Encounters between UAS and non-cooperative aircraft will be relatively infrequent given the fact that, after year 2020, most airspace will mandate ADS-B on aircraft. Even in the airspace outside the ADS-B mandate, i.e., Class E under 10,000 ft MSL, non-cooperative aircraft comprise a small percentage (estimated 15%) of the traffic [12].
- An alternative, smaller DWC should give UAS operators more time to maintain DWC.
- The Phase 1 operations support UAS speeds up to 200 kts, a speed much higher than the optimal speed for many UAS operations with low C-SWaP sensors. The lower closure rate considered allows for more alerting time.
- Even if the surveillance volume is not enough to support correct alerts, a UAS pilot/operator is likely to be able to maintain separation if warning alert and guidance is provided with enough time.

Figure 2 also compares the alerting timeline to the detection time provided by surveillance. The detection time is related to the sensor's detection range, and bearing and elevation to a lesser extent, by the probabilistic distribution of closure rates during encounters.

*The 6.7 nmi is the range for large non-cooperative intruders. Smaller ranges are required for medium and small intruders [13].

C. UAS Operations with a Low C-SWaP Sensor

Some of the operational assumptions specific to low C-SWaP operations are given below:

- Extended UAS operations in non-terminal Classes D, E, and G airspaces, as well as those transitting Classes B and C airspaces.
- UAS mission speed range is between 40 and 100 kts.
- UAS is capable of turning horizontally at a rate of 7 deg/s during a maneuver upon DAA guidance.
- The non-cooperative aircraft's airspeed is assumed to be at or below 170 kts (95% percentile [17]).
- No non-cooperative aircraft exist above 11,000 ft MSL.
- Below 500 ft AGL, the airborne sensor for non-cooperative aircraft is not responsible for detecting intruders.

IV. Experiment Plan

The objectives of this analysis are the following:

1) to identify adequate surveillance volume for detecting non-cooperative aircraft that ensures acceptable DAA alerting performance.
2) to investigate sensitivity of the alerting timeline to variation of the DWC

A surveillance volume is characterized by range (distance), bearing range, and elevation range. For simplicity, bearing and elevation are assumed to be with respect to an aircraft reference frame with zero roll and pitch angles. The following sections discuss the alerting metrics, the DAA algorithm, and the encounter set used for this analysis.

A. Alerting Metrics

The following open-loop (no UAS maneuver) alerting performance metrics are computed:

- Average alert time before LoDWC: the average time before the LoDWC at which the alerting system issues an alert.
- Average alert time before WCR: the average time before the WCR at which the alerting system issues an alert.
- Late Alert probability: a late alert occurs where an intruder has a LoDWC but the alerting system issues an alert less than the required time before LoDWC. The required time is 20 seconds for corrective alerts and 15 seconds for warning alerts.

Only encounters that lead to LoDWCs are considered.

B. Detect-and-Avoid Algorithm

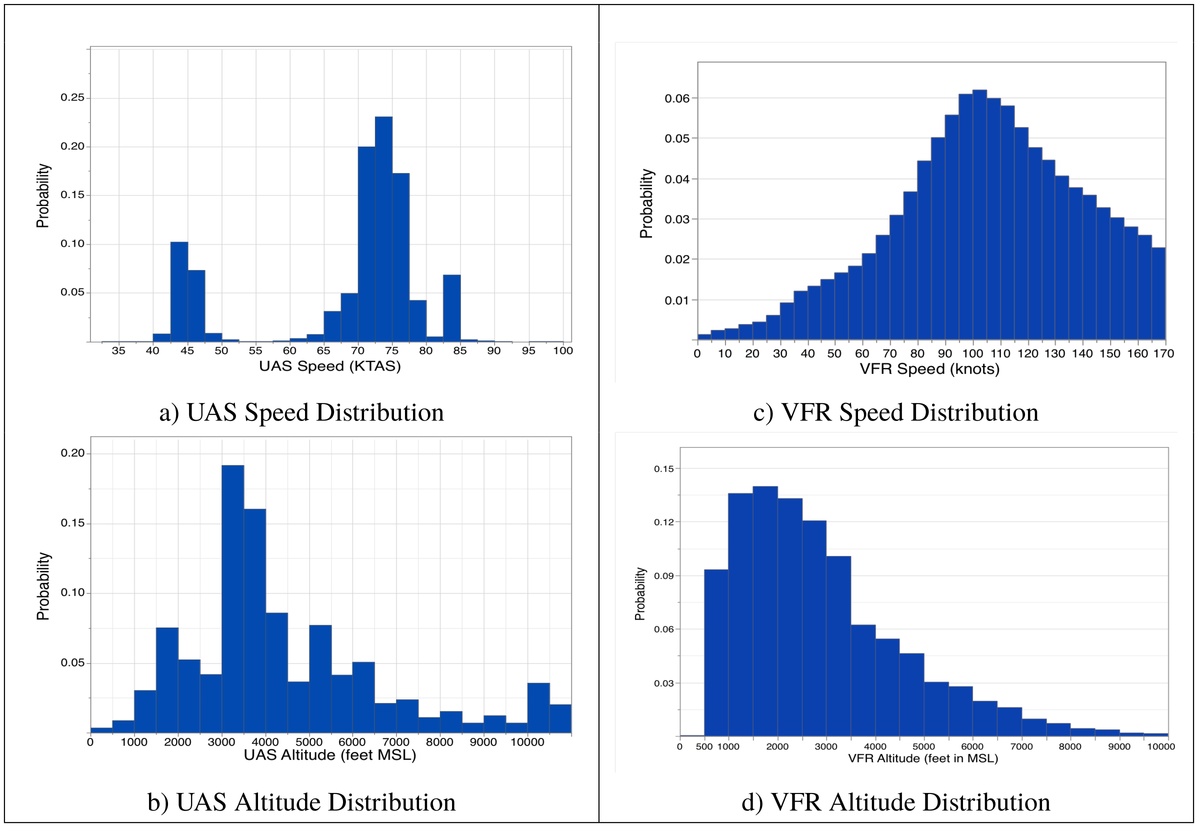
The open-source Detect and AvoID Alerting Logic for Unmanned Systems (DAIDALUS) [10], a reference DAA algorithm for the Phase 1 MOPS, is invoked to generate alerting sequences for the performance analysis. A standard configuration file† containing alerting parameters for DAIDALUS serves as a starting point, while some parameters affine to the DWC are modified according to the candidate DWCs considered. The conflict zone the alerting and guidance protects is based on each DWC with its HMD* buffered by a factor of 1.519 (following the Phase 1 setting). The buffer gives the system a few seconds to alert against aircraft suddenly maneuvering towards the UAS. Corrective and warning alerts are issued if intruders are predicted, with a constant velocity assumption, to enter the conflict zone within 60 and 30 seconds, respectively. DAIDALUS also allows specification of aircraft maneuverability parameters such as the rates of turn, climb, and descent. The turn rate affects the WCR time. For this study the turn rate is set to 7 degrees per second. Only horizontal guidance is considered when calculating the WCR time. The vertical guidance is muct less robust in reality due to the uncertainties of vertical states, including altitudes and vertical speeds.

C. Encounter Set

An entire day's worth of UAS flights are considered for this study. These flights consist of 12 different types of missions considered suitable for UAS with low C-SWaP sensors. The demand and mission profiles were generated based on subject matter experts' opinions and socio-economical analysis [15]. These missions cover the entire continental US and amount to a total of 17,100 hours flight time. Details of the twelve missions are described in a previous publication [16].

For the intruder traffic, nation-wide VFR flight paths flown in 2012 were extracted from the historical Air Force 84th Radar Evaluation Squadron (RADES) radar data. The VFR track data, including non-cooperative aircraft and

† `https://github.com/nasa/WellClear/blob/master/DAIDALUS/Configurations/WC_SC_228_nom_b.txt`



a) UAS Speed Distribution

c) VFR Speed Distribution

b) UAS Altitude Distribution

d) VFR Altitude Distribution

Fig. 4 Speed and altitude distributions of UAS and VFR traffic.

cooperative aircraft with 1200 transponder code[‡] were processed to remove measurement noise and generate continuous trajectory data. Due to the limited number of non-cooperative VFR trajectories available, 1200-code cooperative VFR aircraft are used as a surrogate for non-cooperative aircraft for this study. This is a reasonable approach since the flight characteristics of conventional non-cooperative aircraft are similar to those using cooperative VFR aircraft in terms of airspeed, acceleration, and turn rate [18]. Figure 4 shows the speed and altitude distributions of UAS and intruder by flight hours. Only data within the speed and altitude ranges considered for low C-SWaP encounters are shown.

Encounters are identified when UAS trajectories are overlaid with the VFR traffic. A software suite was developed to detect and produce encounters from these overlaid trajectories [19]. To analyze only the encounters that fit the low C-SWaP operational assumptions, the encounter data were filtered by the altitude and speed of ownship and intruder aircraft. Unmanned aircraft whose speed at the closest point of approach (CPA) is between 40 and 100 kts, and altitude at the CPA is below 11,000 ft MSL and above 500 ft AGL, were selected. Non-cooperative intruder aircraft whose speed at CPA is less than 170 kts and altitude at CPA is below 11,000 ft MSL and above 500 ft AGL were selected for the simulation.

D. Experiment Matrix

Table 2 shows the full experiment matrix with values of these independent variables. The alerting performance metrics computed from the encounter set can be regarded as optimistic upper bounds. Realistic sensors usually have limited bearing and elevation ranges that will reduce the alerting performance.

V. Results

Encounters created from overlaying the VFR traffic recorded for twenty-one days in 2012 with the the same one-day UAS trajectories, respectively, were analyzed. The encounter set was analyzed using DAIDALUS for each combination

[‡] VFR flights in uncontrolled airspace will "squawk VFR" (1200 in the US, 7000 in Europe).

Table 2 The experiment matrix

Variable		Value
DWC		DWC1, DWC2, DWC3, DWC4
Surveillance Volume	Range (nmi)	1, 2, 3, 4, 8
	Bearing Range (deg)	$(-180, 180]$
	Elevation Range (deg)	$(-90, 90]$

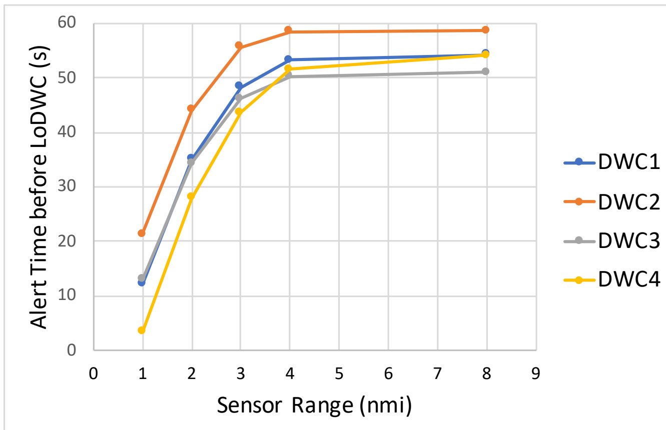


Fig. 5 Comparison of average corrective alert times before LoDWC.

of the four candidate DWC and five surveillance volumes. A total of 434 NMACs were recorded. The number of LoDWCs varies from DWC to DWC. It is about 8120 for DWC1, 8170 for DWC2, 6200 for DWC3, and 11020 for DWC4. Only the first LoDWC in an encounter is analyzed.

A. Alerting Metrics

Figure 5 shows the average corrective alert time before LoDWC. The general trend is that the more range that is available, the more alerting time. The range of the highest end of 8 nmi is slightly greater of the Phase 1 radar and serves as an upper bound for the low C-SWaP sensor. Going down to a 4 nmi range affects the average corrective alert time minimally for DWC1, DWC2, and DWC3. For DWC4, the average corrective time decreases by a noticeable amount of 5 seconds. Below 4 nmi, the corrective alert time for DWC4 falls below that of the other DWCs. This is expected since DWC4 is the largest and thus more sensitive to surveillance volume reduction. DWC2 yields a consistently higher average alert time than the other three DWCs'.

Figure 6 shows the average warning alert time before LoDWC. The values at 4 nmi and 8 nmi are essentially identical, indicating that a 4 nmi range encloses the entire warning alert zone of all four DWCs. The warning alert time for DWC1, DWC2, and DWC3 stays almost the same with a 3 nmi range. The value for DWC4 drops by only 2 seconds at a 3 nmi range. At a 2 nmi range DWC2 is only slightly affected while DWC1 and DWC3's warning alert times drop to 28 seconds. The Phase 1 MOPS expects 25 seconds warning alert time for non-accelerating encounters to support pilot response and maneuver execution. Not all encounters in the encounter set can achieve 25 seconds because some encounters involve maneuvering intruders or ownship. Therefore, an average warning alert time of 25 seconds is likely to be deemed acceptable. This seems to suggest that 2 nmi might be acceptable for DWC1, DWC2, and DWC3. However, these alerting times are optimistic upper bounds and will be reduced by limited bearing and elevation ranges that occur in reality. Therefore, a minimum range of 2.5 nmi seems a more practical requirement.

Since the corrective alert is likely to be regarded as optional for operations of UAS with low C-SWaP sensors, the following discussion will focus on only the warning alert metrics.

Figure 7 shows the average warning alert time before WCR. This metric indicates the amount of time UAS operators or pilots have upon receiving a warning alert until it is too late to maintain DWC. Prior research indicates that it takes

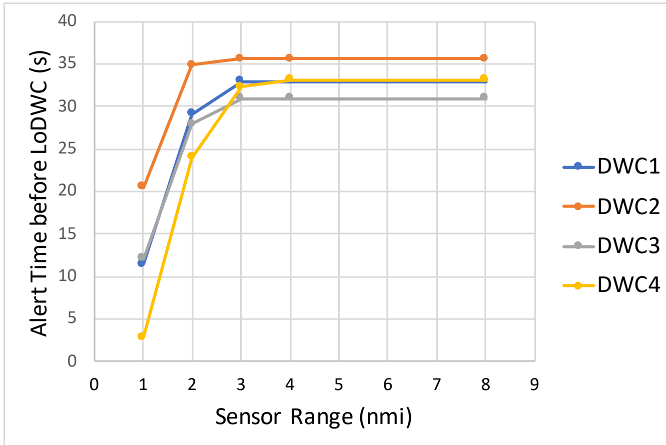


Fig. 6 Comparison of average warning alert times before LoDWC.

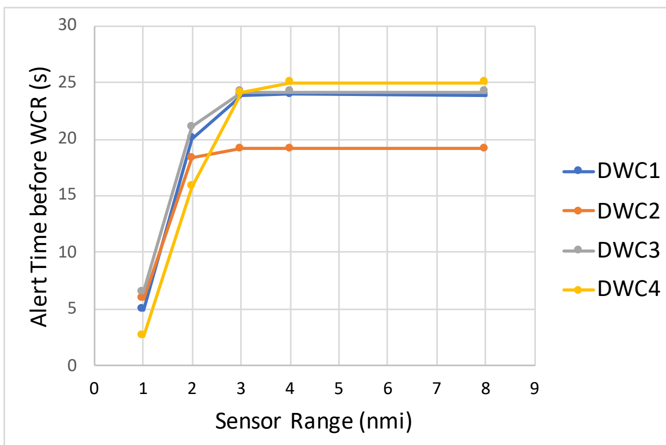


Fig. 7 Comparison of average warning alert times before WCR.

pilots about 10 seconds to respond and execute a maneuver upon a warning alert and guidance [7]. With that information, the alert times for $\geq$ 2 nmi range are deemed acceptable for all four DWCs. Interestingly, DWC2 yields less alert time before WCR compared to the other three DWCs. This is because, in general, alerts with DWC2 start later during an encounter while its WCR time is about the same as that of DWC1.

Figure 8 shows late alert percentages for warning alert. A warning alert is regarded late by the Phase 1 MOPS if the first alert starts within 15 seconds of the LoDWC. An late alert happens usually because an intruder maneuvers towards the ownship when the two aircraft are already close. However, if the surveillance volume is very limited a late alert can occur even for a non-accelerating intruder. This is undesirable. DWC2 is more resilient against surveillance range limitation than the other three DWCs, showing a consistent low percentage of late alerts down to 2 nmi range.

B. Distribution of Initial Warning Alert Location

The surveillance volume should ideally support the warning alert timeline for a majority of the encounters. To investigate what bearing and elevation scan can achieve this, locations of the initial warning alert in the run with an 8 nmi range were further analyzed.

Figure 9 shows the cumulative distribution of the range at the start of a warning alert. The 90 percentile range is 2.6, 2.1, 2.5, and 3.1 nmi for DWC1, DWC2, DWC3, and DWC4, respectively. The 95 percentile range is 2.8, 2.3, 2.8, and 3.5 nmi for DWC1, DWC2, DWC3, and DWC4, respectively. This chart provides insight of what the minimum sensor detection range should be to detect a specified percentile of first warning alerts. If the sensor detection range is less than the required minimum range, then the warning alert timeline is likely to be cut short and may leave operators or pilots

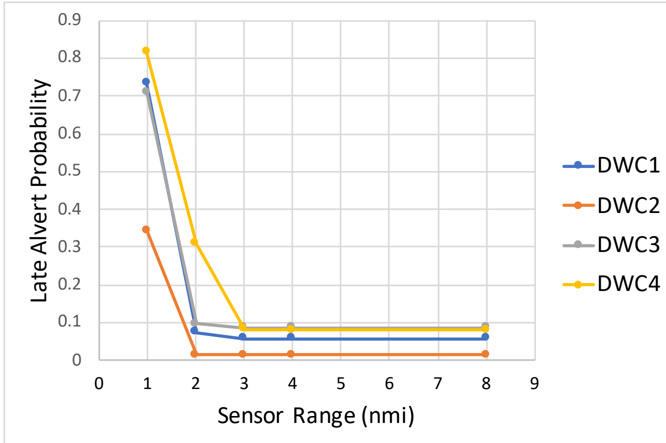


Fig. 8 Late alert percentage for warning alert.

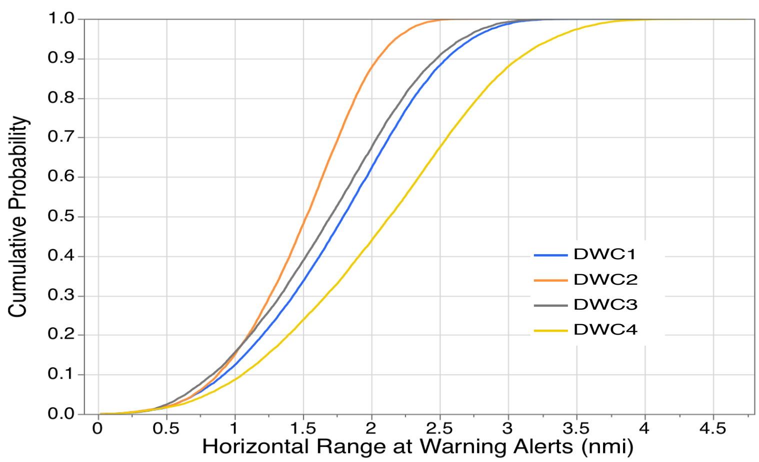


Fig. 9 Cumulative distribution of the range at the start of a warning alert.

insufficient time to maintain DWC.

Figure 10 shows the cumulative distribution of the bearing at the start of a warning alert. The 90 percentile bearing scan happens at 110° and 95 percentile at 140° for all four DWCs. Thus, the minimum required bearing for a sensor needs to be at least 110° for all four DWCs if the sensor is required to detect more than 90 percentile of warning alerts at the start time.

Figure 11 shows the cumulative distribution of the elevation at the start of a warning alert. The 90 percentile elevation scan happens at 6° and 95 percentile at 10° for all four DWCs. This chart shows that ±10° of elevation might be sufficient to detect 95 percentile of warning alerts at the start time for all four DWCs.

VI. Summary and Future Work

This study analyzes dependency of a DAA system's alerting performance on the surveillance volume of an onboard sensor. The operations considered are those in which an UAS is equipped with a low C-SWaP sensor responsible for detecting non-cooperative aircraft. The independent variables are the four candidate DWCs recommended in prior work and five surveillance volumes. Results show that a 2.5 nmi range can comfortably support an average of 25 second warning alert for all the DWCs. DWC2 among the four DWCs is the least sensitive to limited surveillance range and its alerting time is almost unaffected down to a 2 nmi range. A detection range that covers 95% of the beginning of a warning alert varies across DWCs, ranging from 2.3 (for DWC2) to 3.5 nmi (for DWC4). Cumulative distributions of the warning alert start location indicate that an elevation scan of ±10° and a bearing scan of ±140° will ensure that 95%

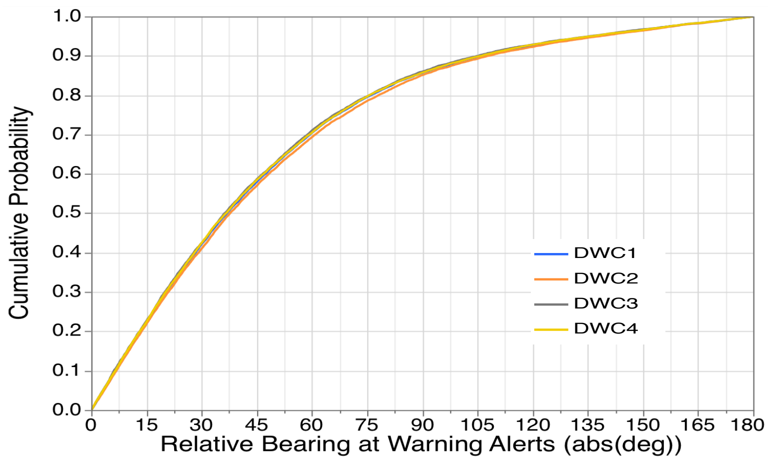


Fig. 10 Cumulative distribution of the bearing at the start of a warning alert.

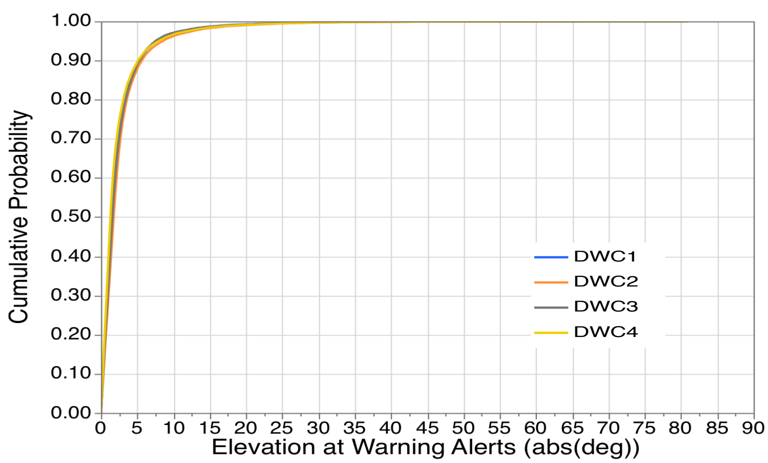


Fig. 11 Cumulative distribution of the relevation at the start of a warning alert.

of intruders are detected at the start of a warning alert. Results of this study will provide supporting information for the RTCA Special Committee 228 about determining low C-SWaP sensor requirements as well as changes to DAA's alerting requirements.

The surveillance volume required for supporting the alerting performance, derived from this analysis, is an optimistic lower bound. Sensor uncertainties and the time taken by radar to declare a target after detection are expected to raise the bound. Moreover, alerting performance by itself is not enough to ensure effectiveness of a DAA algorithm. As a next step, the guidance algorithm will also be evaluated by closed-loop simulations involving realistic sensor uncertainties and pilots' maneuvers. These analyses will evaluate the DAA algorithm's performance as a whole and provide additional supporting information for the requirements of the low C-SWaP operations.

Appendix: DAA Well Clear and Conflict Zone

The DAA well clear (DWC) zone for the UAS targeted in the Phase 1 MOPS is defined by thresholds of three parameters. It does not have distinct physical boundaries because the definition depends on two aircraft's relative position and velocity during an encounter. Figure 12 illustrates a DWC zone.

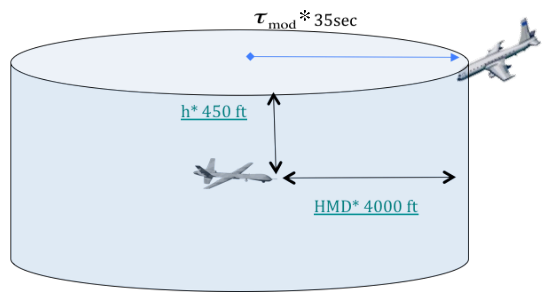


Fig. 12 A schematic representation of the DWC zone.

The Horizontal Miss Distance (HMD) represents the two aircraft's predicted minimum horizontal distance during an encounter assuming constant velocities. The parameter h represents the two aircraft's current altitude difference. The time metric modified tau, τ_{mod}, is an estimated time taken for the two aircraft to intersect the "protection" disk. The range rate is negative for closing geometries. The positive incremental distance modifier D_{mod} defines the radius of a "protection" disk around the Ownship such that any intruder with a horizontal range less than D_{mod} is always considered "urgent". In this case, $\tau_{mod} = 0$. The thresholds, denoted by an asterisk, for the HMD, h, and τ_{mod} are 4000 ft, 450 ft, and 35 sec, respectively. All three parameters must simultaneously fall below their respective thresholds during an encounter for the two aircraft to violate the DWC. Alerting algorithms are designed to reduce the probability of violating DWC to a value required by the MOPS.

The definition of τ_{mod} is [2]

$$\tau_{mod} = \begin{cases} -\frac{r^2 - D_{\text{mod}}{}^2}{r\dot{r}}, r > D_{\text{mod}}, \\ 0, r \leq D_{\text{mod}} \end{cases} \tag{1}$$

where r and $\dot{r}$ are the horizontal range and range rate between the intruding aircraft and the UAS, respectively. The value of D_{mod} must be equal to HMD* to avoid the undesirable on-and-off alert during some constant velocity encounters [20].

DAIDALUS's alert conflict zone is defined in a similar way to the DWC, using thresholds of the three variables HMD, h, and τ_{mod}. For this work, the HMD threshold is increased to 1.529 times each DWC's HMD* to account for sensor and intruder intent uncertainties.

References

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