Detect-and-Avoid Closed-Loop Evaluation of Non-Cooperative Well Clear Definitions

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Four candidate detect-and-avoid well clear definitions for unmanned aircraft systems encountering non-cooperative aircraft are evaluated using safety and operational suitability metrics. These candidates were proposed in previous research based on unmitigated collision risk, maneuver initiation ranges, and other considerations. Non-cooperative aircraft refer to aircraft without a functioning transponder. One million encounters representative of the assumed operational environment for the detect-and-avoid system are simulated using a benchmark alerting and guidance algorithm as well as a pilot response model. Results demonstrate sensitivity of the safety metrics to the unmanned aircraft's speed and the detect-and-avoid system's surveillance volume. The only candidate without a horizontal time threshold, named modified tau, outperforms the other three candidates in avoiding losses of detect-and-avoid well clear. Furthermore, this candidate's alerting timeline lowers the required surveillance range. This can help reduce the barrier of enabling unmanned aircraft systems' operations with low size, weight, and power sensors.

Nomenclature

D_{mod} = distance modification, the radius of a protection disk around the unmanned aircraft

P = unmitigated collision risk

r = horizontal range between two aircraft

$\dot{r}$ = horizontal range rate

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τ_{mod} = modified tau, approximate time needed for the two aircraft to intersect a protection disk

I. Introduction

Successful integration of Unmanned Aircraft System (UAS) operations into airspaces populated with manned aircraft relies on an effective Detect and Avoid (DAA) System. A DAA system provides surveillance, alerts, and maneuver guidance to keep a UAS "well clear" of other aircraft [1, 2]. Despite significant advances in aircraft, surveillance, and communication technologies in the past three decades, lack of research-backed specific requirements for DAA systems continues to hinder the integration of UAS into the national airspace systems (NAS). In recent years, government, industry, and academia started working together on addressing this gap. In the United States, simulations as well as flight tests have provided supporting information for defining a DAA well clear (DWC) [1, 3] and requirements for the alerting and maneuver guidance performance [4–8]. Prototype alerting and maneuver guidance (referred to as guidance in this paper) algorithms have also been developed [9–11]. These developments, along with other technical work, 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 transitioning to and from Class A or special use airspace (higher than 500 ft above ground level (AGL)), traversing Class D, E, and G airspace. The Phase 1 MOPS assumes the UAS operations follow instrument flight rules, involve a pilot in the decision loop, and fly with a speed between 40 and 200 KTAS. A Phase 1 MOPS compliant DAA system must include the following surveillance components: Automatic Dependent Surveillance-Broadcast (ADS-B) In, airborne active surveillance, and an air-to-air radar. Traffic Alert and Collision Avoidance System (TCAS) II [14] is an optional equipment. Phase 2 development for extending the MOPS to additional UAS categories and operations is underway. Ground-based surveillance technology [15] and DAA concept [16] developed in recent years is also to be included in the Phase 2 development.

One objective of the Phase 2 development is to define an alternative DAA Well Clear (DWC) for UAS encountering non-cooperative aircraft, i.e., aircraft without a functioning transponder. Non-cooperative aircraft are estimated to comprise a small but non-negligible 15% of the flights in the airspaces outside the ADS-B mandate rule airspace [12]. While aircraft with a functioning transponder can be detected by ADS-B and/or active surveillance, non-cooperative aircraft can only be detected by the air-to-air radar of the DAA surveillance. If the UAS is also equipped with TCAS II, both DAA and TCAS II alerts and guidance can be active during an encounter. The DWC in the Phase 1 MOPS was selected with considerations of interoperability of the DAA system with TCAS-II. DAA alerts have longer look-ahead time and should trigger before TCAS II alerts do. DAA guidance, when executed, should ideally be able to avoid TCAS II alerts in most situations. With this consideration, the DWC was defined to encompass a large portion of the TCAS II

resolution advisories (RA) alerting volume. The resulting DWC is deemed very safe but is unnecessarily large for encounters of UAS with non-cooperative aircraft, which TCAS-II cannot detect and therefore need not be considered. In a previous study, four smaller candidate DWCs, specifically for non-cooperative aircraft, were proposed for additional evaluation [17]. Selection of these candidate DWCs was based on unmitigated collision rates, maneuver initiation ranges, and a few other factors.

Another objective of the Phase 2 development is to define requirements for operations of UAS equipped with low size, weight, and power (SWaP) sensors, or low SWaP UAS. While ADS-B and active surveillance can fit in the payload of many medium-sized UAS, the large, high-power radar required by the Phase 1 MOPS is physically infeasible and/or economically impractical for many UAS operations. Low SWaP sensors have favorable payloads but provide smaller surveillance volumes. For safety and operational suitability, UAS pilots need sufficient alerting times to evaluate and execute DAA maneuvers in order to maintain separation defined by the DWC. Compared to the Phase 1 radar surveillance volume requirements, two factors can potentially drive down the demand of the low SWaP sensors' surveillance volume, particularly its horizontal range. First, many UAS operations with low SWaP sensors are expected to be conducted at speeds much lower than 200 KTAS. Taking into account these lower mission speeds can reduce the demand of the low SWaP sensors' horizontal range. Second, an alternative DWC smaller than the Phase 1 definition gives UAS pilots more time from the maximum surveillance range to the DWC boundary to evaluate the situation and maneuver away from an intruder. Since UAS pilots do not need more time than what is already allocated in the set of Phase 1 requirement, this reduction of DWC will "free up" part of the originally required surveillance range.

Still another objective of the Phase 2 development seeks to increase the upper bound of the unmanned aircraft (UA) speed assumed in the Phase 1 MOPS from 200 KTAS to 250 KTAS or higher. Note the term UA instead of UAS is used when referring to specifically the vehicle's performance parameters such as speed or turn rate. The ability of a DAA system to maintain separation effectively for such high-speed UAs during encounters needs to be investigated. The adequacy of the Phase 1 radar requirements for high-speed UAs should be assessed as well.

This paper evaluates four candidate DAA Well Clear (DWC) definitions [17] by computing their safety and operational suitability metrics from closed-loop simulations. Execution of DAA maneuvers makes the simulations closed-loop. One million encounters covering a wide range of UA speeds are simulated. DAA maneuvers are computed using a reference alerting and guidance algorithm, and executed according to a research-backed pilot response model. Effects of finite surveillance volume as well as UA speeds on the metrics are also investigated.

The main contributions of this paper are the following:

1) Development of a simulation framework for the evaluation of DWCs

2) Providing safety and operational suitability metrics for informing RTCA SC-228 and the community in areas of the aforementioned three key objectives: 1. non-cooperative DWC, 2. low SWaP sensor requirements, and 3. high-speed UAS operations

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This paper is organized as follows: Section II presents additional background about the development of the DWC. Section II also reviews the considerations taken to propose the candidate DWCs. Section III describes the metrics, simulation architecture, and details of each simulation component. Results are presented in Section IV, additional discussion included in Section V, and conclusions are given in Section VI.

II. Background on Detect-and-Avoid Well Clear

The need for a DWC for UAS operations derives from the requirement for manned aircraft pilots stated under Title 14 of the Code of Federal Regulations (14 CFR). The intent of these regulations is to avoid collisions, remain well clear from other aircraft, and comply with right-of-way rules. For UAS, the pilots are not in the flight deck to "see and avoid," so pilots must rely on surveillance and algorithms for situation awareness and conflict avoidance. In this situation, the separation standard, or the DWC, must have a quantitative definition. The DWC is expected to be larger than the near-mid-air-collision (NMAC), a safety standard for the evaluation of collision avoidance systems. Two aircraft are in an NMAC if they are separated less than 500 ft horizontally and less than 100 ft vertically [14]. The development of the DWC in the Phase 1 MOPS started in the Sense-and-Avoid Science and Research Panel (SaRP). The SaRP-recommended DWC was later modified by SC-228 based on recommendation from the FAA to improve its operational suitability [1, 3]. Note this DWC has been analyzed and researched only within the operational environment defined by the Phase 1 MOPS. It is likely to be also applicable to extended operations to be defined in the Phase 2 MOPS. For operational environments not covered by these MOPS, alternative DWCs may be more suitable [18].

The DWC in the Phase 1 MOPS is defined by thresholds of three parameters. It does not have distinct physical boundaries because its definition depends on two aircraft's positions and velocities. Figure 1 gives a schematic representation of the DWC definition. The Horizontal Miss Distance (HMD) represents the two aircraft's predicted
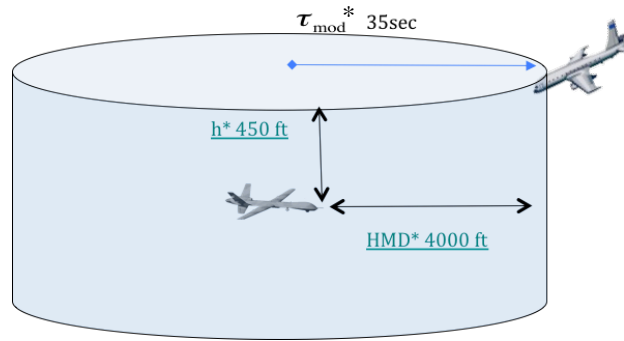

τ_{mod}^* 35sec

h^* 450 ft

HMD* 4000 ft

Fig. 1   A schematic representation of the DWC zone

minimum horizontal distance into the future, assuming constant velocities. The parameter h represents the two aircraft's altitude difference. The time metric modified tau, denoted as τ_{mod}, is an approximate time needed for the two aircraft to intersect a protection disk (see the paragraph below for details). The thresholds, denoted by an asterisk, for the HMD,

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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, thereby resulting in a LoDWC.

The time parameter τ_{mod} was introduced for the purpose of interoperability with TCAS II, because a similar time parameter for alerting is adopted by TCAS II. The definition of τ_{mod} is [2]

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

where r and $\dot{r}$ are the horizontal range and range rate between the intruding aircraft and the UA, respectively. The range rate represents the rate of change of the two aircraft's horizontal distance, and is negative for closing geometries. The positive incremental distance modifier D_{mod} defines the radius of a "protection" disk around the unmanned aircraft such that any manned aircraft close by, namely an intruder, with a horizontal range less than D_{mod} is always considered "urgent." In the case of $r < D_{\mathrm{mod}}$, $\tau_{mod} = 0$. The value of D_{mod} must be equal to HMD* to avoid undesirable on-and-off alerts during certain constant velocity encounters [19]. The value of τ_{mod} provides an estimate of the time for the UA to penetrate the protection disk defined by HMD*.

The DWC in the Phase 1 MOPS was initially selected from three types of DWC definitions using eight performance metrics [1]. The unmitigated collision risk, denoted as P, was used to tune the DWC threshold parameters such that all three DWCs yielded the same value of P [1]. P represents the conditional probability of an NMAC given a LoDWC without executing DAA maneuvers:

$$P = P(\text{NMAC}|\text{LoDWC}). \tag{2}$$

Values of P are usually computed from an encounter set representative of the UAS operations and intruder types considered. The target value of P was reduced from the recommended 5% [20] to 1.5% initially so as to expand the DWC volume to enclose most of the TCAS II RA alerting volume [1]. The selected DWC, however, had an operationally unsuitable vertical separation threshold of $h^* = 700$ ft, above the vertical separation of 500 ft permitted by visual flight rules (VFR) [3]. The vertical separation threshold h^* was hence reduced to 450 ft, and the final DWC resulted in a P of 2.2%. The Phase 1 DWC is expected to continue to be applied to cooperative aircraft in the Phase 2 MOPS development work.

Previous work [17] proposed four candidate DWCs for non-cooperative aircraft. The candidates were selected based on P, maneuver initiation range (MIR), and a few other factors. P was evaluated using encounters representative of UAS against non-cooperative intruders (see [17] for more details). The UA speed for computing P and MIR was between 40 and 100 KTAS. MIR is the minimum horizontal range during a stressing case, head-on encounter at which a non-accelerating UA must start maneuvering away from a non-accelerating intruder to maintain separation defined by

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the DWC [21]. Lower MIRs are preferred as a potential mean of reducing surveillance volume requirements. MIR is a function of both aircraft's airspeeds, encounter geometry, and the UA's maximum turn, climb, and descent rates. If the ranges of UAS and intruder airspeeds are specified, MIR is selected to be the value computed for the most stressing case, i.e., a combination of airspeeds that yield the highest MIR. Both P and MIR were computed based on assumptions for low SWaP UAS operations. The MIR computation considers the non-cooperative intruder to fly at a stressing-case speed of 170 KTAS (95 percentile [22]). The UA turns at a rate of 7 deg/sec, transitioning from a constant heading to a turn with a roll rate of 5 deg/sec, during a DAA maneuver.

The four candidate DWCs' properties are given in Table 1. They are defined by thresholds of the same three parameters that define the Phase 1 DWC. Note that alternative forms of the DWC were explored in [17] but were not selected due to worse performance. These candidate DWCs vary in their HMD* and $\tau_{mod}{}^*$ values. The parameter D_{mod} is set to be equal to the value of HMD* and therefore is not an independent parameter. Only one altitude separation threshold h^* of 450 ft as that of the Phase 1 DWC was considered because 1) h^* cannot exceed the legal separation of 500 ft for VFR flights and 2) decreasing h^* from 450 ft is regarded as increasing collision risk unnecessarily. DWC1 and DWC2 are the two primary candidates because they both achieve a desirable P of 5%, a recommended value from a previous study [20]. While various combinations of $\tau_{mod}{}^*$ and HMD* can achieve this value of P, DWC1 is selected for the minimum MIR it results in among these combinations. One the other hand, DWC2 is also selected for its simple form, representing a physical cylinder and not having a time component. DWC3 and DWC4 are backup candidates to be carried forward in case additional analyses reveal unfavorable metrics for DWC1 and DWC2. Their parameters were selected with certain level of subjectivity. DWC3 achieves a higher unmitigated collision risk of 7%. It was once proposed for terminal area UAS operations [23]. DWC4 achieves an unmitigated collision risk of 3.6% and was considered a safer candidate. In addition to the four DWC candidates selected in [17], the Phase 1 DWC definition is also evaluated for the purpose of comparison.

Table 1   Candidate DWCs for non-cooperative aircraft, their definitions and properties

Name	HMD* (ft)	$\tau_{mod}{}^*$ (sec)	h^* (ft)	P (%)	MIR (NM)	Comment
DWC1	2000	15	450	5	1.8	Primary
DWC2	2200	0	450	5	2.0	Primary
DWC3	1500	15	450	7	1.7	Backup
DWC4	2500	25	450	3.6	2.3	Backup
Phase 1	4000	35	450	2.2	3.3	Phase 1

III. Approach

The four candidate DWCs are evaluated using safety and operational suitability metrics computed from results of open-loop and closed-loop simulations of a DAA system resolving conflicts arising from a large number of aircraft encounters. Closed-loop simulations refer to the utilization of a pilot response model to select and execute the maneuver of the UA, following the guidance from an alerting and guidance algorithm. The concept of UAS operations considered by RTCA SC-228 involves a UAS pilot, as well as air traffic control (ATC) if available, in the decision loop. An automated response is not considered. The following sections discuss the metrics, the simulation architecture, and each component in the simulation architecture in detail.

A. Metrics

The safety and operational suitability metrics evaluate a DAA system's ability to provide timely and effective alerts and guidance. Among the eight performance metrics considered for the Phase 1 DWC [1], the selection process for the four candidate non-cooperative DWCs already considered the MIR. Three of the criteria, mitigated risk ratio, controller acceptability, and well clear volume collision rate, are represented by precise or highly correlated metrics in this work. The closest point of approach (CPA) miss distance and cross track deviation were investigated but not presented due to the size limit of this paper. The remaining two criteria, TCAS II RA rate and vertical deviation, are deemed irrelevant by the authors to the consideration of non-cooperative DWCs.

The metrics presented in this paper and their formulations are described below.

1) NMAC Risk Ratio (Safety):

$$\frac{P\,(\text{NMAC} \mid \text{encounter, with mitigation})}{P\,(\text{NMAC} \mid \text{encounter, without mitigation})} \tag{3}$$

The NMAC risk ratio indicates the system's effectiveness in reducing the occurrence of collision hazards and is a key safety metric for risk assessment. Small values are desirable. The denominator of Eq. 3 represents the probability of an NMAC during an encounter if the UAS pilot does nothing to mitigate the conflict. This is the probability of an unmitigated or nominal NMAC. The numerator represents the probability of an NMAC during an encounter if the UAS pilot follows the DAA system's guidance to mitigate the conflict, and is the probability of a mitigated NMAC. If the ratio is less than one, then the DAA system reduces the risk of NMAC. For example, a risk ratio of 0.1 indicates a 90% reduction in risk.

To compute the NMAC risk ratio, a set of representative encounters are evaluated with (closed-loop) and without (open-loop) engaging a DAA system in mitigating conflicts. Each NMAC resulting from evaluation with a DAA system for conflict mitigation is put in one of two categories. Unresolved NMAC risk is comprised of encounters that lead to nominal NMACs (i.e., without a DAA system) and which still have NMACs with the DAA system. Induced NMAC is comprised of encounters that do not have nominal NMACs but develop into NMACs with the

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DAA maneuver in response to DAA guidance.

2) LoDWC Ratio (Safety):

$$\frac{P\,(\text{LoDWC} \mid \text{encounter, with mitigation})}{P\,(\text{LoDWC} \mid \text{encounter, without mitigation})} \tag{4}$$

The denominator of Eq. 4 represents the probability of an LoDWC during an encounter if the UAS pilot does nothing to mitigate the conflict. The numerator stands for the probability of an LoDWC during an encounter if the UAS pilot follows the DAA system's guidance to mitigate the conflict. Similar to the NMAC risk ratio, if the LoDWC risk ratio is less than one, then the DAA system reduces the risk of LoDWC. Small values are desirable. Unresolved and induced LoDWCs are defined in a similar way to how unresolved and induced NMACs are defined.

3) Alert Ratio (Operational Suitability):

$$\frac{P\,(\text{alert} \mid \text{encounter, with mitigation})}{P\,(\text{NMAC} \mid \text{encounter, without mitigation})} \tag{5}$$

This metric computes the number of encounters that issue actionable alerts (alerts that require pilots to start coordinating a DAA maneuver) per encounter that leads to an unmitigated NMAC. Lower alert ratios are desirable, since fewer alerts indicate fewer unnecessary maneuvers.

4) Time before the unmitigated LoDWC (Operational Suitability, see details below), and

5) Horizontal distance, at the first maneuver-triggering alert (Operational Suitability): These two metrics are computed for encounters that have unmitigated LoDWCs. The first maneuver-triggering alert, referred to as the first alert in remaining sections, is the first alert that starts the pilot response model's evaluation time ticking that eventually leads to the execution of a DAA maneuver. More details about the pilot response model will be given in Section III.F. The time at the first alert is compared to the time of unmitigated LoDWC to assess the adequacy of alerting times for a UA pilot to take DAA actions. The horizontal distance of the two aircraft at the first alert informs the surveillance range requirements.

B. Simulation Architecture

Figure 2 depicts the simulation architecture diagram. Data in both open-loop and closed-loop simulations follow the direction of solid arrows. Data in dashed arrows are for closed-loop simulations only. The box labeled "Encounter" provides the input data of ownship and intruder trajectories to the simulation.

Each component in the diagram will be described in the following sections, including the encounter set, the UA navigation errors, the sensor and tracker models, the alerting and guidance algorithm, the pilot response model, and the UA flight model, respectively. Note that communication delays and failures are not modeled in the simulation.
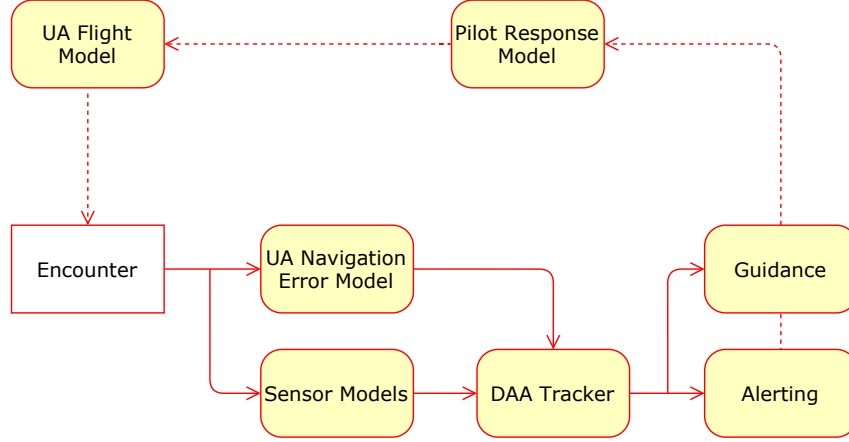
Fig. 2   Simulation architecture

C. Encounters

The safety and operational suitability metrics are computed from simulations of one million encounters. Ideally, a suitable encounter set should provide a predicted statistical representation of the conflicts a UAS will come across during its mission. Encounters for this study are generated by sampling a UAS trajectory segment randomly from NASA's projected UAS mission flights [24] and creating around it an intruder trajectory from MIT Lincoln Laboratory's uncorrelated encounter model [25]. The uncorrelated encounter model is appropriate for this purpose because no coordination of conflict resolution is expected to occur between the UAS and the non-cooperative aircraft. The choice of only pairwise encounters for this study is considered adequate by the authors due to the low density of non-cooperative aircraft and therefore the extremely low probability of multi-non-cooperative-intruder encounters. A majority of encounters (>90%) have a duration of 180 seconds. The rest have up to 300 seconds' duration to ensure sufficient times before the closest point of trajectories. All encounters contain aircraft states with a 1 Hz update rate. NASA's projected UAS mission flights and the uncorrelated model are discussed below.

NASA's UAS mission flights consist of 19 types of missions, including aerial imaging and mapping, law enforcement, and air quality monitoring. The demand and mission profiles were modeled based on subject matter experts' opinions and socio-economic analysis [24]. For example, wildfire monitoring missions were constructed by interviewing subject matter experts such as US Geological Survey, US Forest Service, and National Oceanic and Atmospheric Administration. Air taxi missions, on the other hand, were constructed based on socio-economic analysis that considers population demographics, gross domestic product, and public perception. For this study, no additional considerations or weights were given to passenger-carrying operations, although such operations can be subject to more stringent safety requirements. The trajectories have specific times of the day and cover the entire continental US. These mission trajectories were modeled using the following seven types of UAS airframes: Cessna 208 Caravan, Cessna 510 Citation Mustang, AAI Aerosonde, MQ-9A Reaper, RQ-4A Global Hawk, Shadow B, and Socata Trinidad [26]. Due to lack of
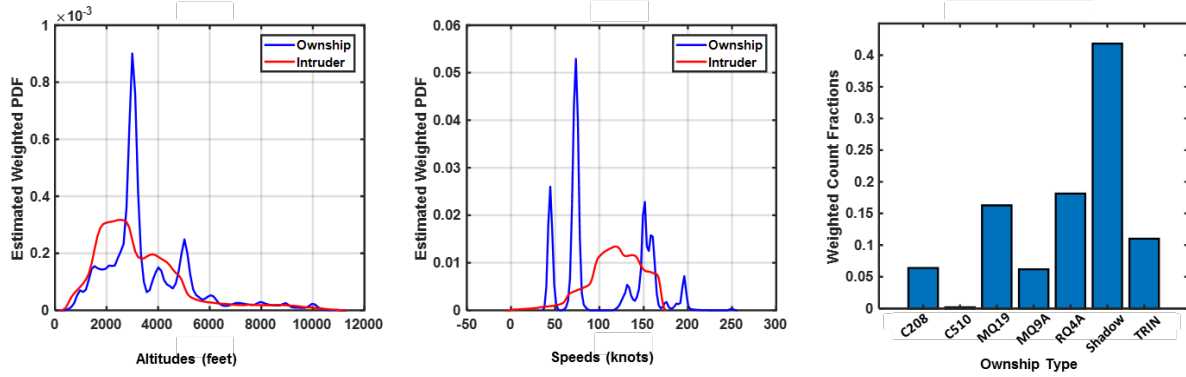
Fig. 3   UAS Encounter Characteristics

suitable UA models for certain missions, a few manned aircraft models were chosen because their performance meet what is required for these particular missions. The speed and altitude performance ranges of these UAS types were taken into account in generating the mission flights.

The uncorrelated encounter model is derived from radar data of observed aircraft operations under VFR in the National Airspace System. This model represents the VFR aircraft trajectories as two discrete Bayesian networks, one for the initial condition and one for the dynamic transitions during the encounter. For each encounter, an aircraft trajectory is constructed from the Bayesian networks and oriented with respect to the UAS trajectory segment.

Filters were applied to the UA (called ownship during an encounter) and intruder speeds and altitudes during the generation of encounters to ensure that the dynamics of the sampled trajectories are within the bounds. The UA must have a maximum speed between 40 and 250 KTAS for the encounter to be selected. Note the upper bound of the speed of the high-speed UA is 50 KTAS higher than permitted by the Phase 1 MOPS so as to explore potential safety issues for faster UAs. The intruder speeds range from 0 to 170 KTAS, the 95th percentile speed for non-cooperative intruders [27]. Intruders with zero speed represent aircraft such as hovering helicopters. No wind was modeled in these trajectories. The encounters occur at altitudes between 500 ft above ground level (AGL) and 10,999 ft mean sea level (MSL) in airspace classes E and G. Although non-cooperative aircraft fly predominantly below 10,000 ft MSL, altitudes up to 10,999 ft MSL were included to represent a few UAS missions that are flown slightly above 10,000 ft MSL. The resulting altitude and speed distributions are shown in the left and middle plots of Figure 3. The fractions of flights in terms of the UAS airframe used for modeling them are also shown in the right plot of Figure 3.

D. Navigation Errors, Sensor, and Tracker Models

The alerting and guidance algorithm takes aircraft states from the UA and the intruder as input for computation of alerts and guidance. For this study, the UA's truth trajectory is sent to the DAA algorithm, and no navigation errors are added to the UA's truth states. The intruder's truth states are filtered by the sensor models in a way described below.

The Phase 1 DAA MOPS requires ADS-B, active surveillance, and an air-to-air radar as onboard sensors. Only the radar can detect non-cooperative aircraft and is the only sensor modeled. This study sets the radar's field of regard (FOR) but does not model its measurement errors.

This study applies two types of radar's FOR. The first type is a hypothetical vertical cylinder around the UA. The radius of the cylinder varies from infinity to 4, 3, and 2 NM. Analysis with this type of FOR sheds light on the sensitivity of the DAA performance metrics to a finite horizontal surveillance range, a key question for UAS operations with low SWaP sensors. A subset of the encounters that represent low SWaP UA operations, in which the maximum UA speed is between 40 and 100 KTAS, is simulated for this FOR. Results can potentially inform the requirements of low SWaP sensors.

The second type of radar FOR is defined by a 8 NM slant range, ±15° elevation, and ±110° azimuth. The azimuth and elevation of an intruder are computed with respect to the UA's attitude. This FOR is comparable to the Phase 1 MOPS radar FOR and allows for comparisons to a previous study. This type of radar FOR is applied to all encounters.

The Phase 1 MOPS also requires a tracker that fuses and correlates measurements from multiple sensors for a single intruder into tracks. The UA's state is also input to the tracker to produce the intruder's state in absolute coordinates. In this study, the tracker is modeled as a simple pass-through tracker, i.e., the radar measurements, including truth positions and velocities, are converted to tracks through coordinate transformations.

E. Alerting and Guidance Algorithm

The Phase 1 MOPS defines three types of alerts in increasing levels of severity: preventive, corrective, and warning. The lowest level, preventive, alerts the pilot to not maneuver vertically when the aircraft are separated vertically by 450 to 700 feet. This alert should not be triggered by non-cooperative aircraft (for its lack of precise altitude information) and is not modeled. The second level, corrective, indicates that a LoDWC is predicted to occur in the future, an avoidance maneuver is necessary, but there is still time for coordination with ATC. The highest level, warning, indicates that a LoDWC is imminent, an avoidance maneuver is needed, and coordination with ATC before maneuvering is not a requirement. The DAA system must present maneuver guidance to UAS pilots about DWC-based, conflict-free aircraft headings or altitude ranges. In case a LoDWC is unavoidable, the DAA system should present regain-DWC guidance, a range of headings or altitudes that, if executed, can increase separation at the CPA and regain DWC effectively.

Detect and AvoID Alerting Logic for Unmanned Systems (DAIDALUS) [10], a reference algorithm developed to validate the Phase 1 MOPS requirements, computes the alerts and guidance during the simulation of encounters. DAIDALUS computes UA trajectories resulting from executing vertical or horizontal DAA maneuvers to determine which maneuvers would result in conflicts and which are conflict-free. Upon alerting, DAIDALUS generates corresponding preventive, corrective, and warning guidance indicating a range of conflict-free headings and altitudes for a pilot to select from in order to maintain DWC separation. DAIDALUS generates regain-DWC guidance if a LoDWC is unavoidable.

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In this study, DAIDALUS alerts were issued based on a buffered DWC volume. Specifically, the HMD* used by the DAA alerting and guidance algorithm is scaled by a factor of 1.52 to be consistent with the parameters referenced in the Phase 1 MOPS. This buffer is meant to guard against maneuvering intruders and surveillance uncertainties (none in this work). A persistent corrective or warning alert would lead to the execution of a DAA maneuver. For maneuver guidance computation, DAIDALUS assumes an immediate transition of the UA from constant velocity to a constant turn rate for the trajectory. The turn rate is assumed to be 7 deg/sec for simulations using the cylindrical radar FOR (first type). This is a feasible turn rate for low UA speeds. For simulations using the Phase 1 comparable radar FOR (second type), the turn rate is set to 3 deg/sec, matching the turn rate assumption in the Phase 1 MOPS.

F. Pilot Response Model

Figure 4 shows the SC-228 standard response pilot model created by MIT Lincoln Laboratory [28]. In this study, the model selects and executes appropriate maneuvers based on DAIDALUS's heading and altitude guidance. Model parameters were derived from human-in-the-loop experiment results [28]. The model has the capability to sample response (or delay) times and maneuvers. For this study where the focus is assessment of the candidate DWCs rather than the total safety of the DAA system, the model is executed in deterministic mode, in which all response times are constant, and maneuvers are selected from the edge of the bands plus an optional buffer (none for the data shown in this study). The response times are set to the expectation value of a distribution, which is either a Gamma distribution (for the ATC coordination time) or an exponential distribution. For corrective and warning guidance, only horizontal maneuvers were executed. This is to reflect the fact that, in reality, vertical maneuvers against non-cooperative intruders are much less robust in these situations due to uncertainties in non-cooperative sensors' vertical measurements. For regain-DWC guidance, both horizontal and vertical maneuvers can be executed due to the improvement of vertical state accuracy in reality. For horizontal maneuvers, the UA always maneuvers in the direction of the minimum heading change suggested by the guidance bands. In the event that the minimum suggestion is inconclusive, the ownship will turn left, as a preference for left turns was observed in human-in-the-loop experiments [28].

After the first alert comes up, the pilot response model implements a 5-second initial delay representing the time it takes the pilot to perceive the alert and devise a plan. For corrective alerts, an additional 11-second ATC coordination time elapses, representing the time it takes the pilot to communicate the intended maneuver with and receive approval from ATC. The model then implements a 3-second execution delay representing the time it takes the pilot to enter a maneuver command into the control station and transmit this command to the UA. The ownship may perform multiple maneuvers per encounter to resolve a conflict. The response time between decisions is determined by the alert state, as shown in Table 2. For example, if the pilot response model selects a maneuver during a warning alert state, the situation will be re-evaluated 6-seconds after the selection time, called the decision update period, and a different subsequent maneuver can be selected and executed, if needed. It takes 3 seconds after re-evaluation to select a maneuver for
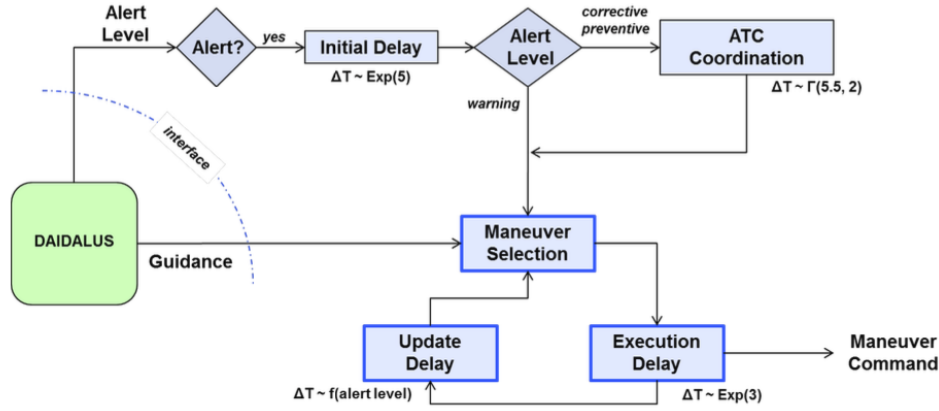
Fig. 4   The SC-228 pilot response model

Table 2   Pilot Response Model Decision Update Times

Alert Condition	Decision Update Period (s)
No Alert	12
Corrective Alert	6
Warning Alert	6
Regain-DWC Guidance	3

corrective and warning alerts. If regain-DWC guidance comes up, the selection of a maneuver occurs immediately. In all cases, another 3 seconds elapse before the maneuver is executed.

If the alert goes away during the evaluation periods of initial delay or ATC coordination time, the pilot response model's state goes back to the No Alert state. However, if the alert goes away during the execution time delay period, the maneuver is still executed. If the severity of the alert level increases during the evaluation periods of time, update times for the more severe alert apply immediately.

G. UA Flight Model

Once the pilot response model selects a DAA maneuver and the execution time delay elapses, the flight model takes control and deviates the UA's trajectory from its nominal trajectory by executing the selected DAA maneuver. Once the target heading or altitude is achieved by the flight model, the UA trajectory stays at that heading or altitude until the end of the encounter or until another maneuver is executed. The intruder's trajectory is not impacted by the UA's maneuvers, assuming a worst case in which the intruder either does not detect the UA or does not attempt to resolve the conflict.

IV. Results

The one million encounters are binned by the maximum UA speed during an encounter into four ranges listed in Table 3. The low-speed bin of 40 to 100 KTAS aligns with the low SWaP UAS operations. The two medium speed bins

are covered by the Phase 1 MOPS's UA range of 40 to 200 KTAS. The high-speed bin of 200 to 250 KTAS represents a potential extension of the MOPS. Table 3 also shows the percentage of encounters in each of these bins.

Table 3   Ownship Speed Bins

Bin #	Maximum Ownship Speed (KTAS)	Percentage (%)
1	40-100	70.0
2	100-150	7.3
3	150-200	22.3
4	200-250	0.4

Figure 5 shows the speed bins and the radar FOR types simulated in this study. A cylindrical radar FOR, defined by a maximum horizontal range around the UA, is applied to encounters in the low UA speed bin. This FOR is meant to shed light on the trade space between safety metrics and surveillance range requirements of low SWaP sensors, which are assumed to be carried by UAs with low mission speeds. The second radar FOR type, comparable to the Phase 1 radar's and defined by 8 NM slant range, ±110° azimuth, and ±15° elevation, is applied to encounters in all UA speed bins.

FOR \ Bin #	Cylindrical Radius	Range, Azimuth, Elevation (Phase 1)
1	infinite / 4 / 3 / 2 NM	8 NM, ±110°, ±15°
2, 3, 4	-	

Fig. 5   Results coverage of UA speed bins and radar FOR types

Because DWC1 and DWC3 have the same $\tau_{mod}{}^*$ but different HMD*s, HMD* is the likely source of any difference in metrics between DWC1 and DWC3. Likewise, because DWC1 and DWC2 have similar HMD* but different $\tau_{mod}{}^*$, $\tau_{mod}{}^*$ is the likely source of most differences in metrics between DWC1 and DWC2.

Results for the safety metrics are presented in Section IV.A, and results for the operational suitability metrics are presented in Section IV.B.

A. Safety Metrics

1. With Cylindrical Radar FOR and an Infinite Horizontal Range

Only low-speed UA encounters in bin 1 are simulated with this radar FOR. Figure 6 shows the NMAC risk ratios (left) and LoDWC ratios (right) for the four candidate DWCs and the Phase 1 DWC. An important observation of the NMAC risk ratios is that there is no statistically significant difference among them, even when compared to the Phase 1 DWC. Interestingly, the Phase 1 DWC does not perform better. This suggests that all candidate DWCs are likely to be acceptable in terms of their resulting DAA performance to avoid NMACs, given sufficient surveillance volume (infinite for this simulation) and small surveillance uncertainties (none for this simulation.)
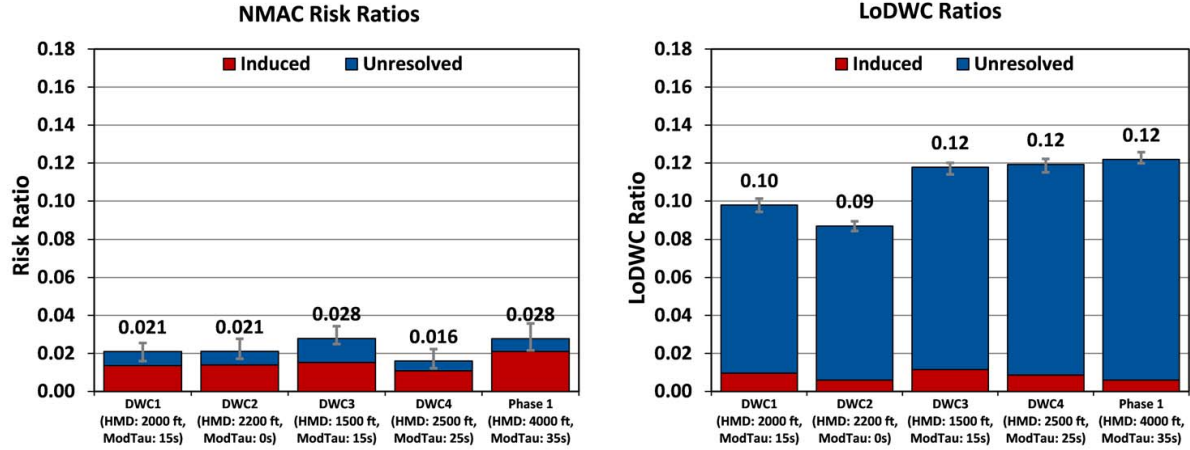
Fig. 6   Safety metrics for low-speed UA encounters

It should be pointed out that there is not a single value for the maximum acceptable NMAC risk ratio. The risk assessment makes use of the NMAC risk ratio in calculating the likelihood of a safety risk incident. Additional variables such as the encounter frequency, which varies greatly with location, must be estimated before the likelihood can be computed for a specific UAS mission.

Regarding results of the LoDWC ratio, DWC2 yields the lowest value of 9%, and DWC1 yields a slightly worse 10%. DWC3, DWC4, and the Phase 1 DWC all have comparable values near 12%. Unresolved LoDWCs comprise the majority of the risk ratio. Adding a buffer of 5 degrees to the heading selected by the pilot response model to keep the selected heading further away from the edge of conflict band was attempted, but results showed no improvement.

Intruder and ownship's nominal maneuvers appear to be the leading cause of unresolved NMACs and LoDWCs. Nominal maneuvers are maneuvers that are part of the unmitigated (original) trajectory. A close examination of encounters with NMACs showed that, in almost all these encounters, either the intruder or ownship had a late nominal maneuver near the nominal time of closest approach (TCA) during the encounter. The nominal TCA is based on unmitigated trajectories. Many LoDWCs are caused by late maneuvers as well. To confirm the impact of late maneuvers, NMAC risk ratios and LoDWC ratios were computed for a subset of encounters in which either the ownship or intruder has a nominal maneuver within 30 seconds of nominal TCA. This subset includes 57.4% of all the encounters. Results in Figure 7 show much higher NMAC risk ratios and LoDWC ratios across candidate DWCs compared to Figure 6. This confirms that late maneuvers (and hence, late alerts) are challenging for the DAA system, regardless of DWCs.

2. With Cylindrical Radar FOR and a Finite Horizontal Range

To assess the impact of finite surveillance ranges on safety metrics, NMAC risk ratios and LoDWC ratios were compared in simulation runs of encounters in the low UA-speed bin 1 with 4 NM, 3 NM, and 2 NM horizontal ranges of the radar FOR imposed. Results are shown in Figure 8. The NMAC risk ratios for DWCs 1, 2, and 3 appear to
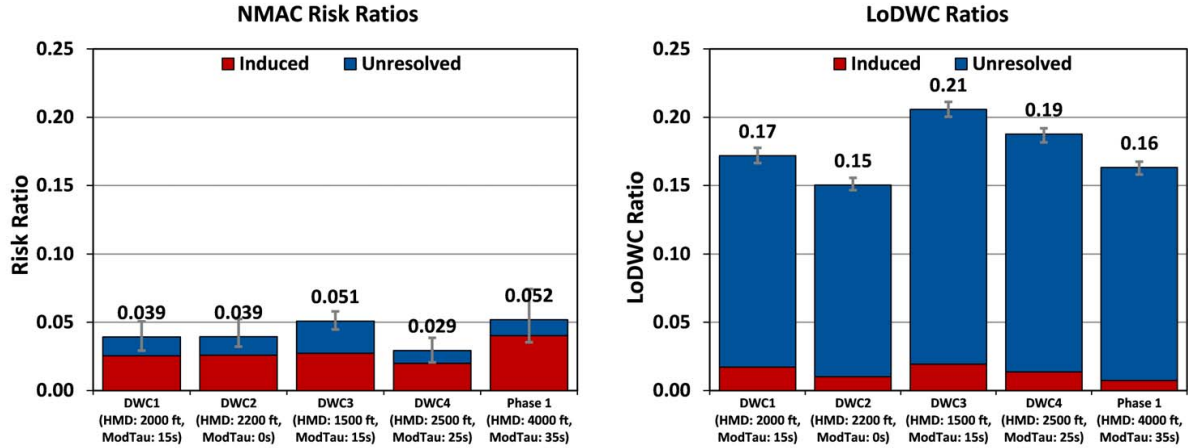
15

Fig. 7   Safety metrics for low-speed UA encounters with late ownship or intruder maneuvering

be insensitive to reduced horizontal surveillance ranges. On the other hand, the NMAC risk ratios for DWC4 and Phase 1 DWC experience large increases as the surveillance range is reduced to 2 NM. With the larger volume of DWC4 and Phase 1 DWC, the intruder is likely to remain undetected until a LoDWC already takes place or is unavoidable. DAIDALUS issues regain-DWC guidance in this situation, but the guidance is likely not as effective in avoiding NMACs. Regarding LoDWC ratios, results for DWC1 and DWC2 increase noticeably as the range is reduced to 2 NM while the value for DWC3 stays constant. The LoDWC risk ratios for DWC4 and the Phase 1 DWC are impacted the most with 2 NM, because 2 NM is inside their DWC volume for many encounters.
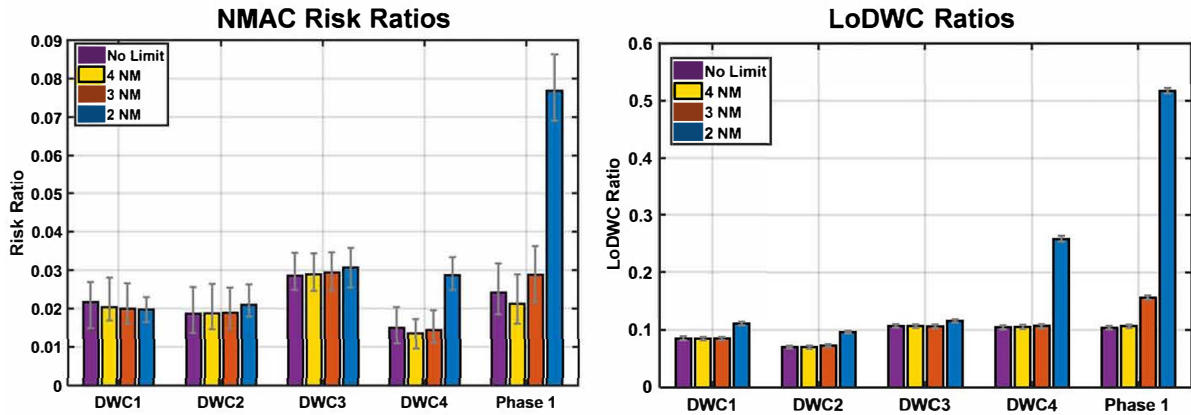

Fig. 8   Safety metrics for low speed UA (bin 1) with a cylindrical radar FOR and varying horizontal ranges

3. With Phase 1 Radar's FOR

The Phase 1 comparable radar FOR has an 8 NM slant range, ±15° elevation range (up and down the nose of the UA), and ±110° azimuth range (left and right of the nose of the UA). With this radar's FOR, an intruder approaching the ownship from behind will not be detected by the DAA system.

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Fig. 9 shows the binned NMAC risk ratios. The NMAC risk ratios in bin 1 are the highest, mainly because the UA in this bin are more likely to be overtaken by aircraft from behind, coming from outside the radar's FOR. Compared to the NMAC risk ratio in Figure 6, the NMAC risk ratios in bin 1 are much higher due to the lack of surveillance of overtaking intruders. Low NMAC risk ratios are observed in higher speed bins. UAs in speed bins 2, 3, and 4 fly faster than most of the intruders and are therefore less likely to have undetected intruders approach from behind. There are no mitigated NMACs in the speed bin 4. indicating the NMAC risk ratio is likely to be extremely low.
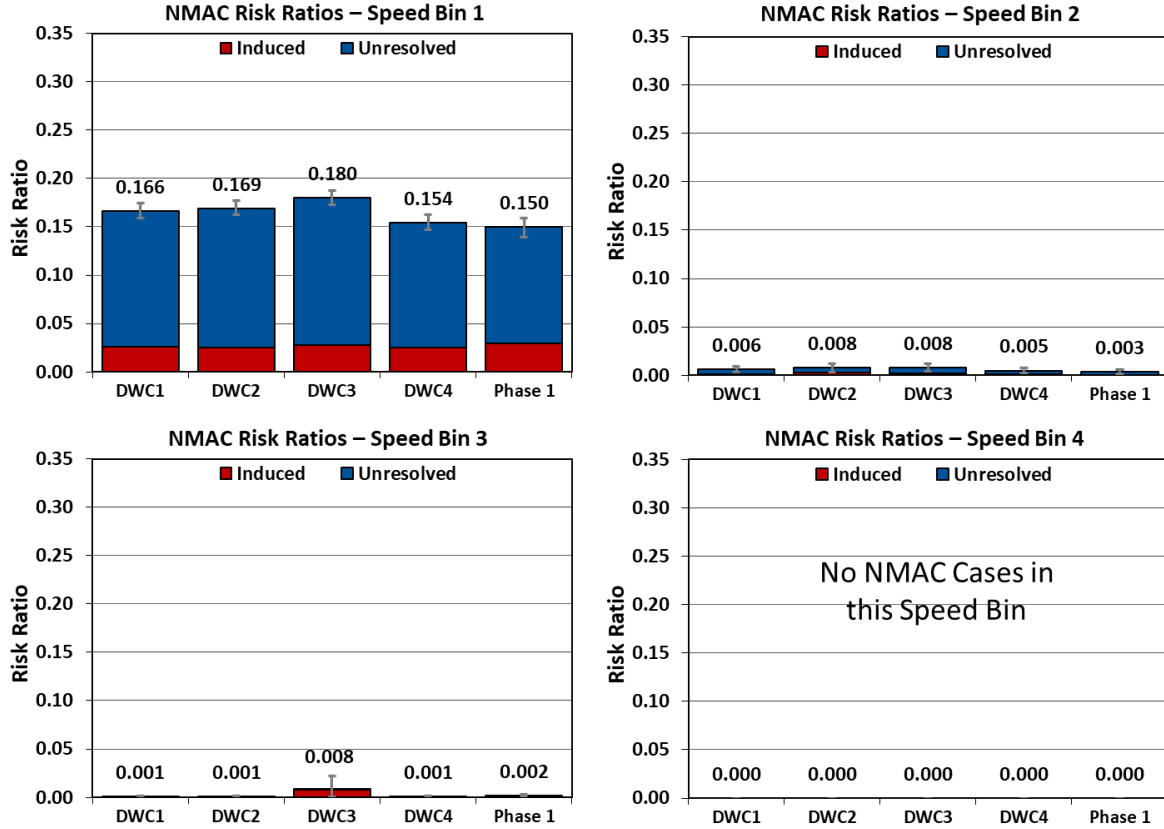

Fig. 9　NMAC Risk Ratios Binned by Speed

Fig. 10 shows the binned LoDWC ratios. For bin 1, LoDWC ratios are comparable across DWCs. For faster UAs in bins 2, 3, and 4, DWC2 consistently yields the lowest LoDWC risk ratio. Since DWC2 is the only DWC without a τ_{mod}, this trend suggests that low τ_{mod}^* leads to lower LoDWC ratios. This effect appears to be more pronounced with an increased UA speed. The addition of τ_{mod} to the DWC appears to degrade the LoDWC ratio.

B. Operational Suitability Metrics

These metrics are evaluated for only the low-speed UA bin 1 with a cylindrical radar FOR and an infinite horizontal range. The alert ratio measures the alert frequency relative to the unmitigated NMAC frequency. Ideally, the alert
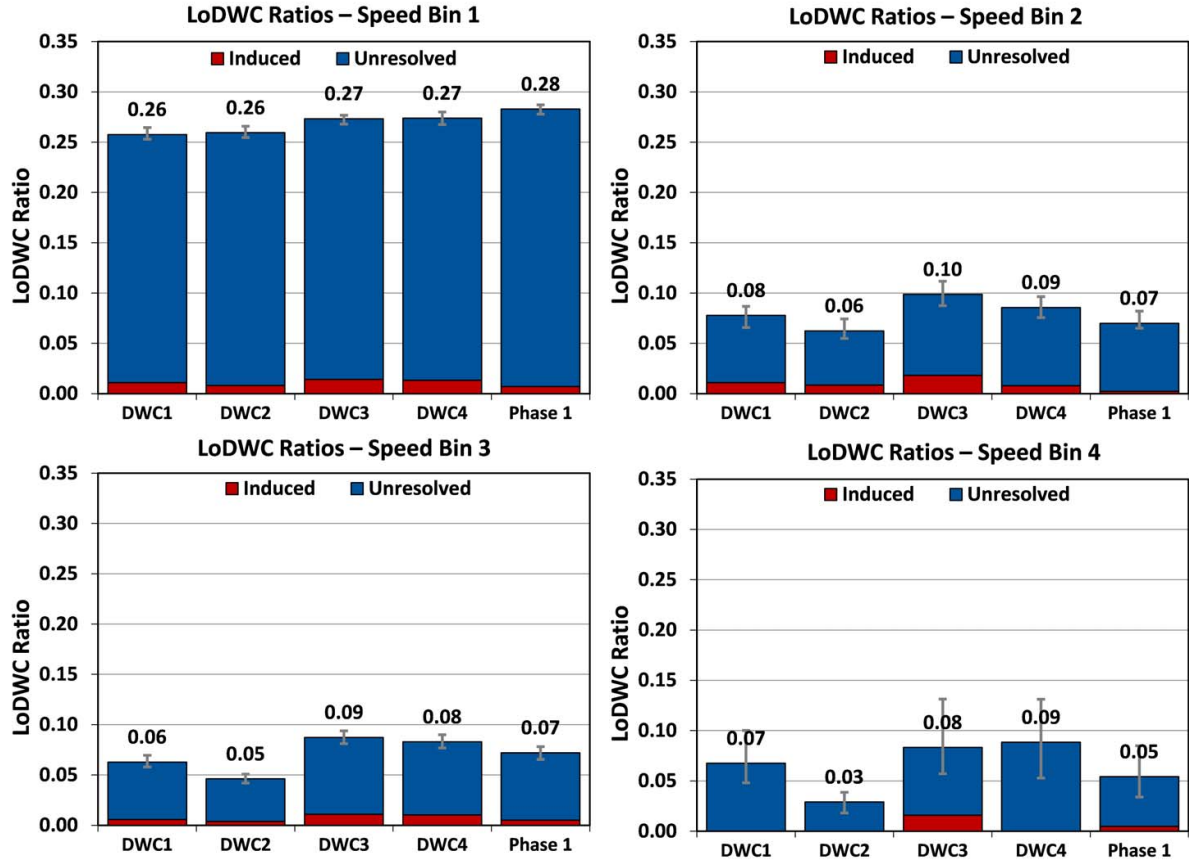
Fig. 10 LoDWC ratios binned by speed

ratio should remain low. The system operating characteristic (Fig. 11) shows both the safety metrics and the alert ratio simultaneously. Low values of both metrics are preferred, and therefore the closer a system is to the origin the better. HMD* appears to have the largest effect on alert ratio; DWC1 and DWC3 have the same $\tau_{mod}{}^*$, but DWC1 has a larger HMD* and alerts more frequently. DWC3 has the lowest alert ratio because it has the smallest HMD*. DWC4 has the worst alert ratio of all four candidates, increasing from DWC3's value by 67%.

Alerting time and range are computed based on the first maneuver-triggering alert of any level that occurs in an encounter. For an alert to trigger maneuvers, the alert must remain on during the initial delay and ATC coordination (if it is corrective). Alerting time values are relative to the time of an unmitigated LoDWC. The solid lines in Figure 12 show the estimated cumulative distribution function for alerting time (left) and range (right) for all encounters that have an unmitigated LoDWC. The cumulative distribution function is the probability that alerting time or range will be less than or equal to the values on the x-axis. For example, the alerting range plot shows that 60% of encounters run with DWC4 have their first maneuver-triggering alert at a range of 3 NM or less. All encounters evaluated with DWC4 have their first maneuver-triggering alert within 6 NM.

The solid lines in the left plot of Figure 12 show that the first alert time is driven more by $\tau_{mod}{}^*$ than by HMD*.
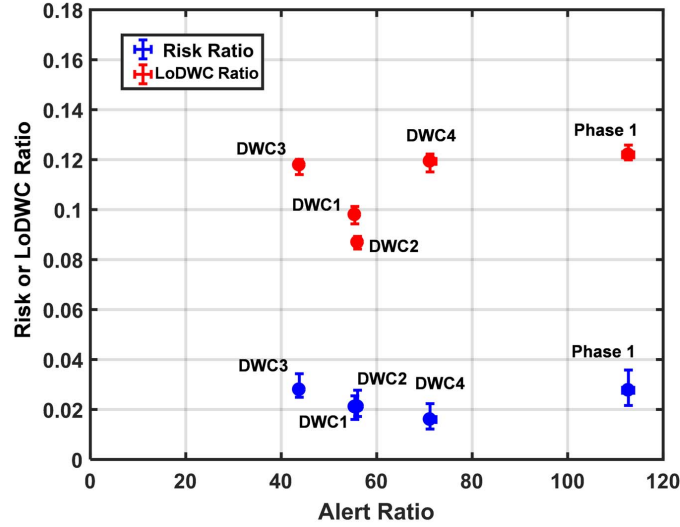
18

Fig. 11   System operating characteristic for low UA speed bin 1

This is indicated by the larger difference between DWC1 and DWC2 than between DWC1 and DWC3. DWC2, which has zero τ_{mod}^*, has more alerting times before a LoDWC. For example, with DWC2 only 33% of the encounters have alerting times less than 50 seconds before a LoDWC. With DWC1 and DWC3, more than 43% of the encounters have alerting times less than 50 seconds before a LoDWC. DAIDALUS is configured to issue an alert when the aircraft is predicted to lose DWC within a specified amount of time, 30 seconds for warning and 60 seconds for corrective. With DWC2, two aircraft lose DWC only if they are within 2,200 ft horizontally. With other DWCs that have a τ_{mod}^*, two aircraft can lose DWC when they are much more horizontally separated. The longer alerting times for DWC2, leading to fewer late alerts as a result, are likely due to the fact that the DWC2 alerts are issued at shorter distances, in which the aircraft's relative velocity vector is more aligned with its relative position vector. This allows a higher percentage of the encounters to trigger alerts early.

The solid lines in the right plot of Figure 12 show the horizontal range at the first alert for all the encounters that have unmitigated LoDWC. The distributions for DWC1, DWC2, and DWC3 are fairly close to one another at ranges below 2 NM. However, DWC1 and DWC3 distributions spread to higher ranges than DWC2. With DWC2, 98% of the encounters have the first alert at a range less than 4 NM. With DWC1 and DWC3, the 98% range increases to 4.7 NM. The smaller alerting ranges of DWC2 can be understood by its lack of τ_{mod}^*. The τ_{mod}^* in DWC1 and DWC3 pushes the alerting range further out for encounters with high closure rates. The smaller alerting ranges of DWC2 can potentially reduce the required surveillance range to provide the required alerting timeline.

The dashed curves in Figure 12 show the alert time and range for encounters that, with DAA maneuvers, progress to unresolved LoDWCs. These encounters are a subset of the encounters that have unmitigated LoDWCs and represent challenging cases for DAA. Most of these unresolved LoDWCs are caused by late nominal (non-DAA) maneuvers by
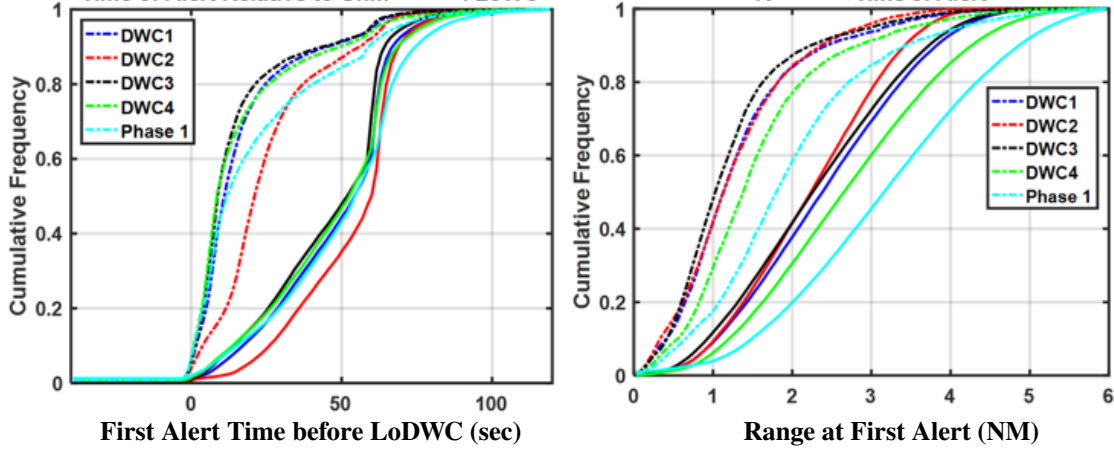
19

Fig. 12   First alerting time before LoDWC and range at the first alert. Solid lines are computed from all encounters that have an unmitigated LoDWC. Dashed lines are computed from a subset of these encounters that still have a LoDWC with DAA maneuvers.

the UA or the intruder. As a result, these encounters have on average shorter alert times and ranges. The left plot shows the shift of alerting times is more pronounced for candidate DWCs with a non-zero τ_{mod} than for DWC2. The right plot show DWC3 has the lowest range. This can be explained by the small HMD* of DWC3 and the fact that many of these unresolved LoDWCs are from encounters with low closure rates, for which ${\tau_{mod}}^*$ has little effect in increasing the alerting range. The low alerting range of DWC3 does not make DWC3 preferable for reducing surveillance requirements, because these encounters are challenging cases that cannot be aided by surveillance volume.

V. Discussion

Section IV.A.1 shows the impact of ownship or intruder's late nominal maneuvers on the safety metrics. The causes of NMACs and LoDWCs in this study, even with DAA maneuvers, can be summarized as follows:

1) Intruder and/or ownship's nominal maneuvers

2) Surveillance volume limitations

3) Guidance's ineffectiveness or instability

4) Pilot response unable to keep up with the situation

For any specific encounter leading to an NMAC, all causes could have contributed. For example, analysis of a few select encounters leading to NMACs indicates an intruder maneuver near the TCA (cause 1), which causes the conflict-free guidance bands to shrink to zero width, leaving no conflict-free heading available. In this situation, the regain-DWC guidance comes up, is executed, but changes turn directions multiple times during the UAS's maneuver (cause 3). Combined with the pilot response delay (cause 4), this instability of guidance can cause a chase situation, resulting in the DAA system's failure to avoid an NMAC. The LoDWCs result from similar causes.

Nominal ownship maneuvers are likely to bring the ownship into a immediate conflict that leaves little time for the

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DAA system to resolve. This may occur more frequently for UAS missions that fly loitering or grid patterns, accelerating often in horizontal and/or vertical directions. However, these conflicts occur in simulations more frequently than in reality, due to the limitation of the pilot response model. In reality, the DAA surveillance will provide UAS pilots situation awareness by showing peripheral conflict bands for intruders in the vicinity (if the intruder is within the DAA system's surveillance volume). UAS pilots can then make strategic nominal maneuvers different from the planned one to avoid conflicts effectively.

The impact of finite surveillance range on the safety metrics, presented in Section IV.A.2, suggests that a reasonable minimum surveillance range for low SWaP sensors is likely between 2 NM and 3 NM. While 3 NM is sufficient for any candidate DWC to maintain the same level of safety metrics as those with an infinite surveillance range, 2 NM increases the NMAC risk ratio only for DWC4 and LoDWC ratios for DWC1, DWC2, and DWC4. This indicates that, with 2 NM, in some situations UA pilots do not have enough time to evaluate and maneuver the UA in order to maintain separation. Although operationally undesirable, if the likelihood of an encounter with a non-cooperative aircraft is low, the amount of nuisance to pilots might be acceptable. On another note, whether the state-of-the-art low SWaP sensor technologies, such as radar and electro-optical or infrared (EO/IR) sensors, can meet this level of DAA surveillance range requirements (to be defined) and payload requirements constrained by UA and mission types simultaneously remains an open question.

As shown in Section IV.A.3, NMAC and LoDWC risk ratios increase noticeably for the low-speed UA (bin 1) when the Phase 1 radar FOR is applied. This is due to a large number of undetected intruders approaching from the rear of the UAS. For encounters in which an intruder approaches the UA from an azimuth angle smaller than -110° or larger than 110°, SC-228 determined that the responsibility of maintaining separation in these situations falls on the intruder. Nonetheless, since UAs flying in the low-speed range are likely to be smaller than those flying at 200 KTAS, visual identification by pilots of a manned aircraft can be challenging. It may be beneficial in terms of safety for the sensor for the low-speed UA to cover a wider range of azimuth angles.

Operational suitability metrics, presented in Section IV.B, show that DWC2 leads to more alerting times before LoDWC and less required horizontal surveillance range, giving it an edge over the other candidates. Although DWC3 achieves a lower alert ratio than the three other candidate DWCs, the importance of this metric is likely low for all but environments with very high traffic densities of non-cooperative aircraft. Encounters with non-cooperative aircraft are expected to occur with a low frequency everywhere in the National Airspace System [12]. Therefore, the slight increase of alerts as a result of applying a DWC other than DWC3 is regarded as acceptable.

The pilot response model is applied in its deterministic mode for this study, in which all response times take constant values. These response times are representative values, because they are expectation values of their corresponding distributions. Sampling response times from distributions, nonetheless, may have some effects on the metrics. Another aspect not modeled by the pilot response model is the effect of varying candidate DWCs on pilot response times. The

pilot response model's parameters were derived from experiments using a Phase 1 DWC. For a smaller candidate DWC such as DWC2 that issues alerts at shorter ranges, pilots may feel a sense of urgency and act a little quicker.

Sensor uncertainties are expected to increase the NMAC and LoDWC risk ratio. In a recent study by MITRE [29] that applied the same pilot response model, DAA algorithm, and the Phase 1 radar FOR to an encounter set consisting of UA flying between 50 and 100 kts, the NMAC risk ratio and LoDWC ratio for the Phase 1 DWC were computed to be 0.22 and 0.42, respectively. Comparing these values to 0.15 and 0.28 from the speed bin 1 results, without sensor uncertainties, the difference is believed to be the introduction of sensor uncertainties into the simulation.

VI. Conclusion

A detect-and-avoid (DAA) system is a critical component for maintaining safety of UAS missions in the same airspace with manned aircraft. This study evaluates four candidate DAA Well Clear (DWC) definitions for UAS encountering non-cooperative aircraft, using safety and operational suitability metrics. One million encounters, covering a wide range of unmanned aircraft (UA) speeds from 40 to 250 KTAS, are simulated using a reference DAA algorithm, a pilot response model, and two types of radar field of regard (FOR). The findings from this study provide key supporting information for the requirements of DAA systems, and are summarized below.

A general observation of safety metrics computed across candidate DWCs is that they are not improved by the introduction of the time parameter, τ_{mod}^*, into the DWC definition. In fact, the loss of DWC (LoDWC) frequency is worsened by τ_{mod}^*, particularly at high UA speeds. This suggests that τ_{mod}^* is not necessary for a DWC definition. Furthermore, operational suitability metrics show that τ_{mod}^* increases the required alerting range without providing additional safety benefit.

Based on the findings from this work and a few related studies, SC-228 selected DWC2, the only candidate DWC without a τ_{mod}^*, for UAS encountering non-cooperative aircraft. This decision achieves a major milestone in SC-228's Phase 2 work.

For surveillance requirements for UAS operations with low size, weight, and power (SWaP) sensors, this study also provides important supporting information. Simulation results show that reducing the horizontal surveillance range from infinity to 3 NM does not appear to impact safety metrics. Additional reduction from 3 NM is possible, but the value may not go below 2 NM, at which range the LoDWC ratio is impacted. Given the payload restrictions from UAs for low SWaP operations, it remains an open question whether this range is achievable by current surveillance technologies such as radar and EO/IR.

For extending the Phase 1 DAA minimum operational performance standards (MOPS) to UA speeds greater than 200 KTAS, results for UAs flying between 200 and 250 KTAS show the DAA system achieves promising low NMAC risk ratios as well as low LoDWC ratios, given the Phase 1 radar FOR. This suggests the extension of the Phase 1 DAA MOPS to higher UA speeds such as 250 KTAS impacts neither safety nor the air-to-air radar's FOR requirements.

Sensor uncertainties will be the subject of a follow-up study. Specific tasks include the impact of sensor uncertainties on the safety and operational suitability, pilots' performance and acceptance, and flight tests. All of this technical work will contribute to an updated DAA MOPS as well as related radar and EO/IR MOPS, scheduled to be published by early 2021. These MOPS documents will play a key role in reducing the barrier of enabling UAS operations in the national airspace systems.

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