An Examination of Two Non-Cooperative Detect and Avoid Well Clear Definitions

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NASA's Unmanned Aircraft Systems Integration into the National Airspace System (UAS in the NAS) project examines the technical barriers associated with the operation of UAS in civil airspace. The present study explored the differential effects of two candidate non-cooperative Detect-and-Avoid Well Clear (DWC) definitions on pilot and system performance in a human-in-the-loop simulation. Active-duty UAS pilots were recruited to maintain DWC against scripted conflicts with non-cooperative intruders using a low size, weight, and power (SWaP) radar declaration range of 3.5 nautical miles (nmi). Objective performance indicated that pilots could consistently maintain DWC against non-cooperative intruders with either DWC candidate, with negligible differences in response times and separation performance against caution and warning-level threats. While losses of DWC were avoided at rates comparable to Phase 1 findings, pilots uploaded their responses to caution-level alerts over 5 seconds faster in the current setup relative to Phase 1. Encounters with faster closure rates were susceptible to shortened caution-level alert durations, especially when employing the DWC criterion with the additional 'Tau' (temporal) component. Consequently, caution-level threats frequently elevated to warning-level status (nearly twice as often with the Tau candidate). The variable caution alert durations appeared to impact pilots' coordination with air traffic control (ATC), as ATC approval rates were lower with the 'Tau' and 'Disc' candidates relative to Phase 1 research. Ultimately, the increased alerting time enabled by the Disc candidate deemed it more suitable for any reductions to the assumed radar declaration range requirement, which was re-evaluated in a follow-on study. Findings from this study will inform Phase 2 Minimum Operational Performance Standards (MOPS) development for UAS with alternative surveillance equipment and performance capabilities.

I. Introduction

The Unmanned Aircraft Systems Integration into the National Airspace System (UAS in the NAS) project addresses technical issues related to increased demand for civil and commercial UAS operations in the NAS [1]. Routine access to the NAS will require compliance with existing 'see-and-avoid' requirements for separation maintenance as defined by Title 14 of the Code of Federal Regulations (CFR), Part 91 [2]. In conjunction with RTCA Special Committee 228 (SC-228), NASA has been supporting the development of Minimum Operational Performance Standards (MOPS) for UAS equipped with a detect-and-avoid (DAA) system, which provide the UAS operator with a means of complying with CFR Part 91 remotely by generating predictive alerting and guidance that can assist the pilot in remaining DAA Well Clear (DWC) from surrounding aircraft. Color-coded DAA alerting and guidance bands have proven effective at supporting the DAA task of remaining and regaining DWC in past human-in-the-loop simulations with various display configurations [3-8].

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The Phase 1 DAA MOPS [9] focused primarily on DAA system requirements for large UAS that were capable of carrying relatively heavy surveillance equipment while transiting through Class D, E, and G airspace to Class A airspace. Design standards must also consider UAS with unique performance characteristics or equipment [10], along with any implications on pilot performance. A new class of DAA system requirements, referred to as Class 4 systems, are currently under development and would allow smaller UAS to satisfy the UAS DAA MOPS by accommodating surveillance equipment with low size, weight, and/or power/performance (Low SWaP). This new class of system requires that the UAS operates at slower speeds and lower altitudes than the Phase 1 systems - i.e., below 10,000 feet (ft.) mean sea level (MSL) and slower than 100 knots true airspeed (KTAS). Phase 2 efforts aim to extend existing requirements to support these additional categories of UAS, which necessitates refinements to the DWC definition (i.e., separation criteria) for non-cooperative intruders (i.e., aircraft without an operational transponder) and an investigation into the effects of limited sensor performance on the DAA system as a whole.

Considerable research has highlighted the importance of non-cooperative sensor performance on the overall DAA task. Numerous surveys of the current technology have been performed, with particular focus on radar (ground-based and airborne) and vision systems (e.g., EO/IR) [11-13]. Several researchers have also developed multi-sensor fusion trackers that are capable of integrating non-cooperative and cooperative sensor types [14, 15]. Such an architecture can allow platforms to take advantage of the unique benefits of each sensor type. For instance, in Ref. [15], a passive radar was responsible for the initial detection of an intruder and an EO/IR payload was used to classify the aircraft type. While multi-sensor architectures are promising, their ability to reliably detect objects at sufficient distance for a pilot to be "in-the-loop" is not yet supportable by the current state of the technology. As a result, the research surveyed was forced to assume the use of an autonomous DAA capability. A flight test conducted by Ref. [16] found that an integrated radar-EO/IR configuration could reliably result in a declaration range (i.e., the point at which a reliable, stable track could be established, as opposed to the first detection of an object at distance) of ~1 nautical mile (nmi). Similar declaration ranges were found with the EO/IR configurations in Ref. [17, 18]. A declaration range of 1nmi is well-within the existing range thresholds for DAA and collision avoidance, and would not provide enough time for an operator to detect the conflict, determine an appropriate response and execute the maneuver. By comparison, the minimum radar declaration range (RDR) for the Phase 1 radar was 6.7nmi. While current technology cannot support a pilot-in-the-loop configuration, any aircraft flying in the NAS in the near-term will be required to have a human operator performing the DAA function. A critical step, therefore, is to determine how the DAA system – including its associated hardware and processing requirements – may be modified to reduce the burden on the non-cooperative sensors while also providing pilots with sufficient time to resolve DAA conflicts.

One of the most straightforward ways to accommodate the range and field of regard limitations associated with a low SWaP surveillance system is to reduce the size of the DWC threshold for non-cooperative intruders relative to the Phase 1 definition. Doing so would allow Class 4 systems to preserve some of the alerting time necessary to avoid DWC violations at reduced declaration ranges. The Phase 1 DWC definition was defined as 4000 ft. horizontal miss distance (HMD), 450 ft. vertical threshold, and 35 seconds modified Tau (approximately equivalent to time to closest point of approach). Since the Phase 1 DAA hazard zone was originally designed to interoperate with the Traffic Alert and Collision Avoidance System (TCAS II) and prevent excessive Resolution Advisories (RAs), an alternate DWC definition could be applied specifically to non-cooperative intruders since such intruders cannot equip with TCAS II and are therefore not at risk of receiving undesirable RAs from UAS. Although an alternate DWC criterion would support reductions to the surveillance volume requirement, the DAA system must maintain existing levels of safety observed in Phase 1 of the MOPS.

Initial fast-time analyses at NASA proposed four candidate DWC definitions for non-cooperative aircraft based on maneuver initiation range and unmitigated collision risk (i.e., likelihood of violating DWC without a DAA system) [19]. Each candidate DWC definition utilized a reduced hazard zone relative to the Phase 1 DWC definition, and were evaluated using operational suitability and safety metrics computed from a large representative encounter set [20]. Two primary candidates were selected based on desirable unmitigated collision risk (within 5%) and minimal impact on existing alerting and guidance requirements. DWC Candidate 1, referred to as "Tau" in this paper, reduced the HMD to 2000 feet (from 4000 ft.) and the modified Tau criteria to 15 seconds (from 35 seconds). DWC Candidate 2, referred to as "Disc" in this paper, reduced the HMD to 2200 feet and eliminated the Tau component entirely. Both definitions retained the Phase 1 vertical threshold of 450 feet. As a result, the Disc candidate is a static hazard zone, while the Tau candidate's hazard zone is dynamic and reflective of the closure rate and approach angle of a given intruder. Specifically, the fast-time study found that both primary candidates preserved the Phase 1 alerting timeline at a smaller radar declaration range of 3.5nmi, but the alerting was preferable with the Disc candidate. The present study attempts to validate the fast-time analyses and further explore the differential effects of the Disc and Tau DWC definitions on DAA system and pilot performance with a human in-the-loop.

II. Method

A. Experimental Design

The present study consisted of a mixed factorial experimental design with the DWC definition acting as the within-subjects variable and ownship speed as the between-subjects variable. The DWC definition utilized by the DAA system was either the "Disc" candidate or the "Tau" candidate from Ref. [20] (see Table 1). Ownship speed was either slow (i.e., 60 KTAS) or fast (i.e., 100 KTAS). Although the slowest speed assumption for Class 4 UAS technically extends to 40 KTAS, 60 KTAS was selected to emulate the anticipated cruise speed of the ownship aircraft utilized in a follow-on flight test [21]. An additional embedded, within-trial variable consisted of encounter type, which varied by its associated closure rate. Further information regarding intruder characteristics will be provided during discussion of the general DAA task.

Table 1. DWC Candidates.

DWC Criterion	"Disc"	"Tau"
Horizontal Threshold (HMD)	2,200 ft	2,000 ft
Vertical Threshold (ZTHR)	450 ft	450 ft
Modified Tau (modTau)	N/A	15 seconds

B. Participants

Participants for the present study included twelve active-duty UAS pilots (*M* = 36.67 years old). On average, participants had roughly 1,336 hours of unmanned flight experience and 1,731 hours of manned flight experience with most flight hours occurring under military service. Additionally, retired center controllers acted as the confederate ATC for Oakland Air Route Traffic Control Center (ZOA 40/41) and managed simulated background traffic typical for the airspace. Several general aviation pilots performed the role of pilot confederate, or 'pseudo-pilot', and maneuvered the background traffic according to ATC instruction.

C. Simulation Environment

1. Ground Control Station

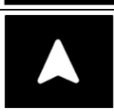
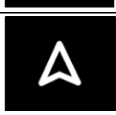
Vigilant Spirit Control Station (VSCS), a ground control station (GCS) developed by the Air Force Research Laboratory, was used to simulate the study's mission flight [22]. The GCS consisted of two monitor displays including a tactical situation display (TSD) and a telemetry panel. Inputs to either displays were made via mouse and keyboard. The TSD acted as the main display and presented vehicle controls, mission route(s), and the associated airspace map in a top-down view. Ownship location on the TSD was represented by an aircraft icon centered in the middle of a compass rose as well as inner and outer range rings that varied measurement size in nautical miles based upon the map's selected zoom level. At the top of the TSD display, a feature called a 'baseball card' displayed aircraft state information such as the aircraft callsign, magnetic heading, altitude in feet relative to MSL, angle of attack, vertical velocity, indicated airspeed (IAS), and an artificial horizon. On the right side of the display, an altitude tape displayed current altitude in MSL as well as any commanded altitudes if the vehicle was in a climb or descent. A 'steering window' provided the interface controls, including two modes of flight known as 'HOLDS' and 'NAV'. The HOLDS mode allowed for maneuvers to be made in response to conflict encounters, whereas the NAV mode acted as the default waypoint-to-waypoint navigation. Participants could make an altitude or heading change by switching to HOLDS mode and either manually typing the new heading or altitude value into the associated textbox or by using the 'spinners' represented by plus and minus buttons that changed the values incrementally. Heading could also be changed by a selecting and dragging a heading bug located on the compass rose surrounding the ownship icon imposed over the moving map, which populated once a participant entered HOLDS mode. The second display featuring the telemetry panel provided vehicle telemetry information, electronic mission checklists, and a chat room with mission command where periodically questions regarding aircraft state were queried to gauge a participant's situational awareness. Participants also were given contingency events (i.e., header tank overpressure and generator failure) which required completing the steps outlined in an electronic checklist.

A simulated generic RQ-7 Shadow UAS model was flown at a mission altitude of 8,000 ft MSL, and either a mission cruise speed of 60 KTAS or 100 KTAS. The aircraft had a turn rate of 7° per second and a climb/descent rate of 500 ft. per minute. The Oakland Center airspace in Class E was emulated with the UAS flying either a long rectangular "racetrack" pattern or a zig-zag "fire line" route depending on the trial. In the case of the "racetrack" route, an active Temporary Flight Restriction (TFR) was visible directly below the route. The TFR was used to replicate an identical TFR that was to be used in a follow-on flight test [21]. Participants and pseudo-pilots communicated with the Oakland Center controller via push-to-talk headsets over a voice-IP-server.

2. DAA System

NASA's Detect and Avoid Alerting Logic for Unmanned Systems (DAIDALUS) powered the DAA system that provided multi-level alerting and guidance against aircraft that were predicted to penetrate the associated DWC volume. DAIDALUS was configured to alternate between the two DWC definitions based on the DWC condition, and filtered traffic based upon associated equipage. Cooperative traffic was displayed on the TSD within a lateral detection range of 20nmi and a vertical range of ± 5,000 ft MSL. In the case of non-cooperative traffic, a lateral declaration range of 3.5nmi, an azimuth of ± 110°, and an elevation of ± 15° was used. The 3.5nmi declaration range was identified in Ref. [20] as the approximate declaration range below which the Phase 1 alerting timeline became significantly less viable. The alerting structure outlined in Table 2 indicated threat level through both visual and auditory cues. The top two levels indicated the highest levels of severity and required pilot intervention to avoid a loss of DAA well clear (LoDWC). The yellow Corrective alert indicated a caution-level DAA conflict that required corrective action to avoid a LoDWC within 60 seconds, but allowed enough time for pilots to notify ATC of their intentions before maneuvering. The red Warning alert indicated a warning-level DAA conflict that required immediate action to avoid a LoDWC within 30 seconds, followed by ATC coordination.

Table 2. DAA alerting logic.

Icon	Alert Level	Expected Pilot Response	Time to LoDWC	Aural Alert Verbiage
	Warning Alert	Maneuver immediately	30 sec	"Traffic, Maneuver Now" x2
	Corrective Alert	Maneuver following ATC approval	60 sec	"Traffic, Avoid"
	Preventive Alert	Monitor traffic; maneuver not currently required	N/A	"Traffic, Monitor"
	Guidance Traffic	No maneuver required	N/A	N/A
	Basic Traffic	No maneuver required	N/A	N/A

Maneuver guidance was provided in the form of conflict resolution bands that appeared on either or both of the heading and altitude regions on the TSD. Banding that appeared on the heading region around the inner range rings are referred to as horizontal DAA bands, whereas those that populated on the altitude tape are vertical DAA bands. Updates to banding were constantly provided by DAIDALUS based upon an intruder's present trajectory without taking into account intent of either the intruder or ownship. Both the horizontal and vertical DAA banding featured the same color coding as the intruder symbols to indicate the threat level corresponding within the alerting structure. Trajectories within the warning-level banding were predicted to result in a Warning alert, and, consequently, a loss of DWC within 30 seconds. Similarly, trajectories within the corrective-level banding were predicted to result in a Corrective alert, and, therefore, a loss of DWC within 60 seconds. In both cases, DAA banding gave pilots guidance on which heading or altitude values to avoid in order to resolve a conflict. However, in the event that a loss of DWC became unavoidable, Regain DWC guidance was displayed in the form of green "wedges" to indicate a range of target values for horizontal and/or vertical maneuvers that would maximize separation at the closest point of approach (CPA). Figure 1 depicts a Corrective DAA alert and corresponding corrective-level DAA bands within the VSCS TSD.

Fig. 1 Screenshot of the VSCS TSD during a Corrective DAA alert. Intruder alert symbol and heading bands are shown near the center-left; altitude bands are depicted on the far right of the TSD.

D. Procedure

1. Training

Following initial in-take documentation and collection of demographics, participants were briefed on the study concept and ground station interface including the behavior of the DAA system. Participants also received hands-on training with the ground control system prior to the start of data collection. Initially, participants practiced making maneuvers without active intruders and later graduated to responding to practice DAA encounters. Pilots received training sessions with both DWC definitions prior to experiencing the given experimental condition. Pilots were not informed of which DWC condition (Tau or Disc) they were experiencing throughout the day. This was done to determine, at the end of the day, whether the two DWC definitions were noticeable at the level at which the pilots interacted with the system. All training routes followed a straight-line track and included a variety of example DAA conflict encounters. Participants also received practice chat message questions and contingency event alerting to practice responding to both secondary tasks.

2. DAA Task

Participants completed a total of four trials each with four scripted non-cooperative DAA conflicts. Intruders varied by approach angle (either head-on or crossing) and by speed (100 or 170 KTAS). The four encounter types are shown in Table 3. The encounter set also included a nominal cooperative threat and a “blunder” encounter that generated an immediate Warning alert with a 25-second look-ahead time instead of the nominal progression, but they were excluded from this paper’s analyses since their encounter outcomes were not sensitive to the DWC candidate variable. Participants were instructed to comply with the traffic display alerting and guidance to maintain safe separation against any DAA threats and to coordinate maneuvers with ATC if appropriate (i.e., during the Corrective alert phase). Following the resolution of a conflict, pilots were instructed to return to the mission route and altitude as soon as able after coordinating with ATC.

Table 3. Scripted non-cooperative DAA encounters.

Encounter	Intruder Speed	Approach Angle
Fast Head On	170 KTAS	0°
Slow Head On	100 KTAS	0°
Fast Crossing	170 KTAS	+/- 90°
Slow Crossing	100 KTAS	+/- 90°

III. Measures

A. Alerting Performance

1. Alert Look-ahead Time

Refers to the predicted time-to-LoDWC, in seconds, at the onset of a Corrective or Warning alert.

2. *Alert Progression*

Refers to the threat severity at the alert onset, as well as the proportion of DAA conflicts that reached warning-level status (including encounters with and without a preceding caution-level alert).

B. Pilot Performance

1. *Aircraft Response Time (Aircraft RT)*

Refers to the elapsed time, in seconds, from the onset of a Corrective or Warning alert to the initial avoidance maneuver uploaded to the vehicle.

2. *Losses of DAA Well Clear (LoDWC)*

Refers to the percentage of conflicts that penetrated the DWC threshold under each DWC criteria, as well as the reason behind each LoDWC instance.

3. *ATC Coordination*

Refers to the proportion of initial avoidance maneuvers for which the pilot notified ATC of intent ('prior notification') and received approval prior to the upload ('pre-approval'). These results apply only to conflicts that generated Corrective alerts, as Warning alerts required immediate maneuvers.

IV. Results

A mixed model Analysis of Variance (ANOVA) was conducted to analyze the impact of DWC candidate (primary independent variable) and Ownship/Intruder Speeds (i.e., closure rates) on the Alert Look-ahead Time and Aircraft RT metrics, utilizing an alpha level of 0.05. Interaction effects from the closure rate variables and significant pairwise comparisons are reported where appropriate. Descriptive statistics are reported for the Alert Progression, LoDWC, and ATC Coordination metrics.

A. Alerting Performance

1. *Alert Look-ahead Time*

Among the metrics included in the statistical analysis, only Alert Look-ahead Time revealed significant effects. There was a main effect of DWC candidate on total Alert Look-ahead Time, $F(1, 11) = 272.82$, $p < .05$. On average, the Disc candidate allowed more alert look-ahead time ($M = 53.04s$, $SE = 0.73s$) compared to the Tau candidate ($M = 46.36s$, $SE = 0.93s$; see Fig. 2). A mixed model ANOVA revealed the main effect of DWC candidate on Alert Look-ahead time was modified by an interaction between two closure rate variables: Ownship Speed and Intruder Speed, $F(1, 11) = 15.74$, $p < .05$. Pairwise comparisons revealed that the alerting time differences between candidates were far more pronounced when intruder and ownship aircraft were both closing at 'Fast' speeds ($MD = 9.86s$) compared to 'Slow' speeds ($MD = 1.45s$), with the Tau candidate experiencing larger reductions in Corrective alert duration during fast-closure encounters. This was supported by the main effect of DWC found on Corrective alert duration, where the Disc candidate allowed more caution alerting time on average ($M = 23.04s$, $SE = 0.73s$) compared to the Tau candidate ($M = 16.58s$, $SE = 0.87s$), $F(1, 11) = 272.60$, $p < .05$ (also shown in Fig. 2). While both DWC candidates provided substantial average Corrective alert durations, Figure 3 demonstrates that only the Tau candidate ever resulted in a time-to LoDWC less than 30 seconds. The Disc candidate, at worst, provided 5 seconds of Corrective alert duration before triggering a Warning alert.

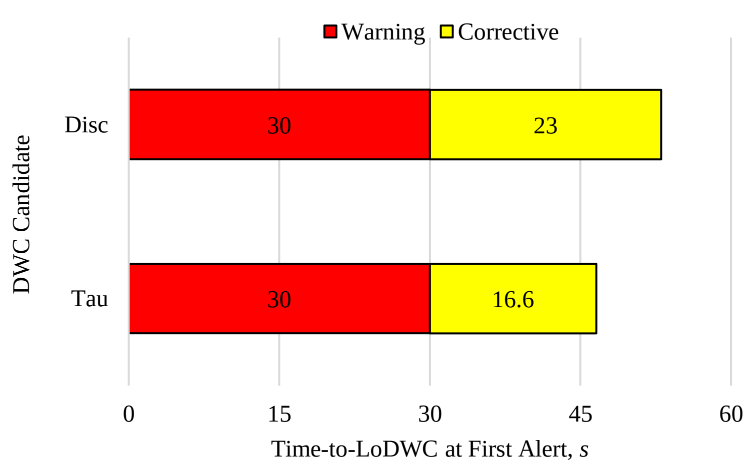


Fig. 2 Average Time-to-LoDWC at First Alert by DWC Candidate.

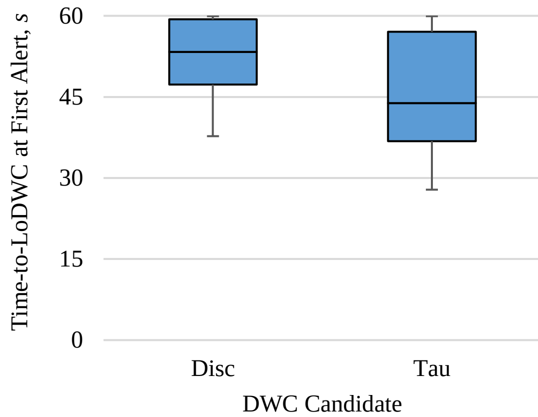


Fig. 3 Median, Minimum, Maximum Time-to-LoDWC at First Alert by DWC Candidate.

2. Alert Progression

There were more than twice as many Warning alerts generated with the Tau candidate (54% of conflicts) compared to the Disc candidate (26% of conflicts) overall (Fig. 4b). It should be noted that 12 of 90 (13%) conflicts with the Tau candidate were Warning at First Alert (Fig. 4a). Nonetheless, when assessing alert progression with these 'Warning-first' encounters excluded, it was still found that Corrective alerts progressed to Warning alerts at higher rates with the Tau candidate, with 47% of caution-level threats reaching warning-level status before clear of conflict. Furthermore, the Disc candidate yielded a smaller proportion of short-duration (<15*s*) Corrective alerts compared to the Tau candidate, where nearly half of Corrective alerts were less than 15 seconds from the Warning alert threshold at onset (Fig. 4a).

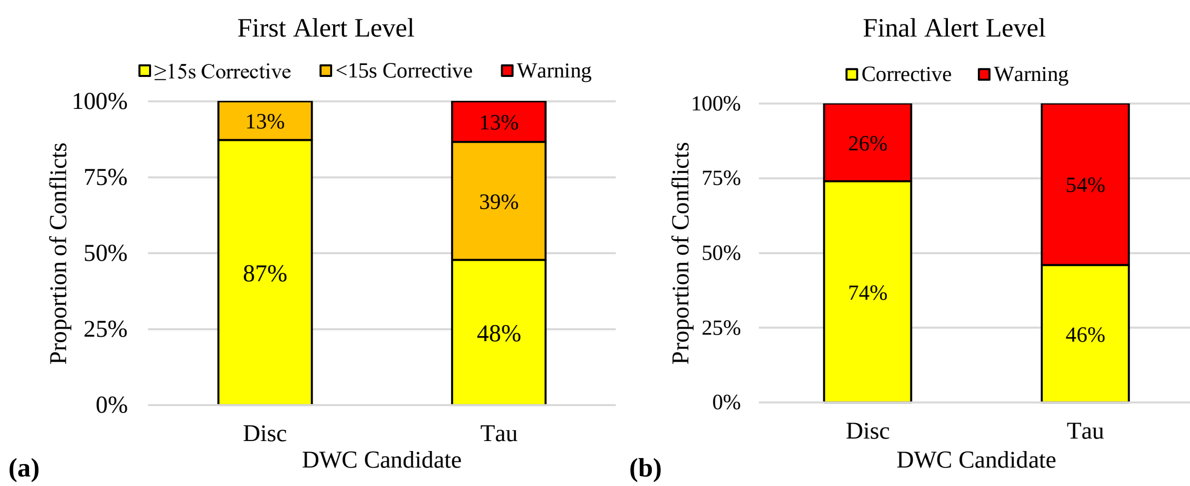


Fig. 4 (a) First Alert Level & (b) Final Alert Level by DWC Candidate.

B. Pilot Performance

1. Aircraft Response Time (RT)

No effect of DWC candidate was found on Aircraft RT, $p > .05$. Response times to Corrective alerts were nearly identical between the Disc ($M = 12.64s$, $SE = 0.72s$) and Tau ($M = 12.31s$, $SE = 0.75s$) candidates (Fig. 5).

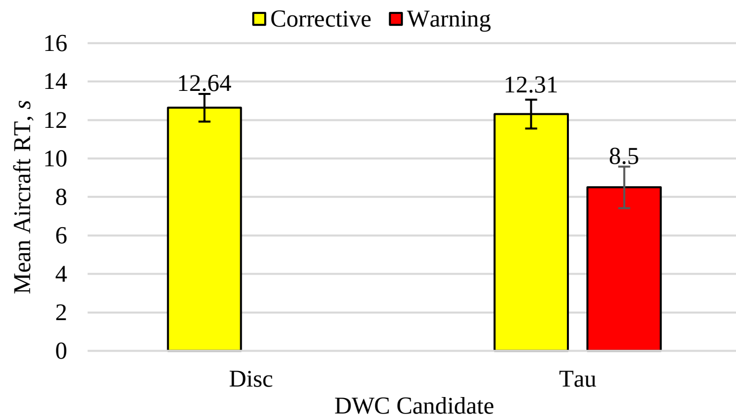


Fig. 5 Mean Aircraft RT by DWC Candidate & First Alert Type.

2. Losses of DAA Well Clear (LoDWC)

Pilots maintained DWC against 99% of scripted conflicts (n = 184) over the course of the study. There was one DWC violation in each DWC candidate condition, resulting in a LoDWC proportion of 1% for both Disc and Tau. Both violations were a result of ineffective altitude-only maneuvers made by the same pilot.

3. ATC Coordination

Overall, ATC coordination was more prevalent with the Disc candidate. For encounters that were caution-level at first alert, pilots notified ATC prior to 93% and 76% of maneuvers with the Disc and Tau candidates, respectively (Fig. 6). Only 51% of maneuvers were pre-approved with the Tau candidate, whereas the Disc candidate yielded a 64% approval rate. These findings can be attributed to the aforementioned differences in the Corrective alert duration afforded to pilots, where the Disc candidate yielded less instances of short-duration Corrective alerts.

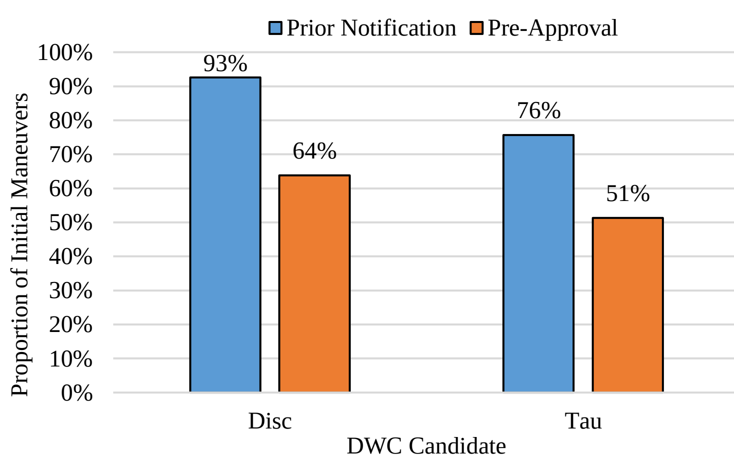


Fig. 6 ATC Notification & Approval Rates by DWC Candidate (Corrective at First Alert).

V. Discussion

Objective performance indicated that pilots could consistently maintain DWC against non-cooperative intruders with either DWC candidate at the 3.5nmi declaration range, with negligible differences in response times (average difference less than 1 second) and separation performance (identical 99% rate) against caution and warning-level threats. While losses of DWC were avoided at rates comparable to Phase 1 findings, pilots uploaded their responses to caution-level alerts for non-cooperatives over 5 seconds faster in the current setup relative to Phase 1 research. It should be noted that the limited vertical maneuverability (500 ft./minute) in these test cases necessitated lateral maneuvers to avoid losses of DWC. Notably, both DWC violations were a result of attempting a lone vertical maneuver without any heading modifications. This ultimately streamlined the decision-making process to focus solely on the direction and magnitude of the turn suggested by the DAA guidance bands. Phase 1 research used both larger radar declaration ranges and better aircraft performance than those modeled in the current study, which provided pilots with more multi-dimensional resolution options to consider (e.g., climb, descent, blended maneuver). This standardized avoidance strategy (i.e., turn quickly outside of conflict bands) was likely applied globally across all encounters due to the unusually high proportion of scripted non-cooperative conflicts and uncertainty about lookahead time.

The DWC candidates did have differential effects on the alerting timeline, which had implications on pilot response times and ATC coordination rates. Nominally, caution-level alerting informs the pilot that there is time to coordinate with ATC prior to maneuvering, while warning-level alerting indicates an immediate maneuver is required. On average, this ATC coordination time (generally assumed to take at least 15 seconds) was allowed by either candidate. However, fast closure rate encounters were susceptible to shortened caution-level alert durations, especially when the Tau candidate was applied. The fast-closure encounters significantly reduced the amount of time spent in the Corrective alert status with the Tau candidate relative to the Disc candidate, with the worst-case encounter type bypassing the Corrective alert entirely. Nearly half (47%) of Corrective alerts generated against the Tau candidate were of short-duration (<15 seconds), and the look-ahead time was not immediately apparent at alert onset. Consequently, pilots responded to conflicts with a higher sense of urgency in the present study, as intruders alerted at first appearance on the display and frequently elevated to warning-level status (47% and 26% of the time with the Tau and Disc candidates, respectively). The results suggest that the alert progression was too rapid for consistent ATC coordination, despite faster pilot responses relative to Phase 1 performance. Pilots were able to obtain approval prior to only 51% and 64% of maneuvers with the Tau and Disc candidates (when Corrective at first alert), compared to 86% of the time as observed against the Phase 1 non-cooperative DWC definition [6]. Pilots always notified ATC when able (~7-8 seconds after first alert on average), but often maneuvered in response to the Warning alert onset before officially receiving ATC acknowledgement/approval. Therefore, the drops in ATC coordination rates should be considered more so a consequence of pilots' compliance with standard DAA procedures than a heightened disregard for ATC procedures.

Subjective feedback indicated that pilots felt they were able to remain DWC with either DWC candidate, and that they only noticed differences between the two during the fast-closure rate encounters where alert progression was quicker and more frequent. Moreover, one-third of pilots indicated they would find an even smaller detection range (e.g., 2.5-3.0 nmi) acceptable for DWC maintenance with either candidate in a similar test setup. During the post-simulation debrief, pilots were adamant about considering their simulation performance "as good as it gets" for these test cases. Vigilance decrement during long duty cycles, latency, and a busier voice communication frequency were among factors cited as a potential hinderance to real-world response times and ATC coordination. In addition to the simulation containing a much higher proportion of non-cooperatives than pilots are expected to encounter in a single sector, the reader should consider the equal frequency at which pilots experienced the best- and worst-case encounter types when digesting the results. The scenarios were designed to emulate the representative encounter sets at each end of the aircraft performance spectrum, but the encounter types do not necessarily have equal likelihood of occurring in a real-world scenario. Thus, the reported averages are weighted by the sample distribution of fast-closure encounters. Pilots relied solely on DAA alerts and guidance to assess conflicts, as they were blind to which DWC candidate was active during a given scenario. The equal variance of encounter types within scenarios likely contributed to the aforementioned uncertainty about alert look-ahead time; this could have influenced faster responses against slower intruders in simulation, for which alerting differences between candidates were less pronounced. Also note that the slowest ownship speed assumption of 40 KTAS, which may have slightly extended the maneuver initiation ranges needed to avoid the fast intruders, was not evaluated in the current design. However, slower ownship speed would also extend alert look-ahead times against fast intruders, so it was not expected to impact separation performance metrics reported in this paper.

VI. Conclusion

The current study found that both the Tau and the Disc DWC candidates provide sufficient time to upload effective maneuvers at the 3.5nmi radar declaration range. This is consistent with Phase 1 research that reported that loss of DWC was effectively avoided so long as pilots had the full Warning alert time [6]. The additional alert lookahead time allowed by the Disc candidate, however, better supported ATC coordination at faster closure rates and renders it less vulnerable to further truncation of the alerting timeline if smaller low SWaP surveillance ranges are examined in the future. These human-in-the-loop findings are in line with preceding fast-time results, which proposed that the Tau component extends the declaration range necessary for timely DAA alerts without added benefits to safety and operational suitability [20]. Added constraints to the alerting timeline at reduced ranges could also impact the assumed timeline for pilot response, and the Disc candidate would provide more solution space for a pilot-in-the-loop configuration that does not require automation support.

The additional alert look-ahead time allowed by the static hazard zone with no temporal component would be better suited for any further reductions to the non-cooperative surveillance range requirement, especially if the Phase 2 DAA MOPS for Class 4 systems preserve caution-level alerting and continue to nominally require ATC coordination when pilots maneuver against non-cooperative traffic. After careful consideration with RTCA, the Disc criterion was deemed the primary non-cooperative DWC definition for ongoing Phase 2 efforts. It served as the DWC definition for follow-on NASA studies that evaluated pilot performance and ATC acceptability at RDRs below 3.5nmi in simulated and live flight environments [21, 23-25]. Findings from this research will inform Phase 2 MOPS development for UAS with alternative surveillance equipment and limited aircraft performance capabilities.

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