UAS Pilot Performance Comparisons with Different Low Size, Weight and Power Sensor Ranges

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***Abstract*— The present study evaluated the performance of UAS pilots under four simulated low size, weight, and power (SwaP) sensor ranges: 1.5nmi, 2.0nmi, 2.5nmi, and 3.0nmi. Nine active-duty UAS pilots responded to scripted DAA conflicts against non-cooperative intruders while flying a simulated RQ-7 Shadow at varied speeds along a pre-filed flight path in Class E airspace. Findings revealed a linear effect of sensor range on alerting time and separation performance, with nearly every DAA well clear (DWC) violation and all Near Mid-Air Collision (NMAC) events occurring below 2.5nmi. Response time differences at these reduced ranges were negligible due to the high frequency of warning-level alerts that require an immediate response. Since caution alert duration was truncated to some degree by each tested declaration range, pilots were often unable to coordinate their avoidance maneuvers with ATC prior to their uploads. Nonetheless, the 2.5nmi range allowed minimum alerting times that were sufficient for acceptable pilot performance. These findings will inform DAA system requirements for UAS with alternative surveillance equipment and aircraft performance capabilities. Implications on DAA display and sensor requirements are discussed.**

Keywords—uas, detect and avoid, low swap, alternative surveillance

I. Background

NASA has worked alongside external partners from government, industry, and academia to address technical barriers related to the integration of Unmanned Aircraft Systems (UAS) in the National Airspace System (NAS) for routine civil and commercial applications [1, 2]. One key issue is ensuring compliance with existing 'see-and-avoid' procedures that require on-board pilots to observe nearby traffic out of the window to maintain safe, visual separation [3]. In conjunction with RTCA Special Committee 228 (SC-228), Minimum Operational Performance Standards (MOPS) are under development for UAS equipped with a detect-and avoid (DAA) system, which generates predictive conflict alerting and guidance to assist pilots with remaining 'well clear' [4-6] of traffic using a ground control station (GCS). The MOPS development is a mutli-phase effort, with each phase expanding the document's scope. Phase 1 of the UAS in the NAS project produced several studies [7-14] that informed minimum requirements for air-to-air radars (ATAR) and DAA systems, including color-coded design principles for DAA displays that led to consistent improvements in separation performance against cooperative traffic detected by automatic dependent surveillance-broadcast (ADS-B In) and non-cooperative traffic detected by an airborne radar.

The Phase 1 DAA MOPS [15] focused primarily on DAA system requirements for large UAS in transit operations with relatively heavy surveillance equipment. Phase 2 MOPS will extend DAA system requirements to a wider of range of operations and vehicles, including smaller UAS with lower size, weight, and/or power (SwaP) non-cooperative sensors than were practical in Phase 1. This new, lower-performing class of airborne radar equipment will be applied to small-to-medium UAS operating at slower speeds and lower altitudes, where transponders with ADS-B coverage are not currently mandatory – i.e., below 10,000 feet (ft.) mean sea level (MSL) and 100 knots true airspeed (KTAS). Low SwaP sensors are expected to achieve a much shorter detection range relative to the Phase 1 radar, which is required to declare the track(s) of non-cooperative traffic within a range of 6.7 nautical miles (nmi). The limited scan coverage capabilities of airborne low SwaP sensors currently reach far below this initial range requirement [16-18]. This is likely to introduce alerting timeline constraints that restrict pilots' ability to maintain operational safety levels outlined in the Phase 1 MOPS without automation support. However, near-term UAS operations in the NAS will require a human in-the-loop to execute the DAA task – i.e., detect a threat, determine a resolution, and execute an avoidance maneuver. Therefore, it is critical to determine the necessary revisions to DAA system requirements that will enable sufficient alerting time and pilot performance during low SwaP operations.

Initial efforts to alleviate the burden of low SwaP sensors on the DAA system focused on modifying the DAA Well Clear

(DWC) definition for non-cooperative aircraft, defined in Phase 1 MOPS as: 4000 ft. horizontal separation, 450 ft. vertical separation, and 35 seconds modified Tau (approximately equivalent to time to closest point of approach). The Phase 1 DWC definition was originally designed to encompass the Traffic Alert and Collision Avoidance System (TCAS II) [19] alerting volume in order to avoid excessive resolution advisories (RAs). Since aircraft that are not equipped with an operational transponder cannot receive TCAS II RAs, the Phase 1 DWC definition was deemed unnecessarily large for non-cooperative aircraft. A fast-time simulation at NASA [20] informed multiple alternate DWC definitions for small-to-medium UAS without a transponder. All four DWC definition proposals contained a smaller hazard zone relative to the Phase 1 DWC volume, and their impact on the DAA system was further evaluated based on numerous open-loop safety and operational suitability metrics computed from a representative encounter set [21]. The primary DWC candidate, which reduced the horizontal threshold to 2200 ft. and eliminated the temporal component (modified Tau) entirely, enabled full-duration Warning alerts and low unmitigated collision risk at a 3.5nmi sensor range. Additional alert look-ahead time allowed by the primary candidate made it more resilient to faster closure rates and alternative surveillance ranges. In line with Phase 1 findings, the full Warning alert duration afforded by the reduced non-cooperative DWC remained adequate for timely DAA conflict avoidance with a 3.5nmi sensor range and a pilot in-the-loop to execute maneuvers [22].

A follow-on fast-time study further investigated the effects of limited sensor ranges on DAA alerting performance with the new non-cooperative DWC definition [23]. Analyses revealed that the DAA alerting timeline remained resilient until the 2nmi range, under which the average alert look-ahead time dipped below 25 seconds – i.e., the minimum amount of time needed for pilots to remain DWC in Phase 1. Moreover, a sensor range of at least 2.3nmi was required to detect 95% of Warning alerts in the study; thus, a minimum range of 2.5nmi was considered a practical requirement to maintain sufficient DAA alert times. The present study sought to verify and validate the open-loop fast-time analyses with a human-in-the-loop (HITL) simulation that evaluated alerting and pilot performance under four low SwaP sensor ranges between 1.5nmi and 3.0nmi (detailed below). Results reported in this paper will help inform Phase 2 MOPS development, including the minimum sensor range needed for low SwaP radars to comfortably support timely conflict detection and resolution.

II. Approach

A. Experimental Design

The present study utilized a repeated measures design to examine DAA system and pilot performance under four fixed low SwaP sensor ranges: 1.5nmi, 2.0nmi, 2.5nmi, and 3.0nmi. Upon recruitment, each pilot was randomly assigned either a slow (60 KTAS) or fast (100 KTAS) ownship speed that remained constant for the duration of the study. The motivation behind assigning 60 KTAS instead of 40 KTAS – the slowest speed assumption for low-SwaP category UAS – was to emulate the anticipated cruise speed of the Tigershark-XP UAS flown in a follow-on flight test [24]. The 100 KTAS ownship speed was selected because it is the highest speed allowed for low-SwaP category UAS. An additional, embedded variable of encounter type was also included in the study design. The encounter type variable was within-trials and determined the closure rate of each scripted conflict. Further information regarding intruder characteristics will be provided during discussion of the general DAA task.

B. Participants

Nine active-duty UAS pilots (M = 35 years old) were recruited for the study. Participants reported between 170 to 2,030 hours of unmanned flight experience (M = 1,178 hours), including averages of 822 flight hours in military combat and 356 flight hours in military non-combat. Researchers from the Human Autonomy Teaming Laboratory (HAT Lab) served the confederate role of air traffic controller (ATC) for Oakland Air Route Traffic Control Center (ZOA 40/41).

C. Simulation Environment

1) Ground Control System: Participants controlled a generic RQ-7 Shadow UAS model via Vigiliant Spirit Control Station (VSCS), an experimental GCS developed by the Air Force Research Laboratory (AFRL) [25]. The GCS featured two displays: the primary display known as the Tactical Situation Display (TSD), and a secondary display which featured more detailed information regarding telemetry information, electronic checklists, and a mission command chat room. The TSD displayed featured a top-down view of the associated airspace map overlay along with ownhip's location (i.e., a highlighted aircraft icon), mission route(s), and basic naviagation controls.

On the TSD, a compass rose surrounding the ownship icon featured two outer range rings that updated based upon the relative zoom layer chosen for the airspace map overlay. Participants could locate aircraft state information via a 'baseball card' positioned at the top of the TSD, including altitude in feet (MSL), magnetic heading, indicated airspeed (IAS), and angle of attack. The right side of the TSD featured an altitude tape that visually displayed the current and commanded altitude.

Participants sent commands to the aircraft via a moveable 'steering window' that featured all aircraft controls and two flight modes. The default flight mode, known as 'NAV' mode, maintains the pre-programmed flight route via waypoint-to-waypoint navigation. The secondary flight mode, known as 'HOLDS' mode, was utilized to make amendments to the flight path during DAA conflicts. Possible deviations included new altitude or heading hold commands, which could be made using either the mouse or keyboard. Participants could input a new altitude through either manual entry of the integer value into the associated text box, or through up/down arrow buttons known as 'spinners' that incrementally increased/decreased altitude by 500 ft MSL. Heading could also be changed through an associated textbox as well as selecting and dragging a heading bug located along the compass rose surrounding the ownship icon.

The aircraft model utilized a simulated climb/descent rate of 500 ft. per minute and a turn rate of 7° per second. Simulated aircraft surveillance included ADS-B for detection of cooperative aircraft and a low SwaP radar for detection of non-cooperative aircraft. Cooperative aircraft were detected within 20nmi of ownship, whereas non-cooperatives were detected at either 1.5nmi, 2.0nmi, 2.5nmi, or 3.0nmi in each trial. The associated low SwaP radar for the aircraft featured an azimuth range of ±110° off the nose and an elevation range of ± 15°. The mission route flown within Oakland Center Class E airspace featured a constant cruise altitude of 8,000 ft MSL, and cruise speed remained constant at either 60 KTAS or 100 KTAS. Communication with ATC was performed via a push-to-talk headsets over a voice-IP-server.

2) DAA System: The DAA system featured a multi-level alerting and guidance logic that indicated potential threats to ownship's DWC volume. The algorithmic element of the system utilized NASA's Detect and Avoid Alerting Logic for Unmanned Systems (DAIDALUS) [26]. Each alert level was associated with unique aural and visual cues. As outlined in Table I below, the alerting structure included two levels that required corrective action from the pilot in command – the Corrective alert and the Warning alert.

The caution-level, Corrective alert indicated that a loss of DAA Well Clear (LoDWC) would occur within up to 60 seconds without pilot intervention. The intruder symbol turned yellow and the DAA system issued the aural, "Traffic, Avoid". For this alert level, the maneuver to maintain DWC would need to be coordinated with ATC prior to its execution. If a DAA Warning Alert was issued by the DAA system, an immediate maneuver needed to be executed to avoid a LoDWC within 30 seconds. In these cases, the intruder symbol turned red and the DAA system issued the aural, "Traffic, Maneuver Now. Traffic, Maneuver Now" (repeated to indicate increased urgency). Due to the small timing window until a potential LoDWC, conflict resolution is prioritized over ATC coordination when responding to Warning alerts. Pilots were trained to notify ATC of the situation after the initial avoidance maneuver. The lower alert levels directed a pilot to simply monitor a nearby aircraft for a possible future escalation to a Corrective or Warning alert. Alerting for these levels became active if ownship and intruder paths were especially close to penetrating the DWC volume (e.g., within 250 ft. of the vertical threshold). The basic traffic level is associated with surrounding aircraft that were within surveillance range, but not anywhere near conflicting with the ownship's current trajectory.

When the system alerted to active DAA threats against ownship, pilots were trained to follow the associated maneuver guidance bands that displayed on either of the TSD's heading and altitude instruments (Fig. 1). Yellow bands indicated unsafe heading or altitude ranges that were predicted to result in a Corrective alert and, therefore, a LoDWC within 60 seconds. Red bands were associated with the Warning alert and indicated trajectories that were predicted to result in LoDWC within 30 seconds. The guidance bands updated every second based on current aircraft states, and future intent was not considered in its projections. In the event where a LoDWC became unavoidable, a green 'wedge' highlighted a more limited range of target heading and altitude ranges that would assist in regaining DWC by maximizing separation between ownship and intruder at the closest point of approach (CPA) [27].

TABLE I. PHASE 2 DAA ALERTING LOGIC

Icon	Alert Level	Expected Pilot Response	Look-ahead Time
	Warning Alert	Maneuver immediately	≤30 sec
	Corrective Alert	Maneuver following ATC approval	≤60 sec
	Preventive Alert	Monitor traffic; no maneuver	N/A
	Guidance Traffic	Monitor traffic; No maneuver	N/A
	Basic Traffic	No maneuver required	N/A

D. Procedure

1) Training: Upon arrival and completion of informed consent and demographics forms, participants were given a high-level overview of the UAS in the NAS project objectives. They were then situated in the pilot booth and trained on VSCS functionality. Participants were given at least 30 minutes of hands-on experience with the GCS controls, flying along a straight-line practice route. Following exposure to VSCS, a briefing on the DAA system's alerting and guidance features was presented. Participants then gained hands-on experience with the DAA system and flew the simulated UAS and responded to example conflict encounters for roughly 20 minutes Participants had to demonstrate proficiency with the controls and DAA system before data collection trials officially began. This 20-minute hands-on practice session was repeated before each subsequent trial with a new sensor range to familiarize themselves with the associated timing and behavior of alerting and guidance under each condition.

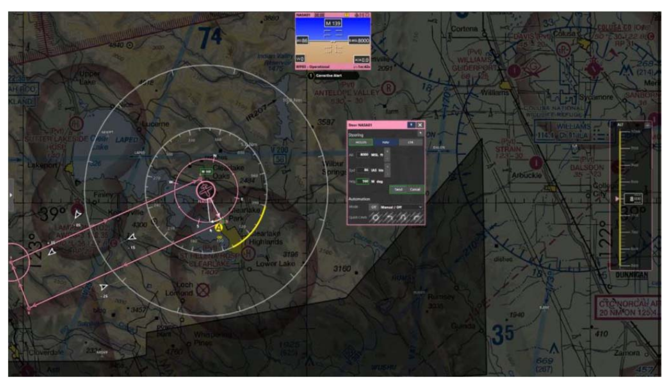

Fig. 1. Screenshot of the VSCS TSD during a Corrective alert. Intruder alert symbol and heading bands are shown near the center-left; altitude bands are depicted on the far right of the TSD.

2) DAA Task: A total of four non-cooperative encounters were scripted in counterbalanced order for each of the four trials. Intruders varied by both speed (i.e., 100 or 170 KTAS) and approach angle relative to ownship (i.e., head-on or crossing at ± 90°). Each trial was around 45 minutes in length and simulated one of the four sensor ranges, which were randomized in order of presentation. Participants were trained to follow procedures associated with each of the DAA alerting levels (e.g., contacting ATC before executing a maneuver in response to a Corrective alert) and any associated guidance to maintain DWC. Participants contacted ATC to request vectors back to original course following successful resolution of the DAA conflict. Note that communication regarding conflict avoidance was initiated by the pilot in this test procedure, with the ATC's role being either to approve the initial maneuver request or acknowledge the pilot's notification of a recent maneuver. In order to assess the efficacy of the DAA system and its ability to inform safe and timely maneuvers, vector requests were not rejected or re-negotiated by the confederate ATC.

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) Separation: Refers to the proportion of conflicts that penetrated the Loss of DAA Well Clear (LoDWC) or Near Mid-air Collision (NMAC) threshold (500 feet horizontal separation, 100 feet vertical separation) under each sensor range out of those scripted to do so. The reason behind each instance of LoDWC will be noted.

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') out of all maneuvers made. These results apply only to conflicts that generated Corrective alerts, as Warning alerts required immediate maneuvers.

IV. Results

A repeated measures Analysis of Variance (ANOVA) was conducted to analyze the impact of Sensor Range on the Alert Look-ahead Time and Aircraft RT metrics, utilizing an alpha level of 0.05. Significant pairwise comparisons are reported where appropriate. Descriptive statistics are reported for the Alert Progression, Separation, and ATC Coordination metrics.

A. Alerting Performance

1) Alert Look-ahead Time: There was a main effect of Sensor Range on total Alert Look-ahead Time, $F(3, 24) = 705.68$, $p < .05$. On average, there were significant differences observed between alert look-ahead times in the 1.5nmi (M = 19.32s, SE = 0.37s), 2.0nmi (M = 29.55s, SE = 0.78s), 2.5nmi (M = 39.30s, SE = 1.01s), and 3.0nmi (M = 46.61s, SE = 1.20s) range conditions. Specifically, there was a significant difference between the Corrective alert look-ahead times observed in the 2.0nmi (M = 8.22s, SE = 0.74s), 2.5nmi (M = 12.56s, SE = 1.03s), and 3.0nmi (M = 16.62s, SE = 1.21s) range conditions, $F(2, 16) = 26.00$, $p < .05$. There was no corrective alerting in the 1.5nmi condition. For conflicts that were warning-level at first alert, Warning alert look-ahead times were significantly shorter in the 1.5nmi (M = 19.33s, SE = 0.37s) and 2.0nmi (M = 25.11s, SE = 0.53s) range conditions compared to 2.5nmi (M = 28.12s, SE = 0.81s) and 3.0nmi (M = 30.00s, SE = 0.00s), $F(3, 24) = 155.82$, $p < .05$. No significant differences in Warning alert look-ahead times were observed between the 2.5nmi and 3.0nmi range conditions, $p > .05$. Pilots needed at least 2.5nmi to experience full-duration Warning alerting for the majority of encounters under test, and at least 3.0nmi to experience Corrective alerting in the worst-case scenario (albeit short-duration; Fig. 2). As shown in Fig. 3, only the 3.0nmi condition resulted in Corrective alert durations that lasted 15 or more seconds in more than 25% of the simulated encounters.

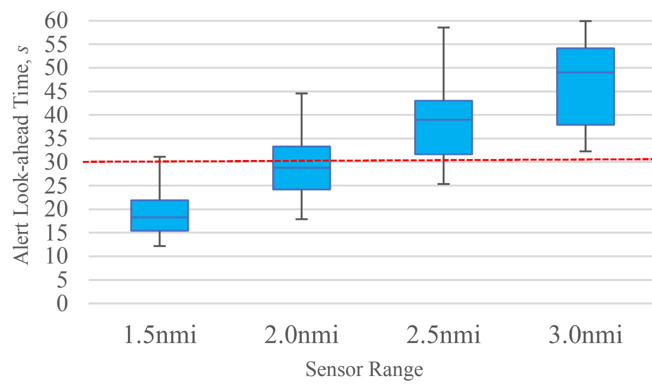

Fig. 2. Median, Minimum, Maximum Alert Look-ahead Time by Range.

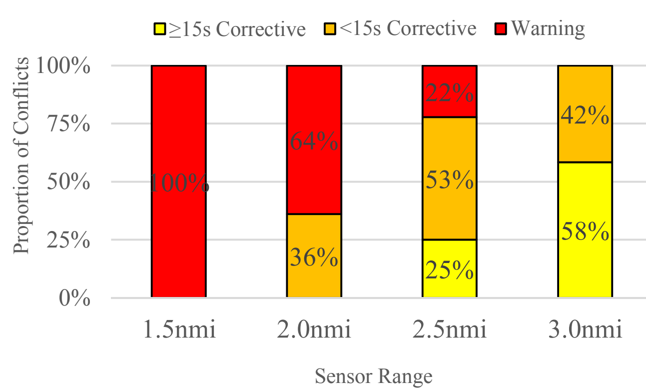

Fig. 3. First Alert Level by Sensor Range.

2) Alert Progression: Alerts commonly progressed to warning-level severity in all Sensor Range conditions; 83% of conflicts generated Warning alerts by the time they were resolved, including every encounter at the 1.5nmi and 2.nmi ranges (Fig. 4).

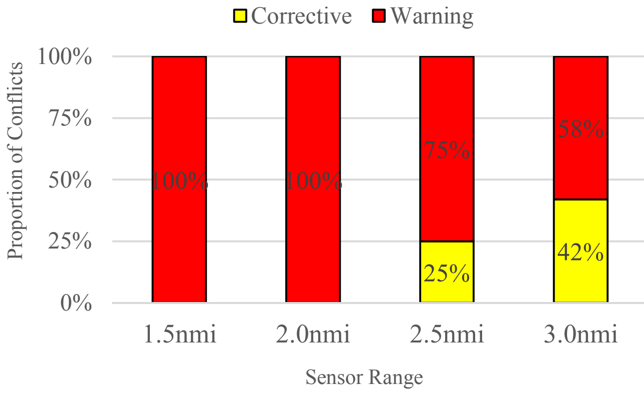

Fig. 4. Final Alert Level by Sensor Range.

B. *Pilot Performance*

1) Aircraft Response Time (RT): Overall, there were differences observed between reponse times at 1.5nmi (M = 6.72s, SE = 0.38s), 2.0nmi (M = 7.67s, SE = 0.43s), 2.5nmi (M = 8.92s, SE = 0.47s), and 3.0nmi (M = 10.58s, SE = 0.67s), $F(3, 24) = 19.96$, $p < .05$. However, this main effect of Sensor Range on Aircraft RT was modified by the effects of First Alert type, $F(1, 8) = 44.84$, $p < .05$. In line with expectations, pilots responded faster to Warning alerts (M = 6.76s, SE = 0.36s) compared to Corrective alerts (M = 9.98s, SE = 0.52s). As shown in Fig. 5, response times to Corrective and Warning alerts were not impacted by Sensor Range, p's > .05.

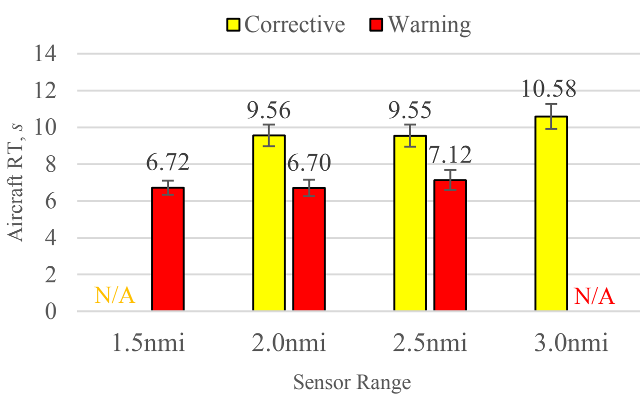

Fig. 5. Mean Aircraft RT by Sensor Range & First Alert Type.

2) Separation: Pilots maintained DWC against 78% of conflicts (n = 144) over the course of the study. As shown in Table II, the majority of DWC violations occurred in the 1.5nmi and 2.0nmi conditions. Both NMACs also occurred in these two conditions. The observed trend was primarily attributed to the minimum look-ahead time afforded by each sensor range. Phase 1 research found that pilot performance remained positive until alert look-ahead times dropped below 25 seconds – i.e., the full Phase 1 Warning alert duration [12]. This remained true in the current test, where pilots were 71% more likely to lose DWC against conflicts with less than 25 seconds of alerting (Table III). The aforementioned Fig. 2 illustrated that the DAA system required at least 2.5nmi to ensure the sufficient, 25-second minimum alert duration in the highest closure rate encounter. Each LoDWC and NMAC with more than 25 seconds of look-ahead time actually occurred during the return to course after the conflict was initially resolved. Intruder aircraft often fell out of the low SWaP radar's field of regard during avoidance, which occasionally resulted in the re-generation of alerts when pilots attempted to return too soon after losing the intruder's DAA display information (as discussed later).

TABLE II. SEPARATION PERFORMANCE BY SENSOR RANGE.

Sensor Range	LoDWC Rate	NMAC Rate
1.5nmi	67% (24/36)	3% (1/36)
2.0nmi	17% (6/36)	3%* (1/36)
2.5nmi	3%* (1/36)	0%
3.0nmi	0%	0%

*Early Return to Course

TABLE III. SEPARATION PERFORMANCE BY ALERT LOOK-AHEAD TIME.

Look-ahead Time	LoDWC Rate	NMAC Rate
Less than 25s	73% (29/40)	3% (1/40)
25s or more	2%* (2/104)	1%* (1/104)

*Early Return to Course

3) ATC Coordination: ATC Coordination rates suffered with each reduction to the sensor range (Fig. 6). Shorter Corrective alert durations leave less time to coordinate with ATC prior to maneuvering. Note that ATC coordination rates are not reported for the 1.5nmi range, as prior ATC notification and approval was not required for warning-level threats.

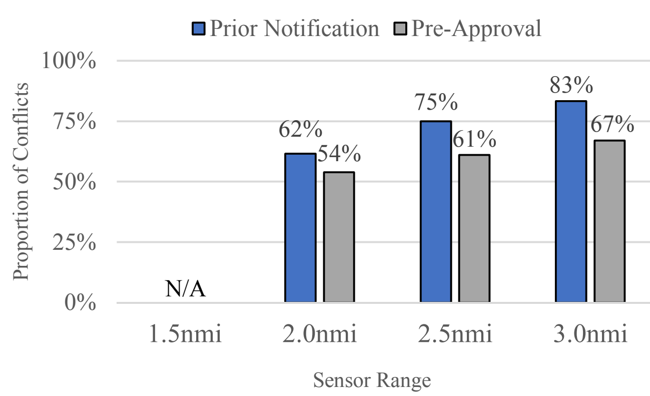

Fig. 6. ATC Coordination Rates by Sensor Range (Corrective at First Alert).

V. Summary & Conclusion

The present study explored the differential effects of low SWaP detection ranges on DAA system performance, which had a direct impact on the pilot performance metrics. As expected, alert look-ahead times were significantly shortened by each reduction to the sensor range. Look-ahead times were typically long enough to experience Corrective alerts for most conflicts at 2.5nmi and above. The majority of conflicts in the 2.0nmi condition were warning-level at first alert, only allowing short-duration Corrective alerting (i.e., fewer than 15 seconds as a Corrective alert). There was no Corrective alerting in the 1.5nmi condition, which significantly reduced overall response times relative to the longer ranges. ATC coordination rates mirrored the trends observed on Corrective alert duration, as larger surveillance volumes better supported pilots' ability to attain ATC approval prior to maneuvering. ATC approval rates with the 3.0nmi range matched those observed with the 3.5nmi modeled in the preceding low SWaP study [22]. Although Corrective alerts at 3.0nmi were generally ~6 seconds shorter in duration (17 seconds vs. 23 seconds at 3.5nmi), this range still allowed more than the nominal 15 seconds of Corrective alerting on average. This finding further justifies the assumption that Corrective alerting is most beneficial to ATC coordination when the nominal alert duration is allowed.

Pilots were not always allowed enough time to receive a response from ATC before executing the maneuver, but they were still able to notify ATC of their intentions before maneuvering for at least 75% of conflicts appearing at 2.5nmi and above. Nonetheless, ATC approval rates with each low SWaP sensor range remained lower compared to Phase 1 performance, which did not constrain the alerting timeline to the same degree given the better radar performance required for Phase 1 DAA systems (6.7nmi declaration range requirement). The low SWaP sensor ranges continue to diminish the utility of Corrective alerts - they encourage ATC coordination at slower closure rates, but the variable alert duration may not always enable pilots to prioritize coordination and execute a response before it elevates to the Warning alert. As detailed in [28], most test pilots did not rate caution-level alerts as an absolute necessity for low SWaP operations. Additionally, a human in-the-loop study conducted at California State University, Long Beach found that uncoordinated DAA maneuvers were minimally disruptive to ATC procedures with this category of UAS, so long as the pilot notified the ATC of their intentions soon thereafter [29]. Any amount of Corrective alerting for low SWaP conflicts is generally considered to be a bonus for this category of operations, and low SWaP DAA system requirements will be tailored to preserve the Warning alert timeline at a minimum.

Consistent with previous research, separation performance was impacted primarily by the minimum Warning alert duration allowed by each sensor range. As mentioned, Phase 1 pilot participants were able to consistently remain DWC until alert look-ahead times dropped below 25 seconds – i.e., the full duration of the Phase 1 Warning alert (see Table III). Results from the current study indicated that Warning alerts were significantly shortened at ranges below 2.5nmi, which was the range necessary to ensure at least 25 seconds of look-ahead time in the worst-case scenarios. Pilots violated DWC against 73% of conflicts that appeared within 25 seconds of penetrating the DWC threshold. Lookahead times were only this short below 2.5nmi, occurring in 75% and 50% of conflicts in the 1.5nmi and 2.0nmi conditions, respectively. It should be noted that pilots never failed to remain DWC with their initial avoidance attempt(s) when alert duration was sufficient. Any separation violations that occurred with sufficient look-ahead time (25*s*) were actually due to a premature return to course. Otherwise, separation performance was in line with preceding research.

The above findings indirectly highlight how the limited field of regard coverage can become more problematic after path deviations during low SWaP operations. The relatively limited vertical maneuverability of low SWaP UAS and the sensor uncertainty associated with non-cooperative intruders make horizontal maneuvers the primary strategy for these types of DAA conflicts. However, shorter detection ranges necessitate larger heading changes that stress the +/-110° azimuth limit on the ownship's radar, especially against encounters with faster closure rates. On average, test pilots turned ~99° off course to avoid the fast-closing encounters where this issue was most prevalent. Turn magnitudes were 15-20° wider when flying in the 1.5nmi and 2.0nmi conditions (M = 108° turn) compared to 2.5nmi and 3.0nmi (M = 90° turn). Consequently, intruders commonly flew outside out of the ownship's bearing scan during conflict avoidance. Once the intruder flies outside of the radar's field of regard, the pilot no longer receives DAA information (i.e., symbology, alerts, guidance) for that aircraft. This event, referred to as an 'azimuth dropout' in this paper, strips the visual aids necessary to determine whether the current track and/or return path is conflict-free. Azimuth dropouts are especially problematic when display information is lost during an active DAA alert, which occurred for over half (56%) of all conflicts in the 1.5nmi condition. While azimuth dropouts were less likely to occur with the three largest ranges tested (22% occurrence), it remains an important consideration for Low SWaP operations that the turn magnitude increases as the sensor range decreases. These results also translated to a flight test environment in a follow-on study using the 2.5nmi sensor range, where all but one conflict led to an azimuth dropout at some point during the encounter [24]. Increased time spent off course and coordinating with ATC can mitigate the risk of uploading an unsafe return path in these cases, in lieu of any 'coasting' logic that extrapolates position estimates of intruder aircraft for a short period following an azimuth dropout. While azimuth dropouts elevate the potential risk of returning to course too soon after the initial avoidance maneuver, insufficient alert look-ahead time remained the primary obstacle to avoiding DWC violations in the current test.

Overall, our findings support 2.5nmi as the minimum range necessary to avoid DWC violations at acceptable rates. The 25-second minimum alert look-ahead time afforded by the 2.5nmi range provided sufficient time for pilot response and aircraft response without automation in-the-loop. Although pre-emptive ATC coordination was not always feasible due to variable Corrective alert duration at each range tested, separation performance remained intact when the Warning alert timeline was preserved. This was further validated by the follow-on flight test, which found no separation violations with the 2.5nmi range despite frequent azimuth dropouts after conflict resolution [24]. The 2.5nmi range also allowed at least 10 seconds to upload an avoidance maneuver before receiving the more limited Regain DWC guidance, which indicates that a LoDWC is imminent. This conforms well to the 10-second response time assumed against Warning alerts, based on Phase 1 research. Below 2.5nmi, it is increasingly likely that pilots' initial maneuver would be in response to Regain DWC guidance (or RA guidance if a collision avoidance system is implemented). Sufficient time with Remain DWC guidance is desirable, as it is more suggestive and allows more flexibility for conflict resolution options.

Multiple design considerations should be made when processing the results of this study. Firstly, pilots were encountering non-cooperative DAA conflicts almost exclusively, and most of their maneuvers were in response to Warning alerts throughout the day. This approach to the scenario design allowed for empirical data to be collected on a wide range of encounter geometries and closing speeds with each range, including the worst-case scenarios. High-severity conflicts were very common as a result, which may have biased faster pilot responses overall. Unlike the preceding fast-time simulations, the sample distribution was not intended to be probabilistic or representative of the likelihood these encounters would occur in a real-world scenario. Remember that these low SWaP non-cooperative encounter types, which alerted at first appearance on the DAA display, are only expected to comprise ~15% of traffic in Class E airspace below 10,000 ft. MSL [15]. An even smaller proportion of these encounters will be converging at the maximum closing speeds simulated in this study. The present study also did not have confederate pilots congesting the voice communication channel, which may have made ATC coordination less feasible and delayed responses to Corrective alerts.

Additional research is being conducted to account for factors not addressed in the current design, such as mitigating realistic sensor uncertainties [30, 31] that may delay the declaration of an intruder's track after detection (the prerequisite for DAA alerting). This declaration time may not remain as stable or constant with real-world systems as it was in simulation, so a slight buffer beyond the 2.5nmi minimum may be more ideal to ensure DAA alerting and guidance processing at this range. Furthermore, if ATC coordination is considered as essential for low SWaP UAS when responding to non-cooperative DAA conflicts as it was in Phase 1, a larger declaration range will be required so that pilots have sufficient time to consistently coordinate with ATC. The objective results of this simulation will support ongoing efforts to inform Phase 2 MOPS development for UAS with alternative surveillance equipment and aircraft performance capabilities.

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