Impact of Airborne Radar Uncertainties on Detect-and-Avoid Systems' Performance

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Impact of sensor uncertainty on Detect-and-Avoid (DAA) systems' performance is investigated. Key metrics analyzed are the loss of DAA well clear ratio, the near-mid-air-collision risk ratio, the alert ratio, and the number of maneuvers per loss of DAA well clear. Sensitivity of these metrics to the magnitude of sensor uncertainty, pilots' selection of maneuver, and surveillance range is investigated. Benefits of a dynamic buffer around the DAA well clear separation boundary, computed based on track accuracies, are also analyzed. These metrics are computed from open- and closed-loop simulations of a large number of representative encounters between an unmanned aircraft system and a manned aircraft. Results show that sensor uncertainty degrades safety metrics considerably but has only a minor effect on the number of maneuvers per loss of DAA well clear. The number of maneuvers, nonetheless, can be reduced by a 5° buffer away from the edge of the range of conflict-resulting heading in pilots' selection of maneuver.

Nomenclature

ADS-B	=	Automatic Dependent Surveillance – Broadcast
ATC	=	air traffic control
AGL	=	above ground level
CPA	=	closest point of approach
DAA	=	detect and avoid
DWC	=	DAA well clear
D_{mod}	=	distance modification
FOV	=	field of view
h	=	altitude separation between two aircraft
KTAS	=	knots true airspeed
LoDWC	=	loss of DWC
LSN	=	large sensor noise
MOPS	=	minimum operational performance standards
MSL	=	mean sea level
NMAC	=	near mid-air collision
NSN	=	no sensor noise
r	=	horizontal range between two aircraft
$\dot{r}$	=	horizontal range rate
SC-228	=	special committee 228
SN	=	(representative) sensor noise
SWaP	=	size, weight, and power
t	=	time
UA	=	unmanned aircraft
UAS	=	unmanned aircraft system
VFR	=	visual flight rules
τ_{mod}	=	modified tau

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I. Introduction

Sensor uncertainties can impact the ability of a detect-and-avoid (DAA) system to maintain separation between an unmanned aircraft system (UAS) and manned aircraft. A DAA system computes alerts and maneuver guidance based on the surveillance data to help UAS pilots maintain "well clear" with manned aircraft. For DAA, the "well clear" is defined by a quantitative separation standard called DAA well clear (DWC). Large uncertainties in surveillance data may create flickering alerts, causing UAS pilots and operators to lose confidence in the system. Uncertainties in the surveillance data may cause the maneuver guidance to be ineffective. As a result, the UAS may violate DWC even after following the DAA guidance. Even if pilots are able to maintain DWC, the increased pilot workload and stress level can make the DAA system operationally unsuitable.

Characteristics of sensor uncertainties vary greatly across sensor types. Three surveillance components were specified in the Minimum Operational Performance Standards (MOPS) for DAA systems [1] published in 2017 by RTCA. This MOPS requires Automatic Dependent Surveillance-Broadcast (ADS-B) In, airborne active surveillance, and an air-to-air radar. A companion MOPS for the air-to-air radar for DAA was also published [2]. These two MOPS are referred to as the Phase 1 MOPS. Additional work to extend these MOPS, the Phase 2 work, is underway. ADS-B can detect intruder aircraft equipped with ADS-B out systems. Active surveillance can detect aircraft that have a functioning mode S or mode C transponder. Air-to-air radar in theory can detect all intruder aircraft. For non-cooperative aircraft, i.e., aircraft without a functioning transponder, the air-to-air radar is the only sensor that can detect it. Both ADS-B and active surveillance provide highly accurate vertical state (altitude and vertical speed) information of the intruder aircraft. Current state-of-the-art air-to-air radar, on the other hand, is not as accurate in its vertical state estimate. For horizontal states, both ADS-B and air-to-air radar provide highly accurate measurements for DAA purposes. The DAA alerting and guidance algorithm needs to be tested with various combinations of sensor measurements to make sure it can adapt to varying degrees of sensor uncertainties. If sensor measurement accuracy information is available, the algorithm can take advantage of such information and adapt its behavior accordingly.

This paper analyzes the impact of airborne radar sensor uncertainties on a few safety and operational suitability metrics of the DAA system. The safety metrics include the loss of DAA well clear (LoDWC) ratio and the near-mid-air-collision (NMAC) risk ratio. The operational suitability metrics include the alert ratio and the number of DAA maneuvers per LoDWC. Minimum accuracy parameters from the radar MOPS [2] will be applied as a worst-case sensor noise. The analysis focus on encounters between low-speed unmanned aircraft (UA) and non-cooperative aircraft. More than 72,000 encounters are simulated in both open and closed-loop configurations. Close-loop simulations involve the application of a pilot response model to select and execute DAA maneuvers.

This paper is organized as follows. Section II presents additional operational assumptions for this simulation. Section III describes the simulation approach and various components in the simulation architecture. Section IV shows results and discuss trends. Conclusion is made in Section V.

II. Background on Detect-and-Avoid

A DAA system consists of surveillance components, datalink capabilities, an alerting and guidance algorithm, and a display to the UAS pilot. UAS operations considered in the Phase 1 MOPS are those 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 and involve a pilot in the loop of decision making. UAS pilots are expected to contact air traffic control to negotiate a DAA maneuver if time permits.

The DAA system issues guidance maneuvers to help the UAS maintain DWC with other aircraft. The DWC is expected to be reasonably larger than the NMAC, a safety hazard the FAA defines as a separation less than 500 ft horizontally and less than 100 ft vertically [3]. This study focuses on the non-cooperative DWC, which is for encounters between a UAS and a non-cooperative aircraft, i.e., an aircraft without a functioning transponder. The non-cooperative DWC is a cylinder that has a radius of 2,200 ft and a height of 900 ft, 450 ft above the UAS and 450 ft below. For more information about the selection of this DWC, see [4].

The Phase 1 MOPS defines three types of alerts in increasing levels of severity: preventive, corrective, and warning. The first time an alert is issued by DAA is typically 1 to 2 minutes before the predicted time of closest point of approach (CPA). The lowest level, preventive, is primarily used to alert the pilot not to maneuver vertically when the aircraft are separated vertically by 450 to 700 feet. This alert should not be triggered by non-cooperative aircraft 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 air traffic control (ATC). The highest level, warning, indicates that a LoDWC is imminent, an immediate avoidance maneuver is needed, and coordination with ATC before maneuvering is not a requirement, although ATC should be contacted about the deviation as soon as possible. The DAA system should present maneuver guidance to UAS pilots as DWC-based conflict-ensuing aircraft heading ranges or altitude ranges to avoid. In case a LoDWC is unavoidable, the DAA system presents regain-DWC guidance, a range of heading or altitude that can be executed to increase separation at CPA and regain DWC effectively.

While the required surveillance volume in the Phase 1 MOPS of the radar has been derived from adequate pilot response times, and the DWC, sensor accuracies were derived from rudimentary engineering analysis. Assessment of the sensor accuracy requirements conducted at the end of the Phase 1 MOPS development [5] did not explore sensitivity of the DAA performance metrics to the magnitude of sensor uncertainty or pilots' selection. All but the simplest sensor uncertainty mitigation schemes were attempted. Another systematic study investigated the effect of a new scheme on the DAA performance and showed benefit to the safety metrics [6]. However, the encounters analyzed there were limited to a few hundreds and were not enough to provide statistical trends. This gap in research motivated the study in this paper.

III. Approach

Closed-loop simulations refer to the utilization of a pilot response model to drive the maneuver of the UA upon maneuver guidance of an alerting and guidance algorithm. Figure 1 depicts the simulation architecture diagram. Each component in the diagram will be described in the following sections, which discuss the metrics, the encounter set, the UA navigation errors, the sensor and tracker model, the alerting and guidance algorithm, the pilot response model, and the UA flight model, respectively. The solid lines represent data flow for both open-loop and closed loop simulations. The dashed lines represent data flow only for closed-loop simulations.

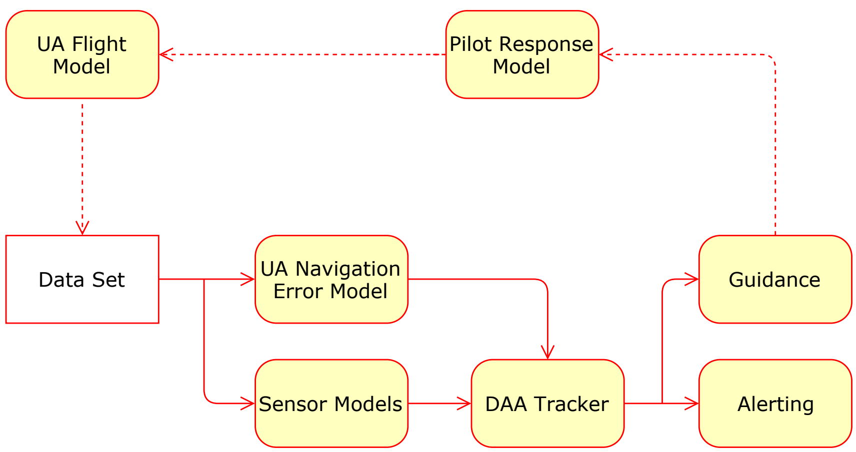

Fig. 1 Simulation architecture

A. Metrics

The safety and operational suitability metrics evaluate whether a DAA system provides adequate and effective alerts and guidance. These metrics and their formulation are described below.

1) LoDWC Ratio (safety):

$$\frac{P\,(\text{LoDWC} \mid \text{encounter, with mitigation})}{P\,(\text{LoDWC} \mid \text{encounter, without mitigation})} \tag{1}$$

The denominator of Eq. 1 stands for the probability of a 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 maneuver guidance to mitigate the conflict. If the LoDWC risk ratio is less than one, then the DAA system reduces the risk of LoDWC. For example, a LoDWC ratio of 0.1 indicates a 90% reduction in LoDWC rates. Smaller values are desirable. To compute the LoDWC ratio, a set of representative encounters are evaluated with and without engaging a DAA system in mitigating conflicts.

2) NMAC Risk Ratio (safety):

$$\frac{P\,(\text{NMAC} \mid \text{encounter, with mitigation})}{P\,(\text{NMAC} \mid \text{encounter, without mitigation})} \tag{2}$$

The denominator of Eq. 2 stands for the probability of an NMAC during an encounter if the UAS pilot does nothing to mitigate the conflict (unmitigated NMAC). The numerator stands for the probability of an NMAC during an encounter if the UAS pilot follows the DAA system's guidance to mitigate the conflict. If the ratio is less than one, then the DAA system reduces the risk of NMAC.

3) Alert Ratio (operational suitability):

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

This metric computes the number of encounters that trigger alerts per encounter that progresses to an unmitigated LoDWC. Ideally, only encounters that progress to an unmitigated LoDWC should trigger alerts. In this ideal case, the alert ratio is 1. Due to sensor uncertainties and aircraft maneuvers, alerts may also trigger for those encounters that do not progress to an unmitigated LoDWC. This tends to increase this ratio. On the other hand, limited surveillance volume tends to decrease this ratio.

4) Number of Maneuvers per LoDWC (operational suitability):

$$\frac{\text{Total \# of DAA Maneuvers}}{\text{Total \# of LoDWCs}} \tag{4}$$

This metric computes the average number of DAA maneuvers per unmitigated LoDWC. Lower values are desirable, since fewer maneuvers correspond to lower pilot workload. Note encounters that do not lead to unmitigated LoDWC also contribute to this metric if they trigger alerts that eventually lead to DAA maneuvers. Note that if on-and-off alerts are likely to lead to more DAA maneuvers. Unstable DAA guidance is also likely to lead to more DAA maneuvers.

B. Encounters

The safety and operational suitability metrics are computed from simulation of more than 72,000 encounters. A suitable encounter set should provide a predicted statistical representation of the conflicts a UAS will come across during its mission. Since the encounters considered are between a UA and non-cooperative aircraft, no coordination of conflict resolution is expected to occur. The following paragraphs describe how the encounters are prepared.

An entire day's worth of projected UAS flights in the near future are considered for this study. These flights consist of 19 different types of missions, including aerial imaging and mapping, law enforcement, and air quality monitoring. The demand and mission profiles were generated based on subject matter experts' opinions and socio-economical analysis [7]. These missions cover the entire continental US and amount to a total of 20,000 hours of flight time. Details of the missions are described in a previous publication [8].

For the intruder traffic, nation-wide visual flight rules (VFR) flight paths recorded in 2012 were extracted and processed from the historical Air Force 84th Radar Evaluation Squadron (RADES) radar data. Due to the limited number of non-cooperative trajectories available, 1200-code cooperative VFR aircraft (also extracted from the RADES data) are used as a surrogate for non-cooperative aircraft for this study. This is a reasonable approach since the flight characteristics of conventional non-cooperative aircraft are similar to those using cooperative VFR aircraft in terms of airspeed, acceleration, and turn rate [9].

Encounters are identified when UAS trajectories are overlaid with the VFR traffic. A software suite was developed to detect and produce encounters from these overlaid trajectories [10]. Filters were applied to the ownship (the UA) and intruder speeds and altitudes during the generation of encounters to ensure the dynamics of the sampled trajectories is within the bounds for the UAs and the intruders. The UA must have a speed between 40 and 110 knots true airspeed (KTAS) for the encounter to be selected. The upper bound of 110 KTAS was selected so as to focus on low-altitude UAS missions that usually have lower mission speeds. This speed range fits the assumption of UAS operations with low size, weight, and power (SWaP) sensors. The requirements of low SWaP sensors are a key objective of the Phase 2 work at RTCA special committee 228 (SC-228). The intruder speeds range from 0 to 170 KTAS, the 95 percentile speed for non-cooperative intruders [11]. Only encounters occurring at altitudes between 500 ft above ground level (AGL) and 10,999 ft mean sea level (MSL) in airspace classes E and G are selected. Although non-cooperative aircraft will be present only below 10,000 ft MSL due to the ADS-B-mandate in the year 2020, altitudes up to 10,999 ft MSL were included to represent a few UAS missions that are flown slightly above 10,000 ft MSL. Figure 2 shows the speed and altitude distributions of UAS and intruder by their values at the closest point of approach (CPA).

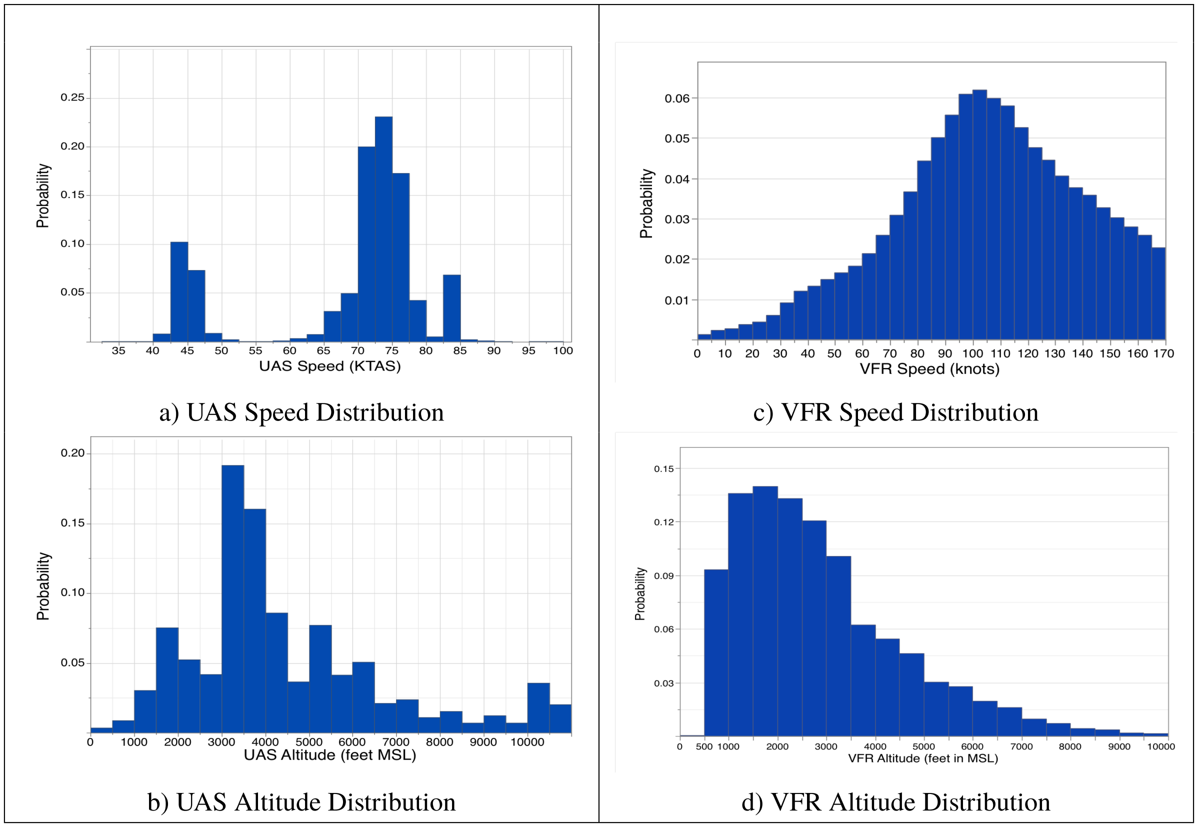

Fig. 2 Speed and altitude distributions of UAS and VFR traffic.

C. 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 track is perturbed by small magnitudes of sensor errors before it is sent to the DAA algorithm. The intruder's truth states are processed by the sensor models that will be 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 applies a vertically cylindrical radar field of view (FOV). The radius of the cylinder varies from 8 NM to 4, 3, and 2 NM. Analysis with this type of FOV sheds light on the sensitivity of the DAA performance metrics to a finite surveillance range, a critical question for UAS operations with low SWaP sensors.

Table 1 shows the key parameters in the radar model for measurement accuracies. The representative values, denoted as SN, are the values achieved by an airborne radar during a previous flight test. The Phase 1 MOPS values, denoted as LSN, are the required accuracy by the Phase 1 radar MOPS (DO-366).

Table 1 Radar measurement accuracy parameters in terms of bias and error.

Configuration	Range (m)	Azimuth (°)	Elevation (°)	Velocity (m/s)
(Representative) Sensor Noise (SN)	5.5 ± 10	0 ± 0.4	0 ± 0.4	0 ± 2
Large Sensor Noise (LSN)	15 ± 21	0.5 ± 1.0	0.5 ± 1.0	0 ± 2

The Phase 1 MOPS requires a tracker that fuses and correlates measurements from multiple sensors for a single intruder into tracks. The UA's state is also inputted to the tracker to produce the intruder's state in absolute coordinates. A fusion tracker developed by Honeywell [12] is used for this work. This tracker output the intruder's track position and velocity as well as estimated accuracies of the track.

D. Alerting and Guidance Algorithm

The Detect and AvoID Alerting Logic for Unmanned Systems (DAIDALUS) [13], a reference algorithm developed to validate the Phase 1 MOPS requirements, computes the alerts and guidance during the simulation of encounters. A sensor uncertainty mitigation (SUM) feature has been added to DAIDALUS recently [14]. The effect of SUM on the DAA performance metrics is investigated in this study.

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. In the absence of an alert, DAIDALUS computes peripheral guidance by projecting candidate vertical and horizontal DAA maneuvers into future times to determine which would result in conflicts. This information aids UAS pilots in their situation awareness. It is worth noting that, for this study, no wind was assumed for the computation of the guidance or the flight model.

DAIDALUS alerts guard against a buffered DWC. The buffer is meant to protect the UAS from sensor uncertainties and maneuvering intruders. This study investigates both static and dynamic buffers. For runs with a static buffer, the horizontal separation distance 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.

Runs with a dynamic buffer utilize SUM that computes the buffer from track accuracy data supplied by the tracker and a set of configurable scaling factors. Generally speaking, larger measurement errors and scaling factors increase the dynamic buffer and cause the algorithm to be more conservative, resulting in earlier alerts and wider conflict bands. Table 2 shows the scaling factors assigned for SUM in this study. These factors are selected from results of a companion study [15]. Note the horizontal velocity scaling factor decreases linearly from 2.0 to 0.4 between 0 and 3 NM.

Table 2 DAIDALUS SUM scaling factors

Name	Horizontal Position	Horizontal Velocities at 0 NM and 3 NM	Vertical Position	Vertical Velocity
value	2.0	2.0 and 0.4	1.0	1.0

In addition to the buffering scheme around the DWC, a wrapper of DAIDALUS ensures the processed alert sent to the pilot response model (see Section III.E) remains on for at least 4 consecutive seconds. This wrapper also ensures the processed alert comes on only after at least 2 of 4 consecutive raw alerts are on. These basic alert stability schemes are required by the DAA MOPS and hence applied to all run configurations.

E. Pilot Response Model

The following discussion in this and the next sections apply only to closed-loop simulations. In open-loop simulations, alerts and guidance are recorded as the encounter progresses, but no DAA maneuvers are executed. Therefore, the pilot response model does not apply.

Upon alerting, DAIDALUS provides maneuver guidance indicating a range of conflict-free headings and altitudes. The SC-228 standard pilot model created by MIT Lincoln Laboratory [16] selects and executes an appropriate maneuver (see Figure 3). Model parameters were derived from human-in-the-loop experiment results 3. The model has the capability of stochastic sampling of response times and maneuvers. For this study, the model is executed in deterministic mode, in which all response times and maneuvers are deterministic. 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 because vertical maneuvers against non-cooperative intruders are much less robust in most situations due to uncertainties in non-cooperative sensors' vertical measurements. 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 [16].

After the first alert comes up, the model exerts 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 the pilot spends to communicate the intended maneuver with ATC and receive approval. The model then follows with 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 UAS. 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 3. For example, if the pilot model selects a maneuver during a warning alert state, then the situation will be reevaluated after 6 seconds (the decision update period), and a different subsequent maneuver can be issued at that time, if needed.

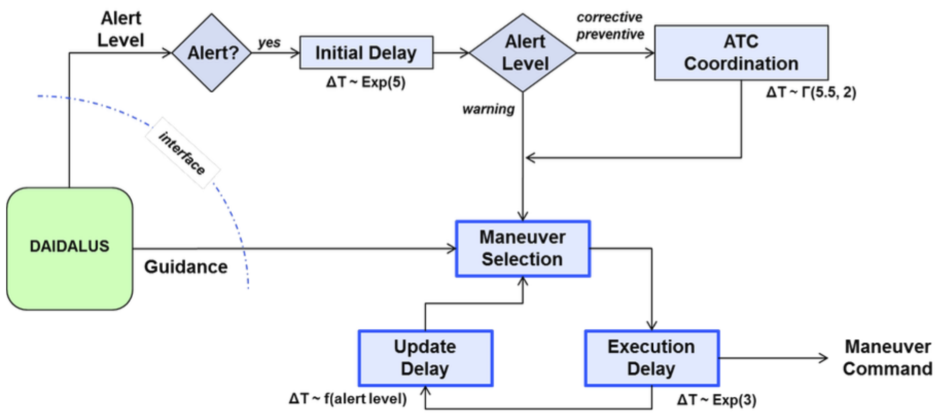

Fig. 3 The SC-228 pilot response model

Table 3 Pilot response model decision update times

Alert Condition	Decision Update Period (s)
No Alert	12
Preventive Alert	9
Corrective Alert	6
Warning Alert	6
Regain-DWC Guidance	0

Human-in-the-loop simulations and flight tests have shown that UAS pilots' selection of a DAA heading maneuver tends to have a buffer away from the edge of the conflict heading range. For example, if the DAA guidance indicates that a 30-degree or more right turn can resolve the conflict, UAS pilots are likely to turn the UA by 35 degrees or more. This extra buffer, which appears to be unnecessary at the time the guidance is presented to the pilot, may be beneficial in guarding against intruder maneuvers or sensor uncertainties. This study attempts both zero and 5° buffers to identify potential benefits of this pilot-initiated buffer.

F. 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. The intruder's trajectory remains unchanged. Once the target heading is achieved by the flight model, the UA trajectory remains at that heading. If the ownship remains conflict-free for 15 consecutive seconds after the last maneuver and is at least 3 NM away from the intruder, simulation of this encounter terminates.

IV. Results

A. Experiment Matrix

Table 4 shows the experiment matrix for the closed-loop simulation runs. The matrix consists of two parts: the first part (top) shows runs with an 8 NM horizontal surveillance range. The second part (bottom) shows runs with shorter horizontal surveillance ranges. In addition to these runs, a separate open-loop simulation, using a static buffer, as performed in order to provide the LoDWC and NMAC counts for the denominators of the metrics.

The first part has a total of 10 runs. The two no-sensor-noise (NSN) runs, one with a turn buffer and one without, represents the baseline configuration. A static buffer around the DWC is applied to these two runs. The SN and LSN runs investigate the impact of the magnitude of sensor noise on DAA performance metrics. For SN and LSN configurations,

Table 4 Mitigated simulation test matrix. Configurations included in the experiment matrix are marked with a circle.

	Surveillance Range = 8 NM					
Noise / Simulation	No Sensor Noise (NSN)		SN		LSN	
5° Turn Buffer	No	Yes	No	Yes	No	Yes
Static Buffer	x	x	x	x	x	x
Dyanmic Buffer			x	x	x	x
	Surveillance Range < 8 NM					
Dyanmic Buffer, 4 NM			x			
Dyanmic Buffer, 3 NM			x			
Dyanmic Buffer, 2 NM			x			

a total of 4 runs are simulated by turning on and off the following two configuration parameters:

1) the 5° pilot turn buffer from the edge of the heading conflict bands,
2) the dynamic buffer computed by DAIDALUS SUM.

The second part of the experiment matrix has three more runs with 4, 3, and 2 NM horizontal surveillance ranges. The sensor noise level is SN, and SUM is turned on for these runs. Results from these runs give insight to the sensitivity of the performance metrics to a limited surveillance range.

Section IV.B presents results for the first part of the experiment matrix. Section IV.C presents results for the second part of the experiment matrix.

B. Surveillance Range of 8 NM

Figure 4 shows the LoDWC ratio from various runs. The baseline run, shown on the left, as expected, achieves the lowest LoDWC ratio of 7.3%. The SN without SUM run (meaning a static buffer around the DWC) doubles the LoDWC ratio. The SN with SUM run is effective in reducing the LoDWC ratio to below 10%. The LSN run without SUM results in the highest LoDWC ratio of all. The LSN with SUM run effectively reduces the ratio to 11.2%. The 5° turn buffer appears to provide limited benefit to the LoDWC ratio.

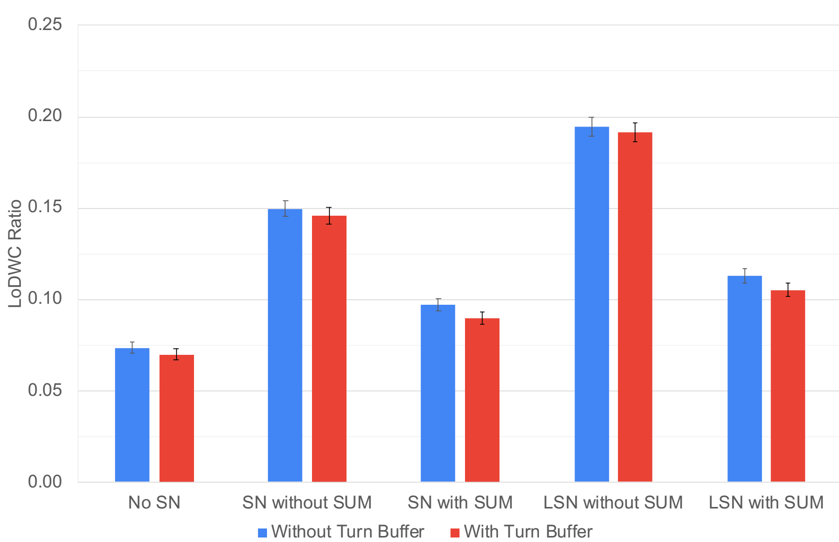

Fig. 4 LoDWC ratios

Figure 5 shows the NMAC risk ratio from various runs. Due to the large error estimates, no definitive trends can be ascertained except that the No SN runs result in lower NMAC risk ratios.

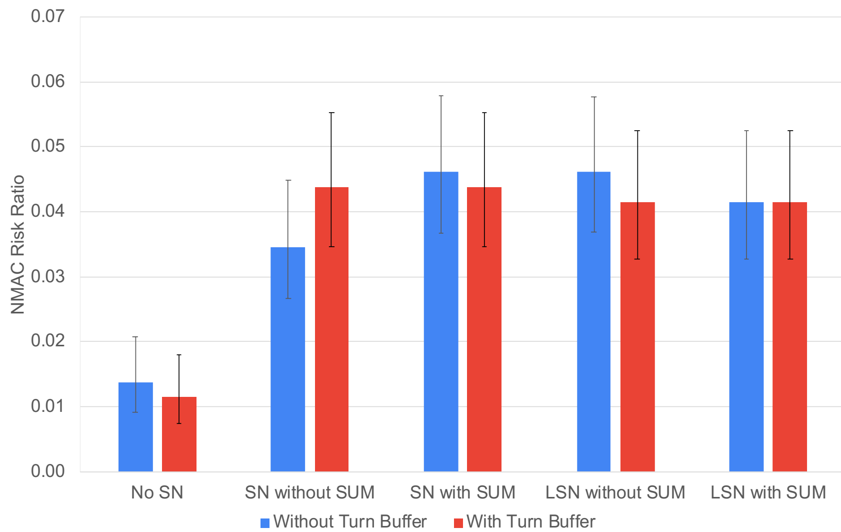

Fig. 5 NMAC risk ratios

Figure 6 shows the alert ratio for the five combinations of sensor noise and SUM configurations. Note that the turn buffer does not change this metric. Therefore, results from runs with a turn buffer are not shown. Compared to the baseline run on the leftmost, SN increases the alert ratio. SUM (middle bar) also increases the alert ratio by triggering alerts in more encounters. This shows the trade space between the safety metric such as the LoDWC ratio and an operational suitability metric such as the alert ratio. While the dynamic buffer improves the safety metric, it appears to create more nuisance alerts. This trade space is likely to be acceptable if such encounters occur with a low frequency. Interestingly, increase the sensor noise to LSN only increases the alert ratio slightly (<5%.)

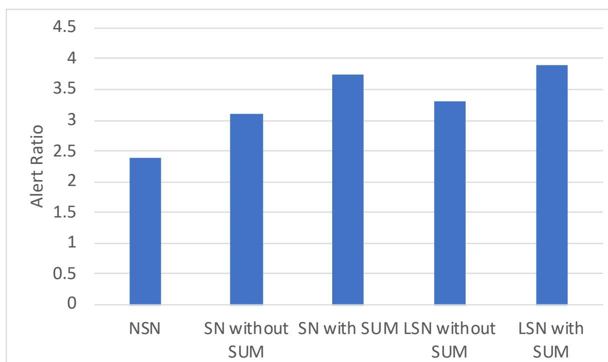

Fig. 6 Alert ratio

Figure 7 shows the number of maneuvers per LoDWC. Results without a turn buffer, shown in blue, are discussed first. The baseline run, NSN, indicates more than 4 maneuvers per LoDWC. SN increases this metric only marginally. SUM increases this metric from the sensor noise run (middle bar) by more than 20%. LSN yield similar results to the SN runs. With a turn buffer, the baseline run is much improved by 25%. With SUM on, the benefit of the turn buffer appears to diminish, reducing to 10% for the SN and LSN runs.

C. Surveillance Range Less than 8 NM

For the runs with limited surveillance range, only the safety metrics are presented. The operational suitability metrics are similar across runs and thus omitted.

Figure 8a shows that the LoDWC ratio essentially remains the same as the radar's surveillance range reduces from 8 NM to 3 NM. Reducing the surveillance range to 2 NM increases the LoDWC ratio from 10% to 12%. This is consistent with results from a prior study [4] that performed closed-loop simulations without sensor noise. Results from that study showed lower LoDWC ratios that remain the same (8%) when the surveillance range is 3 NM and above and increases when the range reduces to 2 NM (10%.)

Figure 8b shows a similar trend for the NMAC risk ratio, which remains the same at and above 3 NM. The NMAC

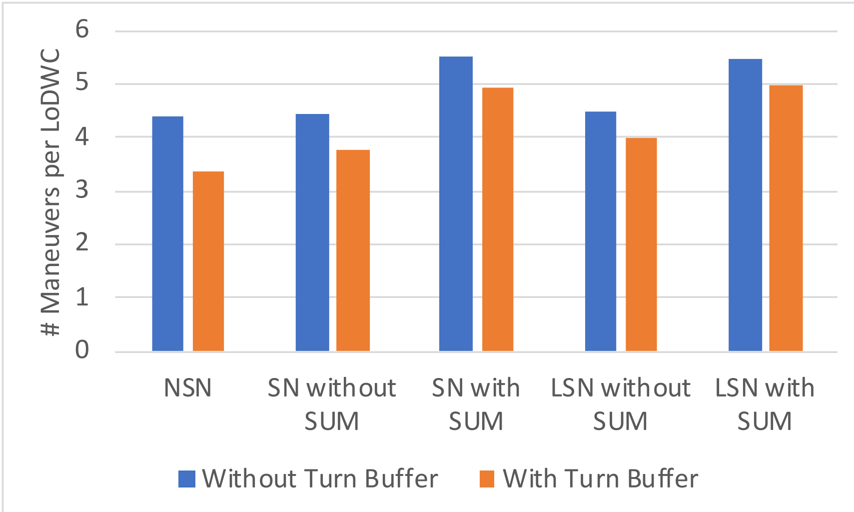

Fig. 7 Maneuver count per LoDWC

risk ratio appears to be slightly higher at 2 NM. However, the large errors make these values statistically indistinguishable. Similar results were observed in the prior study [4], although the NMAC risk ratio was smaller (2.0%) mainly due to the lack of sensor noise.

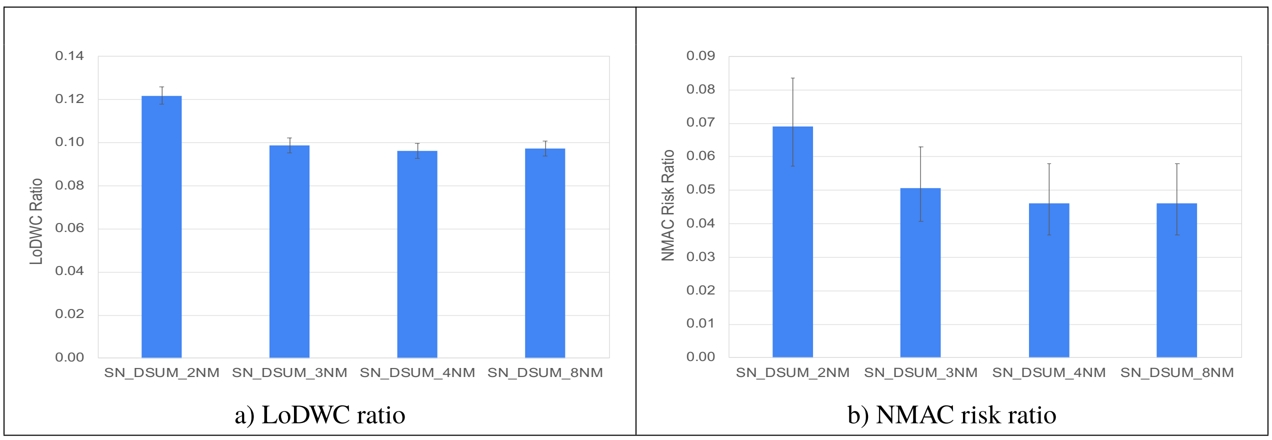

Fig. 8 LoDWC ratio and NMAC risk ratio varying with surveillance range

V. Conclusion

This study analyzes the impact of sensor noise on the DAA system's performance using a few key safety and operational suitability metrics. More than 72,000 encounters, representative of UAS against non-cooperative manned aircraft, were analyzed using a reference DAA alerting and guidance algorithm for the DAA MOPS. Results show that, while sensor noise degrades safety metrics, suitably chosen buffers around the DWC, especially those computed by DAIDALUS SUM, can mitigate most of its impact. Larger buffers around the DWC tend to worsen operational suitability metrics such as the number of maneuvers per loss of DAA well clear. A 5° buffer away from the heading range leading to a conflict selected for the pilot response model appears to reduce the pilot maneuver count.

Results from this work will inform RTCA SC-228 directly in terms of validating sensor uncertainty requirements as well as selecting default parameters for DAIDALUS SUM. Trends observed from results of various configurations indicate trade space between safety and operational suitability, and can help manufacturers of DAA systems balance design and runtime parameters. The results may also provide supporting data to the FAA's system safety assessment.

The trade space demonstrated by this study is likely to behave differently with higher UA speeds or a different type of sensor. For example, UAs flying with higher speeds need to start a maneuver away at a greater distance but with a lower turn rate. Also, the electro-optical/infrared sensor has very different error characteristics than an air-to-air radar. Additional work to expand this study to these areas is being planned.

Acknowledgments

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