Unmanned Aircraft Systems Detect and Avoid System: End-to-End Verification and Validation Simulation Study of Minimum Operations Performance Standards for Integrating Unmanned Aircraft into the National Airspace System

Rania W. Ghatas[1]
NASA Langley Research Center, Hampton, Virginia 23681

Devin P. Jack[2]
Adaptive Aerospace Group, Hampton, Virginia 23513

Dimitrios Tsakpinis[3] and James L. Sturdy[4]
SAIC, Inc., Hampton, Virginia 23681

Michael J. Vincent[5]
NASA Langley Research Center, Hampton, Virginia 23681

Keith D. Hoffler[6]
Adaptive Aerospace Group, Hampton, Virginia 23513

Robert R. Myer[7]
SAIC, Inc., Hampton, Virginia 23681

and

Anna M. DeHaven[8]
Craig Technologies, Inc., Hampton, Virginia 23681

As Unmanned Aircraft Systems (UAS) make their way to mainstream aviation operations within the National Airspace System (NAS), research efforts are underway to develop a safe and effective environment for their integration into the NAS. Detect and Avoid (DAA) systems are required to account for the lack of "eyes in the sky" due to having no human on-board the aircraft. The technique, results, and lessons learned from a detailed End-to-End Verification and Validation (E2-V2) simulation study of a DAA system representative of RTCA SC-228's proposed Phase I DAA Minimum Operational Performance Standards (MOPS), based on specific test vectors and encounter cases, will be presented in this paper.

[1] Human/Machine Systems Research Engineer, Crew Systems and Aviation Operations Branch, NASA Langley Research Center, Mail Stop 152, Hampton, Virginia 23681, AIAA Member

[2] Research and Development Engineer, Adaptive Aerospace Group, Inc., 100 Exploration Way, Suite 330, Hampton, Virginia 23666, AIAA Member

[3] Modeling/Simulation Engineer Principal, SAIC, Inc., NASA Langley Research Center Mail Stop 152, Hampton, Virginia 23681, Non-Member

[4] Modeling/Simulation Engineer Chief, SAIC, Inc., NASA Langley Research Center Mail Stop 152, Hampton, Virginia 23681, Non-Member

[5] Research Engineer, Crew Systems and Aviation Operations Branch, NASA Langley Research Center, Mail Stop 152, Hampton, Virginia 23681, Non-Member

[6] President, Adaptive Aerospace Group, Inc., 100 Exploration Way, Suite 330, Hampton, Virginia 23666, AIAA Associate Fellow

[7] Senior Software Engineer, SAIC, Inc., NASA Langley Research Center Mail Stop 152, Hampton, Virginia 23681, Non-Member

[8] Senior Software Engineer, Craig Technologies, Inc., NASA Langley Research Center Mail Stop 152, Hampton, Virginia 23681, Non-Member

I. Introduction

AS Unmanned Aircraft Systems (UAS) make their way to mainstream aviation operations within the National Airspace System (NAS), research efforts are underway to develop a safe and effective environment for their integration into the NAS. Detect and Avoid (DAA) systems are required to account for the lack of "eyes in the sky" due to having no human on-board the aircraft. The current NAS relies on pilot's vigilance and judgement to remain Well Clear of other aircraft (CFR 14 91.113). RTCA SC-228 has defined DAA Well Clear (DWC) to provide a quantified Well Clear volume to allow systems to be designed and measured against. Extensive research efforts have been conducted to understand and quantify system requirements needed to support a UAS pilot's need to remain well clear of other aircraft. The efforts have included developing and testing sensor, algorithm, alerting, and display requirements. More recently, sensor uncertainty and uncertainty mitigation strategies have been evaluated.

This paper discusses results and lessons learned from an end-to-end verification and validation (E2-V2) simulation study of a DAA system representative of RTCA SC-228's proposed Phase I DAA Minimum Operational Performance Standards (MOPS). NASA Langley Research Center (LaRC) was called upon to perform the end-to-end study, and developed a system that evaluates a specific set of encounters, in a variety of geometries, with end-to-end DAA functionality including the use of sensor and tracker models, a sensor uncertainty mitigation model, DAA algorithmic guidance in both vertical and horizontal maneuvering, and a pilot model which attempts to maneuver the ownship aircraft well clear from intruder aircraft based on that guidance. LaRC had a functioning batch simulation and added a sensor/tracker model from the FAA Tech Center, an in-house developed sensor uncertainty mitigation strategy, and an in-house developed pilot model similar to one from Massachusetts Institute of Technology Lincoln Laboratory (MIT/LL). The resulting simulation provides the following key parameters, and many more, to evaluate the effectiveness of the MOPS DAA system: severity of loss of well clear (SLoWC), closest point of approach (CPA), alert scoring, and alert jitter. The technique, SLoWC results, and lessons learned from a detailed examination of DAA system performance over specific test vectors and encounter cases during the simulation experiment will be presented in the paper.

II. Method

An end-to-end fast time simulation tool was developed that encompasses simplified unmanned aircraft (UA) maneuver dynamics and all of the components of a DAA system. The system provides for one UA and a single intruder to fly a pre-determined encounter trajectory while having the UA either continue the trajectory and measure DAA system alerting or follow DAA system maneuver guidance per a simple deterministic pilot model. Figure 1 shows the simulation architecture used in E2-V2, which portrays the data flow of the simulation used in the study including a model of aircraft dynamics, a representative DAA algorithm, a sensor/tracker model that encompasses uncertainty modeling, and a deterministic pilot model that was used to close the loop on aircraft encounters. Aircraft dynamics are modeled using the 2-degrees-of-freedom Prototyping Aircraft Interactions Research Simulation (2PAIRS) tool. DAIDALUS (Detect-and-AvoID Alerting Logic for Unmanned Systems) is the representative DAA algorithm that computes maneuver guidance based on the ownship and intruder state information from the sensor/tracker models or the sensor uncertainty mitigation (SUM), which is discussed later in this section.
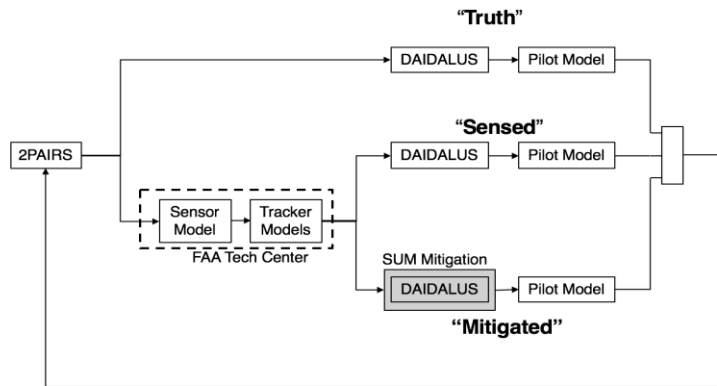

Figure 1. E2-V2 Simulation Architecture

The deterministic pilot model was developed and provided by MIT/LL; NASA LaRC developed and implemented a functionally representative version for this simulation. The model was explicitly constructed to handle single intruder cases only and avoidance maneuvers in the lateral dimension. The Java implementation of the MIT/LL Matlab model deviates slightly from the source to be compatible with the state-machine that governs timing in the processing functions.

The sensor and tracker models were developed and delivered by the Federal Aviation Administration (FAA) William J. Hughes Technical Center in support of RTCA SC-228. The sensors used in this study were each tested individually and included: Automatic Dependent Surveillance – Broadcast (ADS-B) In, Active Surveillance Transponder (AST), and an air-to-air radar. The simulation architecture allows for the capability of flying in three modes, including:

- Truth: Uses perfect state information,
- Sensed: Uses sensor degraded state information from the sensor, and
- Mitigated: Uses sensor degraded state information with a SUM approach

The SUM approach, used in the Mitigated mode, creates phantom aircraft position and velocity based on estimated sensor uncertainty (Figure 2). Scaling factors were optimized to reduce frequency and severity of losses of well clear and to increase probability of accurate alerts and guidance. Jack, et al. (2017), a closely related paper, presents the mitigation approach, results, and lessons learned from the SUM simulation study.

Multiple encounters from multiple sources were designed to show, through detailed examination of specific test vector and encounter cases, whether a MOPS-representative DAA system behaves acceptably. Each encounter was run several times through all three modes (Truth, Sensed, and Mitigated) for replication purposes to verify and validate the output data.

The data was analyzed to determine the overall acceptability of a MOPS-representative system via the end-to-end simulation study.
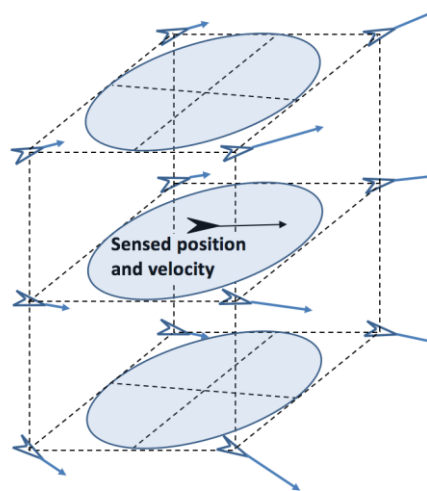

Figure 2. Sensor Uncertainty Mitigation Approach

III. Scenarios

Multiple encounters were utilized to show whether a MOPS-representative DAA system behaved acceptability. Encounters were run in a closed loop simulation environment to mimic maneuvering behaviors of a human pilot with human response delay times. A fixed pilot delay time, relative to alert issuance times, was used to make sensor uncertainty the only variable between runs of the same sensor/encounter set. Open loop encounters were also run, which provided the ability to characterize the original encounter geometry, with no pilot response, along with timing and alert jitter issues. Open loop encounters were compared to the closed loop data.

Encounters originated from two main categories: National Airspace System (NAS)-Derived Encounter Sets and MOPS Requirements-Derived Test Vectors. This paper, however, focuses on the results of the NAS-Derived Encounter Sets.

The National Airspace System (NAS)-derived encounter sets were developed and provided by MIT/LL. A total of 180 encounters were provided for use in E2-V2. The 180 encounters are a subset of two fundamental types of encounters: Correlated (120 encounters) and Uncorrelated (60 encounters).

In correlated encounters, both aircraft (ownship and intruder) are equipped with a transponder and are, therefore, cooperative. Additionally, at least one of the two aircraft is in contact with ATC and will likely receive some notification about the impending traffic conflict and take action prior to the involvement of the DAA system. These scenarios are termed "correlated" because "the trajectories of each aircraft may involve maneuvers that are correlated to some degree due to this prior intervention" (Kochenderfer, Espindle, Kuchar, Griffith, October 2008).

In uncorrelated encounters, at least one aircraft is not using a transponder and is, therefore, non-cooperative, or it involves two aircraft flying under Visual Flight Rules (VFR). Under these circumstances, it is unlikely that ATC would become involved prior to the close encounter. As a result, the two aircraft must rely solely on either visual acquisition or a DAA system to ensure safe separation. The assumption for this type of encounter is that "the two aircraft blunder into close proximity" (Kochenderfer, Espindle, Kuchar, Griffith, November 2008).

An analysis of both correlated and uncorrelated encounters was necessary for a complete evaluation of a MOPS-representative DAA system.

Table 1 shows the closed and open loop encounter set used for each category; the final numbers are based on Truth tracks. Closed and open loop runs had identical encounter sets in each category for analysis comparison purposes. The column titled "Total" shows the initial number of test vectors developed. The remaining three columns show the number of encounters according to category description and sensor type after the initial encounters were filtered.

Table 1. E2-V2 Test Vectors Set

Category Description	Total	E2-V2 Test Vectors (based on Truth Tracks)		
		Radar	AST	ADS-B
NAS-Derived: Correlated	120	72	100	119
NAS-Derived: Uncorrelated	60	44	53	56
Total	180	116	153	175

IV. Metrics

A. Severity of Loss of Well Clear (SLoWC)

Several metrics were used to analyze the large data set, one of which is the Severity of Loss of Well Clear (SLoWC). SLoWC is a metric used "to assess the severity of Loss of DAA Well Clear on a per-encounter basis by capturing the most serious instance of Loss of Well Clear throughout an encounter" (RTCA, Inc., In Press). It is based on the severity of violation into all three of the Well Clear components, which include: Horizontal Proximity, Horizontal Miss Distance Projection, and Vertical Separation. The resulting SLoWC ranges from 0% (DAA Well Clear maintained throughout the encounter) to 100% (mid-air collision).

B. Alert Scoring

Another metric used to analyze the large data set was Alert Scoring. For the ownship to remain well clear from an intruder aircraft, pilot cues, such as alerts, are needed to maintain safe separation. According to the Phase I DAA MOPS, "an alert is required for any encounter where the intruder aircraft violates the Hazard Zone at any given point throughout the encounter."

Figure 3 shows a notional depiction of what constitutes a Hazard Zone (HAZ), in addition to a May-Alert Zone (MAZ), and Non-Hazard Zone (HAZNot) and Table 8 shows the parameters for calculating the size of the HAZ and HAZNot zones. These hazard and non-hazard zones are used to define the trade space for when alerts must and must not be generated, but are not meant to imply a specific alerting algorithm. The hazard/non-hazard zone alert requirement structure is used to simplify compliance determinations without extensive analyses of alerting system performance. Figure 4 quantifies an alerting system's performance. The Hazard Zone is based on the DAA Well Clear volume (Table 2), and an alert is required if the intruder enters this region. The May-Alert Zone defines a volume around the ownship aircraft in which an alert may be signaled if an intruder aircraft is within that volume but is not required. Lastly, an intruder aircraft within the Non-Hazard Zone constitutes as remaining Well Clear; no alerts should be signaled for this zone (see RTCA, Inc., In Press for a full explanation of alerting requirements).

Using the HAZ and HAZNot definitions, the flow diagram in Figure 4 shows the methodology of scoring the alerting performance throughout an encounter. Upon completion of the simulation run, each alert was analyzed by comparing the time of HAZ entry and HAZNot departure are compared to the timing of each alert type, which is a function of sensor-degraded data. In Figure 4, the green region indicates where truth data is used, while the purple represents degraded alert timing information.
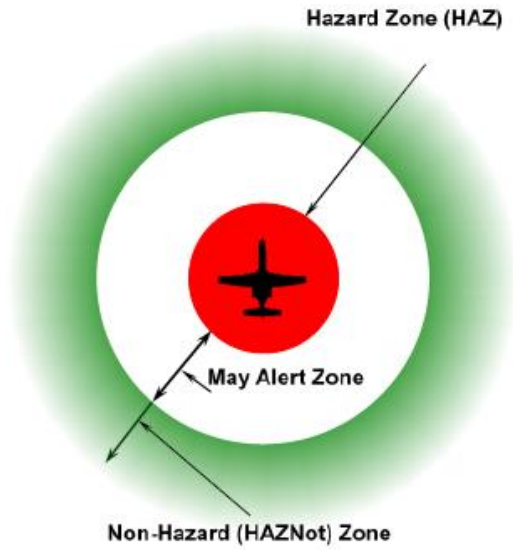
Figure 3. Notional Depiction of Hazard, May Alert, and Non-Hazard Zones

Table 2. Parameters for Calculating the Size of Hazard and Non-Hazard Zones

			Preventive Alert	Corrective Alert	Warning Alert
Hazard Zone (HAZ)	Tau* mod		35 seconds	35 seconds	35 seconds
	DMOD and HMD*		0.66 nmi	0.66 nmi	0.66 nmi
	h* (fixed)		700 feet	450 feet	450 feet
Non-Hazard Zone (HAZNot)	Tau* mod		110 seconds	110 seconds	90 seconds
	DMOD and HMD*		1.5 nmi	1.5 nmi	1.2 nmi
	VMOD		800 feet	450 feet	450 feet
Minimum Average Time of Alert	Seconds before HAZ Violation		55 seconds	55 seconds	25 seconds
Late Threshold (THR$_{Late}$)	Seconds before HAZ Violation		20 seconds	20 seconds	15 seconds
Early Threshold (THR$_{Early}$)	Seconds before HAZ Violation		75 seconds	75 seconds	75 seconds
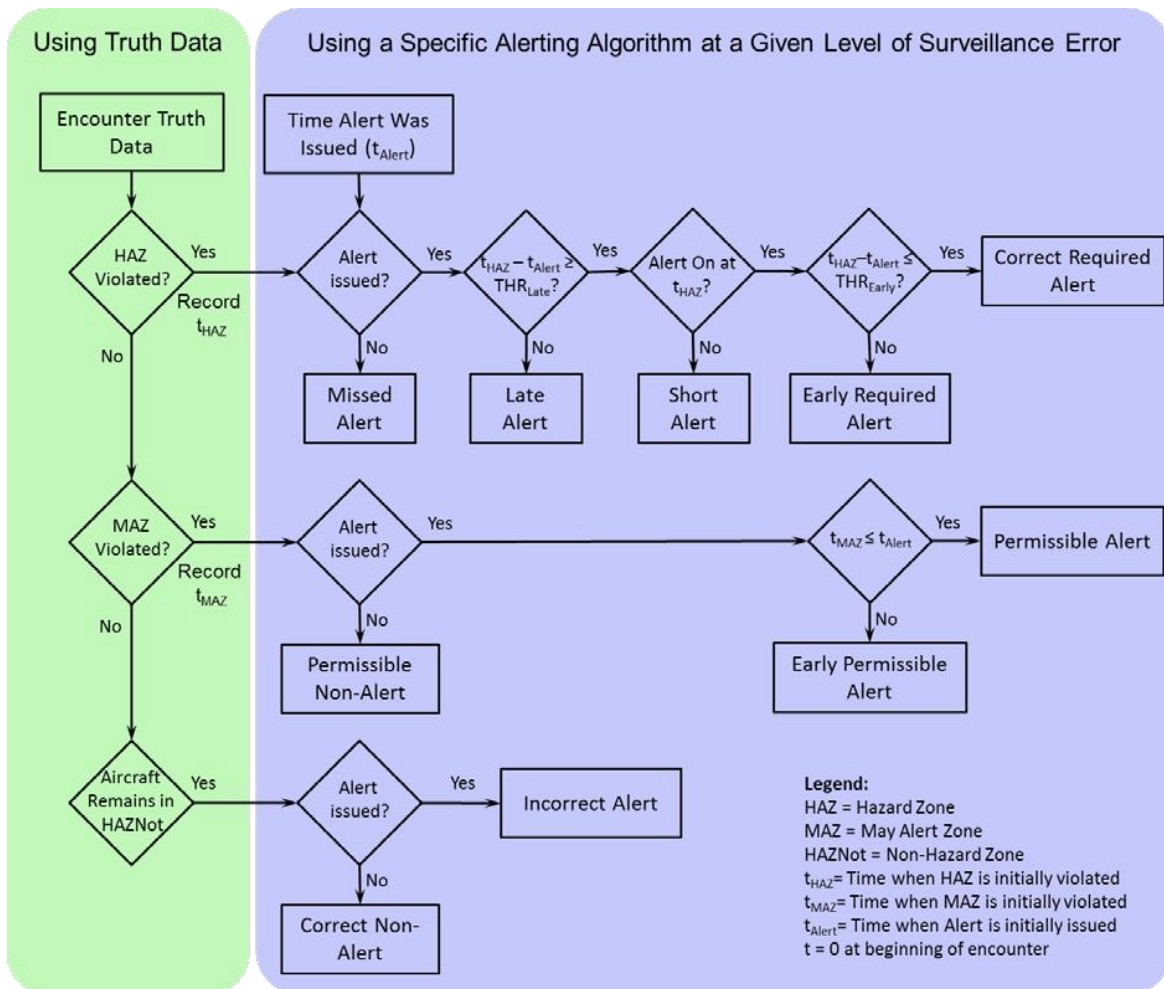
Figure 4. Alert Scoring Process

Encounter tracks with a HAZ violation are required to have an alert signaled. Together, the following performance metrics quantify an alerting system's performance for required alerts:

- Missed Alert
- Late Alert
- Short Alert
- Early Required Alert
- Correct Required Alert

Encounter tracks within the MAZ are allowed to alert but are not required. The following performance metrics quantify an alerting system's performance for MAZ alerts:

- Permissible Non-Alert
- Early Permissible Alert
- Permissible Alert

For encounter tracks within the HAZNot, no alerts should be signaled. The following performance metrics quantify an alerting system's performance for HAZNot alerts:

- Correct Non-Alert
- Incorrect Alert

C. Alert Scoring Types
Encounter tracks were scored against ten alert types (RTCA, Inc., In Press), which included:
- Correct Required Alert: Occurs for encounters "where an intruder aircraft enters into the Hazard Zone, and the alerting system issues a timely alert" (i.e., occurs when an alert is neither late, short, nor early).

- Correct Non-Alert: Occurs for encounters "where an intruder aircraft never leaves the Non-Hazard Zone, and the system does not issue an alert." This type of alert is desirable.

- Permissible Alert: An "alert issued for an encounter where an aircraft enters into the May-Alert Zone but not the Hazard Zone, and is not early." This type of alert is neither desirable nor undesirable.

- Permissible Non-Alert: Occurs for encounters where "an alerting system does not issue an alert and the intruder aircraft entered into the May-Alert Zone but not the Hazard Zone." This type of alert is neither desirable nor undesirable.

- Early Required Alert: Occurs when "an intruder aircraft enters into the Hazard Zone, but the system issues an alert prior to the Early Threshold" as defined in Table 9. This type of alert is undesirable and is approximately the same as the boundary between the May-Alert Zone and the Non-Hazard Zone for non-accelerating cases.

- Early Permissible Alert: Occurs for encounters where "an intruder aircraft enters into the May-Alert Zone, but the system issues an alert while the aircraft still meets the criteria for the Non-Hazard Zone." The logic for this alert type is based on the boundary between the May Alert Zone and the Non-Hazard Zone.

- Short Alert: Occurs for encounters where "an alerting system is not in alert state at the time at which the intruder aircraft violates the Hazard Zone, but had previously issued an alert." This is an undesirable type of alert.

- Late Alert: Occurs when "an intruder aircraft enters the Hazard Zone, but the alerting system issues an alert less than the required time before Hazard Zone violation" as defined in Table 9. If an alert "is issued late and does not persist until the Hazard Zone is violated, (then) the alert is scored as a late alert, as lateness is considered to affect safety more drastically as compared to shortness."

- Incorrect Alert: An "alert issued on an encounter for which the intruder aircraft remains in the Non-Hazard Zone." For purposes related to analyzing this type of alert, incorrect alerts are not referred to as false or nuisance alerts. It should be noted that, as defined, an incorrect alert is essentially an early alert in that it alerts the operator to an impending hazard before it is permitted to.

- Missed Alert: Occurs when "an intruder aircraft enters the Hazard Zone, but the alerting system does not issue an alert." This type of alert is undesirable.

D. Alert Jitter
Surveillance sensors (onboard the aircraft or on the ground) have inherent errors, bias and noise, which will skew the reported position and velocity of all aircraft in the range of coverage. A DAA guidance system with sensors, tracker, algorithm, filtering mechanism and displays, must be able to show the representative stages of alerting symbology to the pilot. These alerts must be accurately depicted within a timely manner, with faithful representation of airplane motions, and without significant jerkiness or latency (i.e., display lag, slow update rate), which would adversely affect the pilot's ability to maneuver the aircraft. As a result, the final metric used for analysis was Alert Jitter, which refers to "the average number of increasing alerting transitions that occur within an encounter set, where an increasing alert transition is considered to be a transition between no alert to any other alert level (preventive, corrective, or warning), as well as from a lower alert level (i.e. preventive) to a more severe alert level (i.e. corrective)" (RTCA, Inc., In Press).

V. Results: NAS-Derived Correlated Encounter Set

A. Severity of Loss of Well Clear (SLoWC)

Figure 5 shows a histogram of SLoWC for closed loop simulation for NAS-derived correlated encounters equipped with radar. The histogram also shows the open loop Truth data in navy blue color. Open loop Truth data shows the results with no pilot response in order to characterize the original encounter geometry and is compared to the closed loop Truth data shown in light blue. Results for these encounters show that the closed loop truth guidance resulted in 85% of encounters having a SLoWC value of 0%. 38% of closed loop Sensed radar runs resulted in a SLoWC value of 10% or less. The Mitigated source guidance increased the number of encounters with 0% SLoWC by 20% when compared to sensed only guidance.
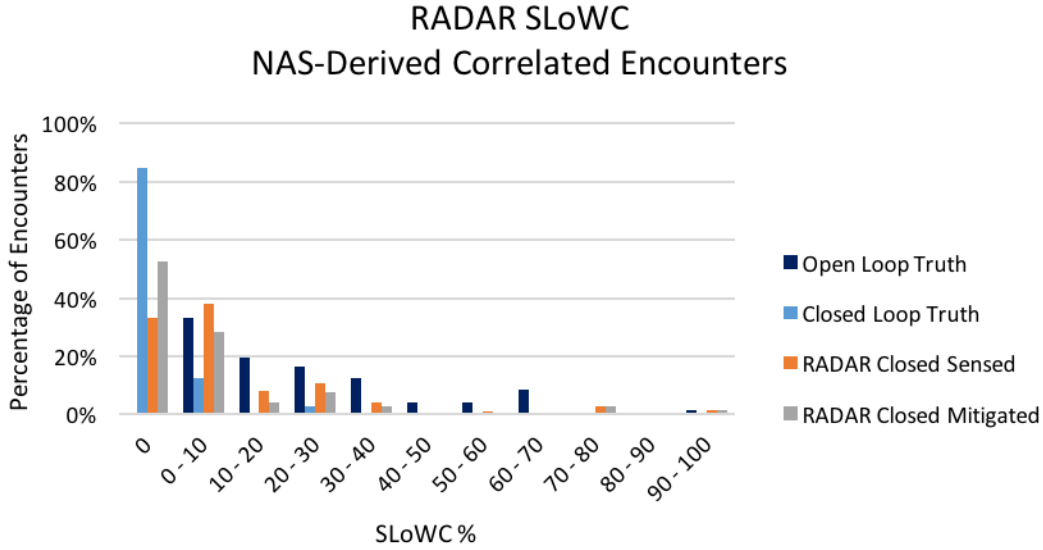
Figure 5. Radar SLoWC for NAS-Derived Correlated Encounters

Figure 6 shows a SLoWC histogram for AST guidance type. The SUM approach, enabled the DAA system to increase the number of runs with 0% SLoWC by approximately 26% more than Sensed guidance.

Figure 7 shows a SLoWC histogram for ADS-B guidance type. Findings show that the Mitigated source guidance resulted in 8% more runs with 0% SLoWC than truth guidance, and 13% more runs than sensed guidance.

American Institute of Aeronautics and Astronautics
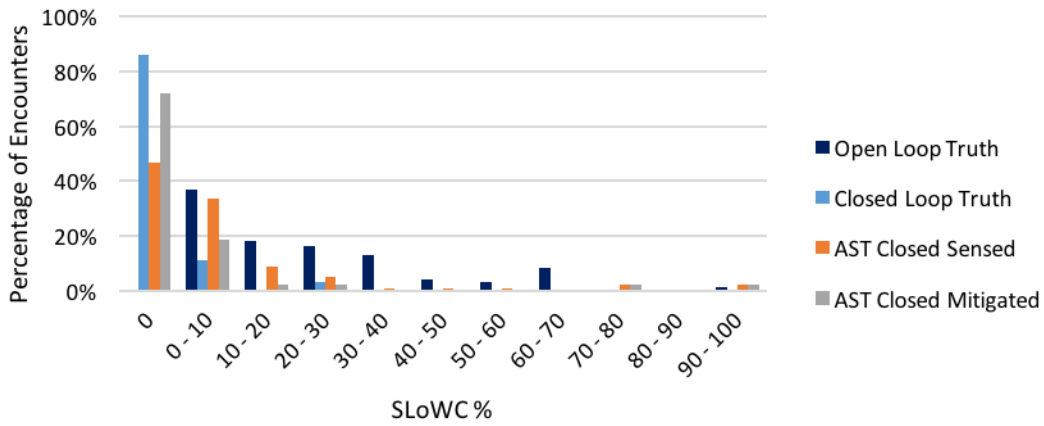
Figure 6. AST SLoWC for NAS-Derived Correlated Encounters
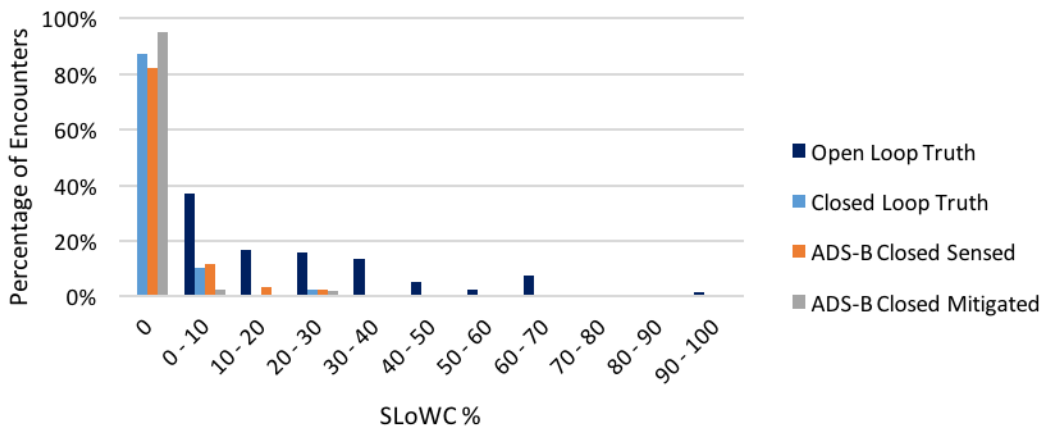
Figure 7. ADS-B SLoWC for NAS-Derived Correlated Encounters

American Institute of Aeronautics and Astronautics

B. Alert Scoring

Corrective Alert Scoring

Figure 8 shows a histogram of the corrective alert scoring for the radar sensor used in a closed loop simulation for NAS-derived correlated encounters. Results show that 85% of closed loop Truth runs fell within the "Permissible Alert" category, while 13% fell within the "Missed Alert" category. There were 56% fewer sensed guidance runs scored in the "Permissible Alert" than Truth guidance runs. The addition of the mitigated guidance resulted in 7% more runs scored in the "Permissible Alert" category than sensed guidance alone. 54% of runs using sensed guidance resulted in being scored in the "Missed Alert" category, however mitigated guidance resulted in 39% of runs being scored in the "Missed Alert" category. Similar trends were seen for encounters using the AST sensor (Figure 9). Results for the ADS-B sensor (Figure 10) show that more than 80% of closed loop encounters were within the "Permissible Alert" criteria signifying better performance by the ADS-B sensor.
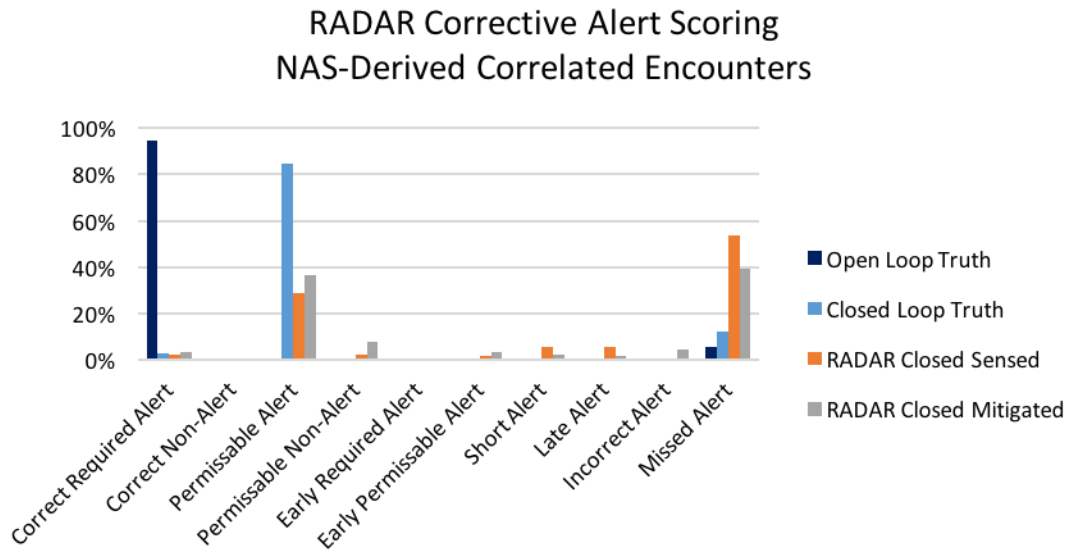
Figure 8. Radar Corrective Alert Scoring for NAS-Derived Correlated Encounters

AST Corrective Alert Scoring
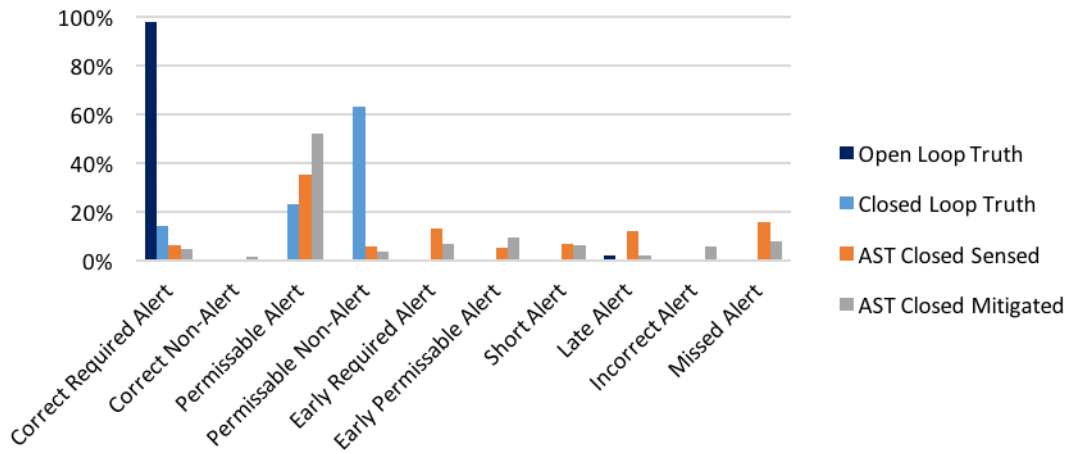## NAS-Derived Correlated Encounters
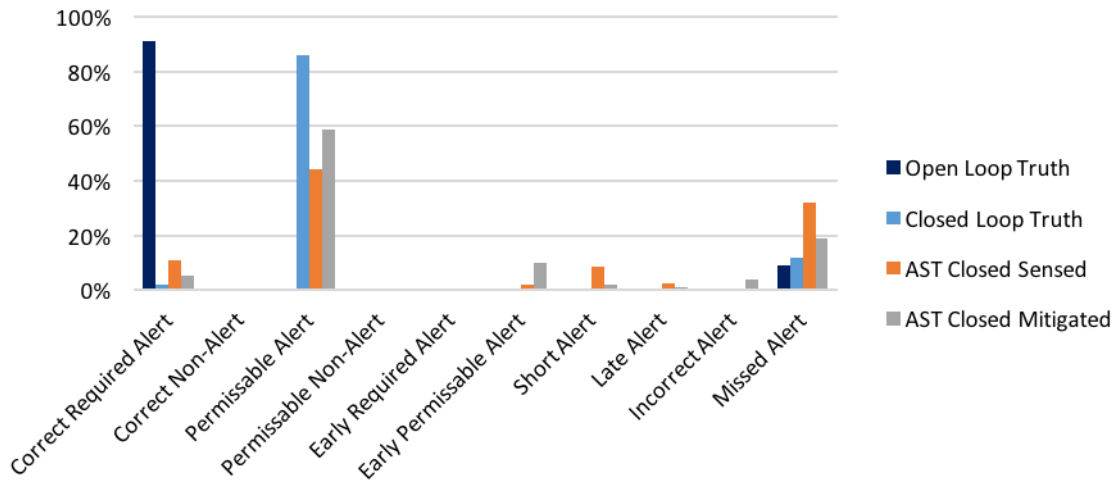
Figure 9. AST Corrective Alert Scoring for NAS-Derived Correlated Encounters

ADS-B Corrective Alert Scoring
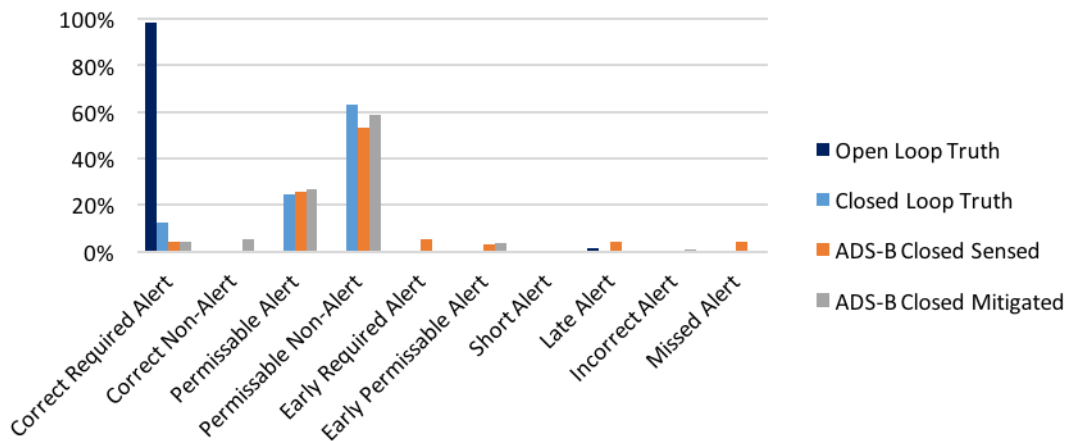## NAS-Derived Correlated Encounters
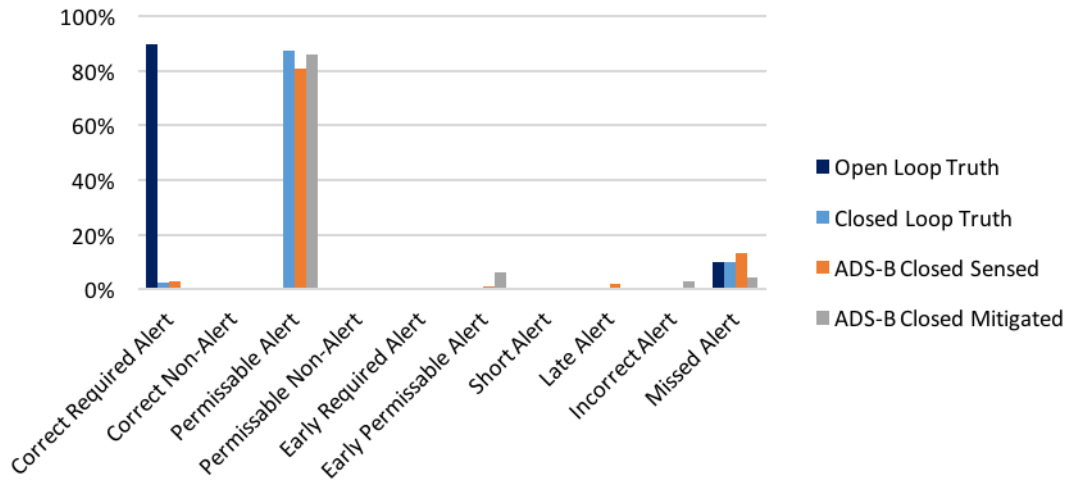
Figure 10. ADS-B Corrective Alert Scoring for NAS-Derived Correlated Encounters

Warning Alert Scoring

A histogram of the warning alert scoring as a function of the radar sensor is shown in Figure 11. Results show that 22% of encounters in the closed loop truth guidance were scored as the "Permissible Alert" category and approximately 63% within the "Permissible Non-Alert" scoring category. No encounters were scored in the "Missed Alert" category using Truth guidance. There were 59% fewer sensed guidance encounters scored as a "Permissible Alert" when compared to truth guidance runs. The mitigated guidance resulted in 9% fewer runs scored in the "Missed Alert" category. 32% of encounters using Sensed guidance were within the "Missed Alert" scoring category, while the Mitigated guidance resulted in 23% of runs being scored in the "Missed Alert" category. The Mitigated guidance accounted for 10% more runs being scored in the "Permissible Alert" than the Sensed guidance runs.
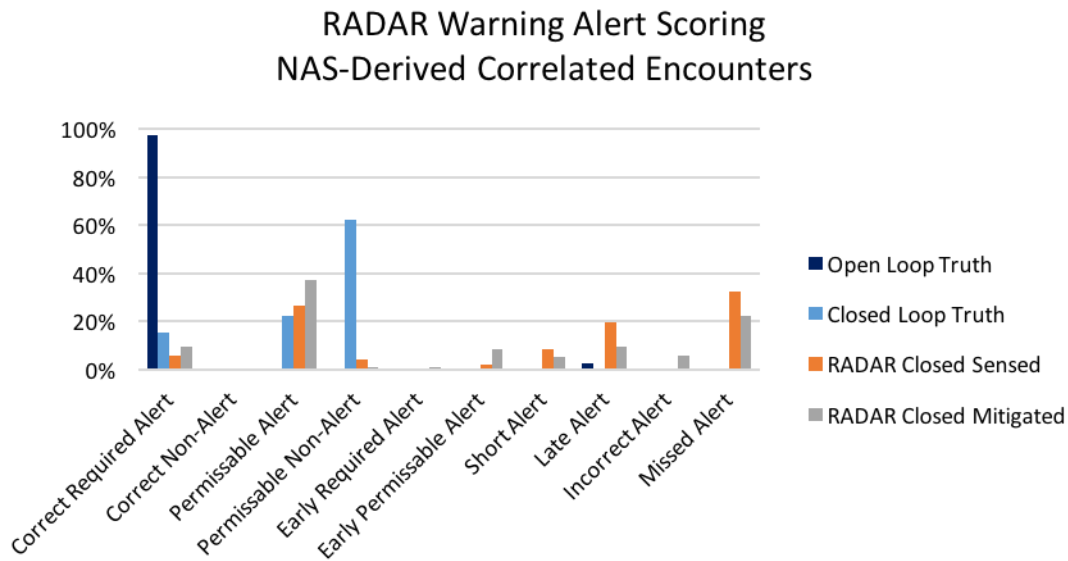
Figure 11. Radar Warning Alert Scoring for NAS-Derived Correlated Encounters

Result trends for encounters using the AST sensor (Figure 12) were similar to the radar sensor results.

Results shown in Figure 13 show encounters with Truth, Sensed, and Mitigated guidance had roughly similar results for the number of runs in the "Permissible Non-Alert" category (within 10% of each other) and were within 3% of each other in the "Permissible Alert" category. ADS-B showed better performance for warning alerts in comparison to the radar and AST sensors.

American Institute of Aeronautics and Astronautics

Figure 12. AST Warning Alert Scoring for NAS-Derived Correlated Encounters

Figure 13. ADS-B Warning Alert Scoring for NAS-Derived Correlated Encounters

American Institute of Aeronautics and Astronautics

Alert Jitter

An alert jitter histogram is shown in Figure 14 as a function of the radar sensor used in a closed loop simulation for NAS-derived correlated encounters. Open loop results with Truth guidance show 74% of encounters with an alert jitter of "2". One or two increasing alerts is ideal as it indicates a normal, steady progression in alert level without any alerts appearing and then disappearing. Closed loop Truth guidance shows 54% and 44% of encounters that experienced one and two alert increases, respectively. Mitigated results show that the SUM approach accounted for 10% more runs with an Alert Jitter of "2" than sensed guidance runs.
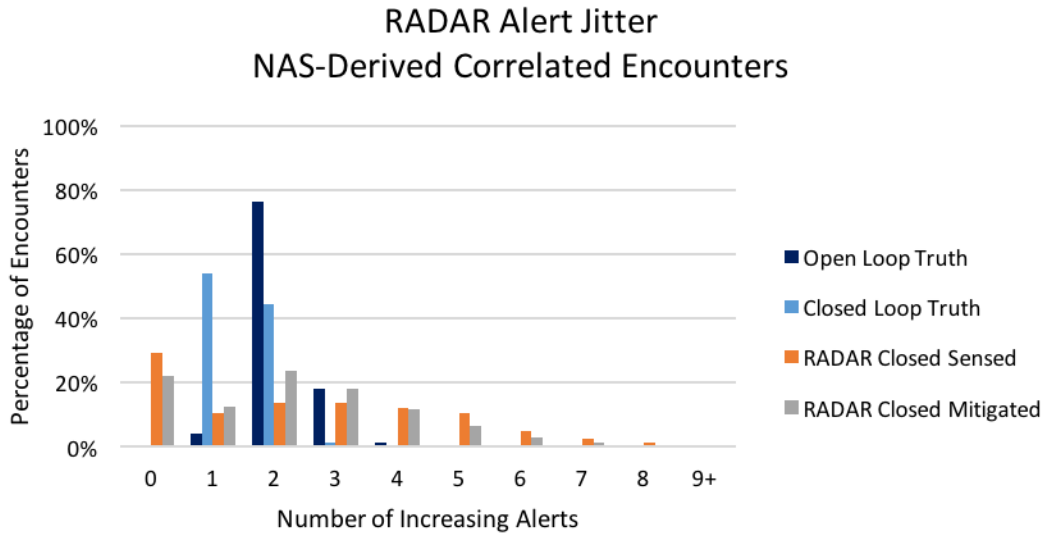
Figure 14. Radar Alert Jitter for NAS-Derived Correlated Encounters

Findings for encounters using the AST sensor (Figure 15) shows that Sensed and Mitigated guidance performed at comparable percentages among all the alert jitter values.

Results for the ADS-B sensor (Figure 16) show that a high proportion of encounters had either an Alert Jitter of either "1" or "2". Mitigated guidance with ADS-B shows the SUM approach had a less than 1% offset in comparison with the closed loop Truth guidance for the alert jitter value of "1." However, it also spreads out the distribution to higher jitter values, which is undesirable.
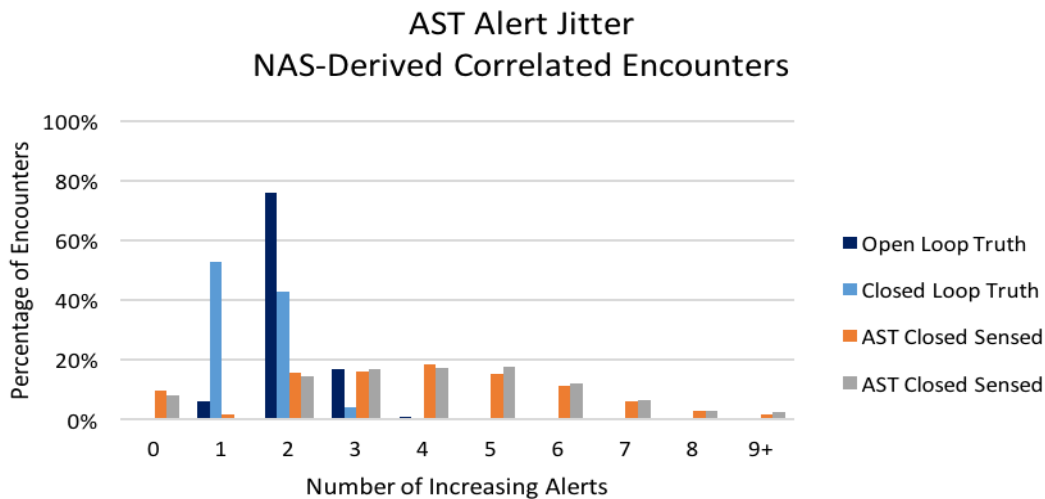
Figure 15. AST Alert Jitter for NAS-Derived Correlated Encounters

14
American Institute of Aeronautics and Astronautics

ADS-B Alert Jitter
NAS-Derived Correlated Encounters
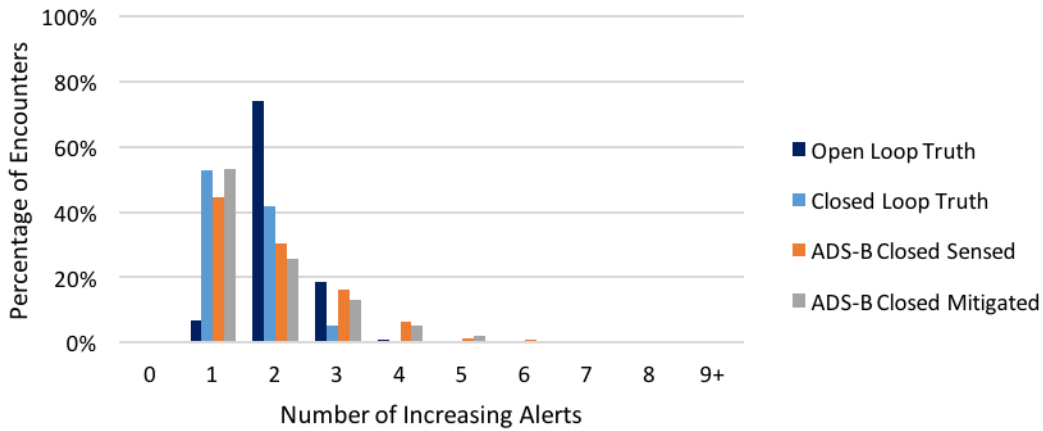
Figure 16. ADS-B Alert Jitter for NAS-Derived Correlated Encounters

VI.   Results: NAS-Derived Uncorrelated Encounter Set

A. Severity of Loss of Well Clear (SLoWC)

Figure 17 shows a histogram of SLoWC for ownship using radar as the guidance source in a closed loop simulation in NAS-derived uncorrelated encounters. Results for these encounters show that the closed loop system resulted in 0% SLoWC for 55% of the encounters using Truth guidance. Whereas, using radar data for guidance with no uncertainty mitigation (Radar Closed Sensed) resulted in only 16% of the encounters achieving a 0% SLoWC. The SUM approach (Radar Closed Mitigated) enabled the DAA system to keep SLoWC at 0% approximately 50% more often than using Sensed guidance alone.

RADAR SLoWC
NAS-Derived Uncorrelated Encounters
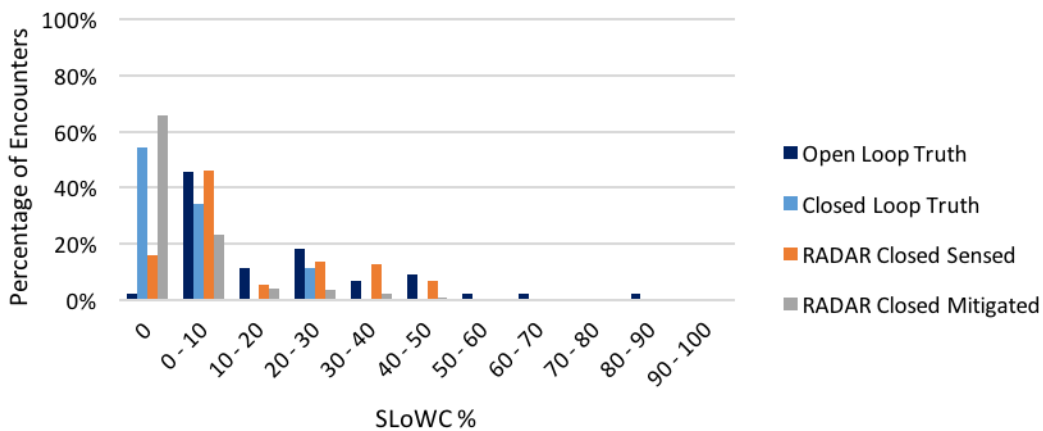
Figure 17. Radar SLoWC for NAS-Derived Uncorrelated Encounters

Figure 18 shows a SLoWC histogram for ownship using AST as the guidance source in NAS-derived uncorrelated encounters. The SUM approach enabled the DAA system to keep SLoWC at 0% approximately 28% more often than Truth guidance and approximately 43% more often than Sensed guidance.
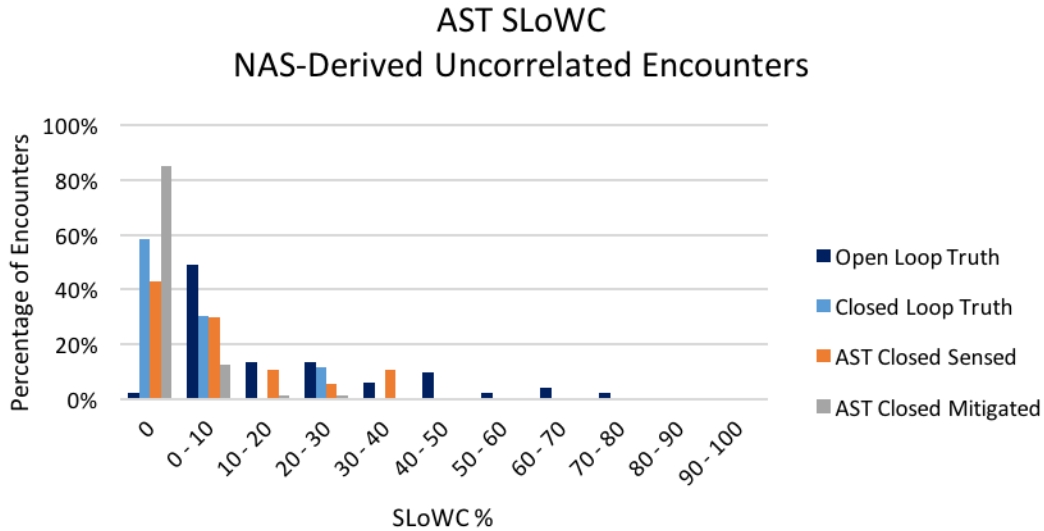
Figure 18. AST SLoWC for NAS-Derived Uncorrelated Encounters

Figure 19 shows a SLoWC histogram for ownship using ADS-B data as the guidance source in NAS-derived uncorrelated encounters. Findings show that the Mitigated source guidance, as a result of the SUM model approach, kept SLoWC at 0% by approximately 22% more than Truth guidance and 26% more than Sensed guidance.
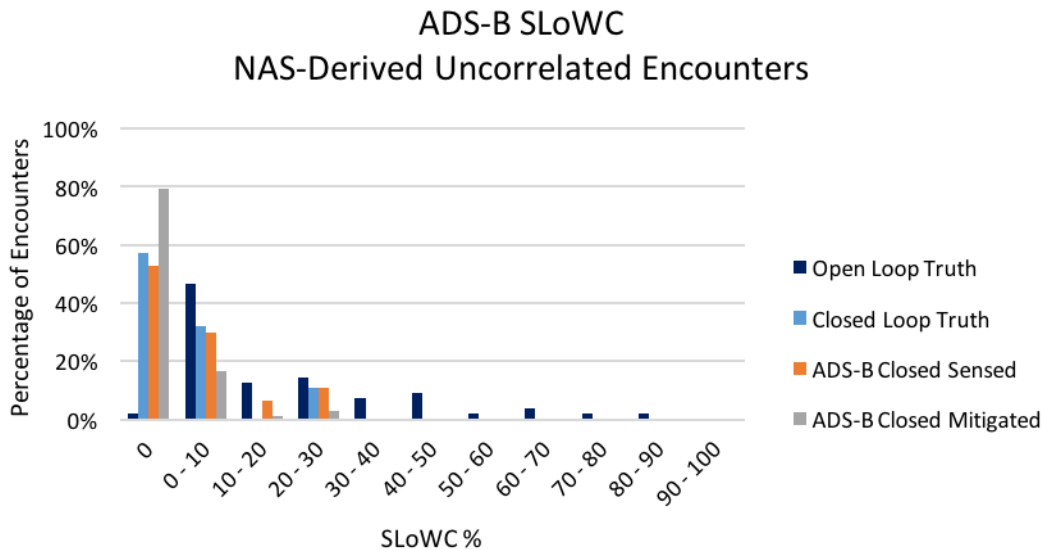
Figure 19. ADS-B SLoWC for NAS-Derived Uncorrelated Encounters

B. Alert Scoring

Corrective Alert Scoring

Figure 20 shows a histogram of the corrective alert scoring as a function of the radar sensor used in a closed loop simulation for NAS-derived uncorrelated encounters. Results from closed loop data runs using Truth guidance show almost all of the encounters scored in desirable categories (34% within the "Correct Required Alert," 50% within the "Permissible Alert" criteria, and 5% for "Permissible Non-Alert") and relatively few scored in undesirable categories (5% for "Late Alert," and 7% within the "Missed Alert" scoring criteria). The Sensed guidance dropped significantly in comparison to the Truth guidance for "Permissible Alert;" however, the Mitigated guidance was able to increase Permissible Alerts modestly. Mitigated guidance also enabled the DAA system to significantly decrease "missed alerts" at 21%.
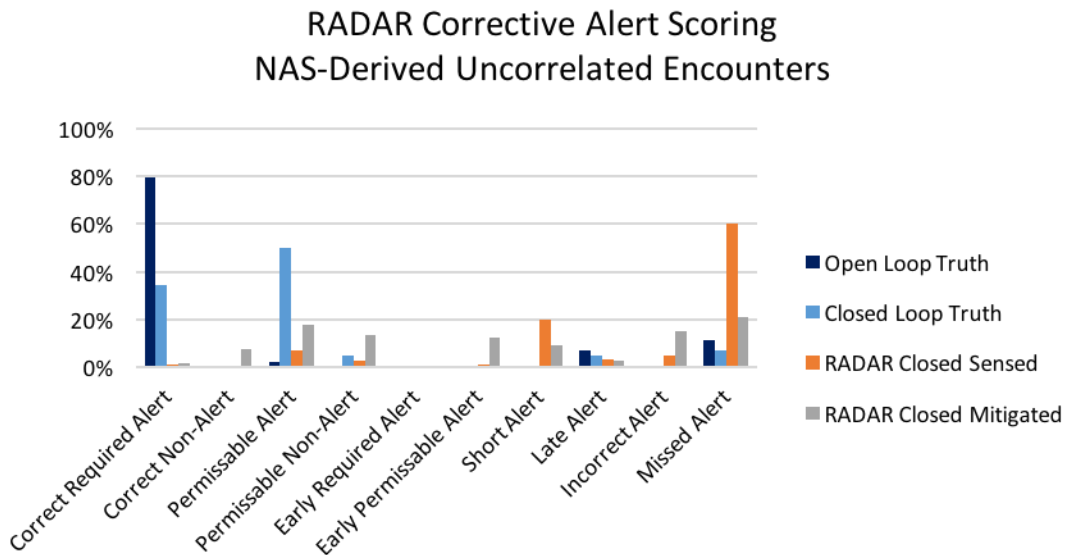
Figure 20. Radar Corrective Alert Scoring for NAS-Derived Uncorrelated Encounters

Figure 21 shows results seen for the AST sensor. Using Truth guidance, results show most closed loop encounters scored in desirable categories (28% within the "Correct Required Alert," 53% within the "Permissible Alert" criteria, and 6% within the "Permissible non-Alert" criteria), and some scored in undesirable categories (8% within the "Missed Alert" and 5% within the "Later Alert" scoring criteria). Using Sensed guidance, the correct required and permissible alerts dropped significantly with a corresponding increase in short, incorrect, and missed alerts. The SUM approach was able to significantly decrease missed alerts, but the AST data is problematic enough that the uncertainty mitigation actually decreased the correct and permissible alerts and non-alerts but was able to increase the early permissible alerts.
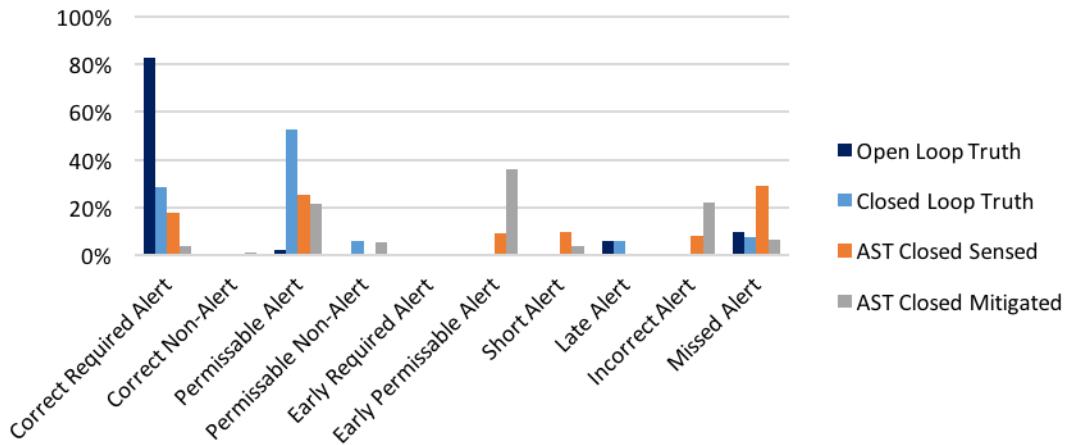
Figure 21. AST Corrective Alert Scoring for NAS-Derived Uncorrelated Encounters

Results for the ADS-B sensor are shown in Figure 22. Truth closed loop encounters scored within a 3% margin for the "Permissible Alert" criteria when compared to Sensed and Mitigated guidance. 15% of encounters using Sensed guidance were missed alerts. However, the Mitigated guidance enabled the DAA system to match the Truth guidance results for that criteria. The ADS-B sensor performed better than the radar and AST sensors.
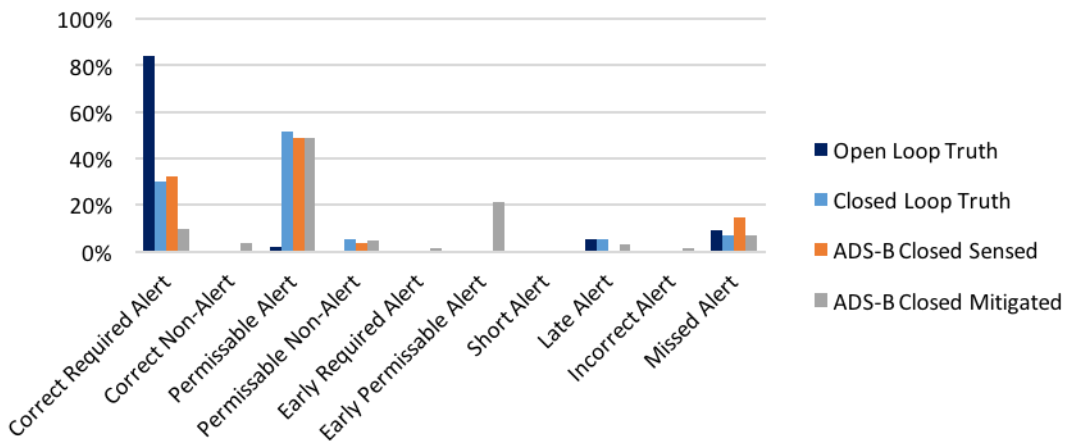
Figure 22. ADS-B Corrective Alert Scoring for NAS-Derived Uncorrelated Encounters

American Institute of Aeronautics and Astronautics

Warning Alert Scoring

Figure 23 shows a radar sensor histogram of the warning alert scoring used in a closed loop simulation for NAS-derived uncorrelated encounters. Closed loop results show most encounters scored in desirable categories (34% within the "Correct Required Alert" and 55% for the "Permissible Alert" criteria), and 11% scored within the "Late Alert" criteria using Truth guidance. The Sensed guidance dropped precipitously in comparison to the Truth guidance for correct required and permissible alerts, with a corresponding increase in short and missed alerts. The Mitigated guidance was able to increase correct required alerts, correct non-alerts, and permissible alerts, and decrease short, late, and missed alerts. Unfortunately, using radar data it also increased incorrect warning alerts.
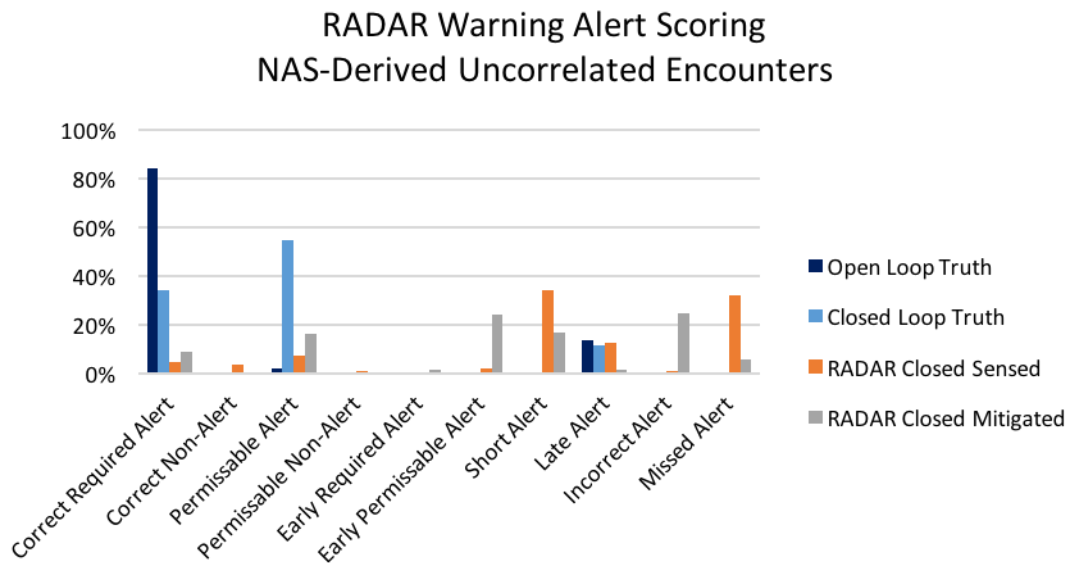
Figure 23. Radar Warning Alert Scoring for NAS-Derived Uncorrelated Encounters

Figure 24 shows results seen for the AST sensor. Results show 90% of the closed loop encounters scored in desirable categories (32% within the "Correct Required Alert," 58% within the "Permissible Alert" criteria), and 9% within the "Late Alert" scoring criteria using Truth guidance. The Sensed guidance decreased scores in desirable categories and increased scores in all undesirable categories. Mitigated guidance resulted decreases in short, late, and missed alerts, but also decreased correct required alerts and permissible alerts and non-alerts, and significantly increased incorrect alerts. The AST sensor performed least favorably in comparison to radar and ADS-B.
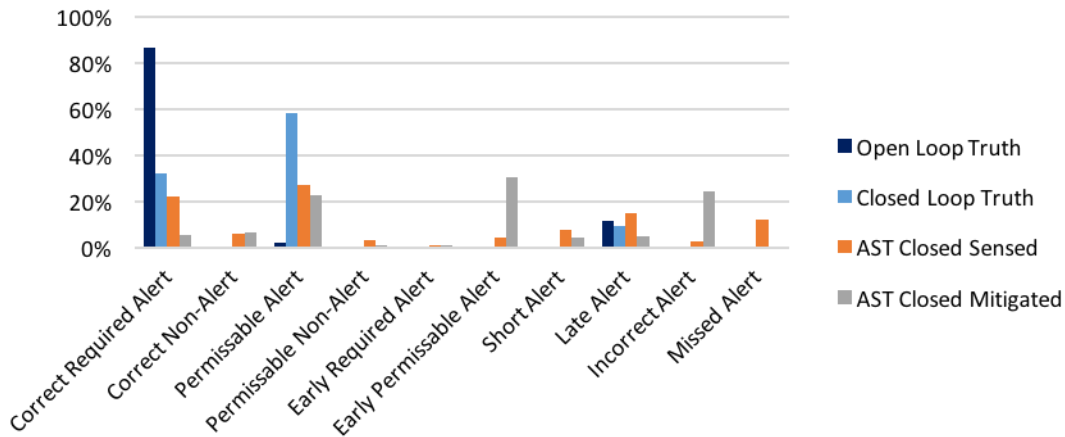
Figure 24. AST Warning Alert Scoring for NAS-Derived Uncorrelated Encounters

Results for the ADS-B sensor are shown in Figure 25. For permissible alerts, Sensed scored within 8% of Truth closed loop encounters and Mitigated scored within 7%. The "Correct Non-Alert" criterion contains 32% of encounters using Truth guidance, which is comparable to the 34% seen while using Sensed guidance. Mitigated guidance increased most desirable categories and decreased most undesirable categories.
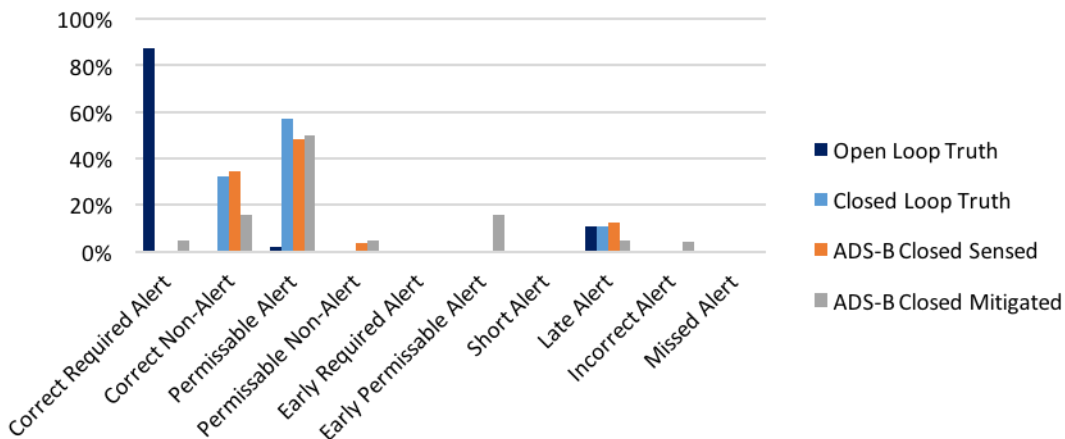
Figure 25. ADS-B Warning Alert Scoring for NAS-Derived Uncorrelated Encounters

C. Alert Jitter

Figures 26 through 28 show alert jitter performance of the DAA system using the three different sensors. For comparison, open loop results with no DAA system and no avoidance maneuvers are also shown alongside the closed loop results. In all three figures, just under 40% of the open loop with truth encounters scored an alert jitter of "2," which is the desired number of increasing alerts, and the vast majority of the rest form a well-behaved tail out to 7. This tail indicates that in a significant number of these uncorrelated encounters one or both of the aircraft are maneuvering to the extent that DAAWC is lost or predicted to be lost more than once. Also, as can be seen in all three figures, using Truth data to guide the ownship only slightly increases the desired score of 2, and significantly increases a score of 4, indicating that very likely in most of those cases the ownship was able to maneuver to avoid LoWC or to regain DAAWC but the intruder subsequently maneuvered back into a LoWC situation. For reference, alert jitter is explained in Section IV.D.

Figure 26 shows an alert jitter histogram for the radar sensor used in NAS-derived uncorrelated encounters in a closed loop simulation. Using the radar data for closed loop Sensed guidance pulled the distribution generally to the left, indicating the ownship maneuvered earlier and more drastically to avoid a LoWC because of the uncertainty in the data. Mitigated results show that the SUM approach was able to reshape the Sensed distribution to be closer to the Truth distributions.
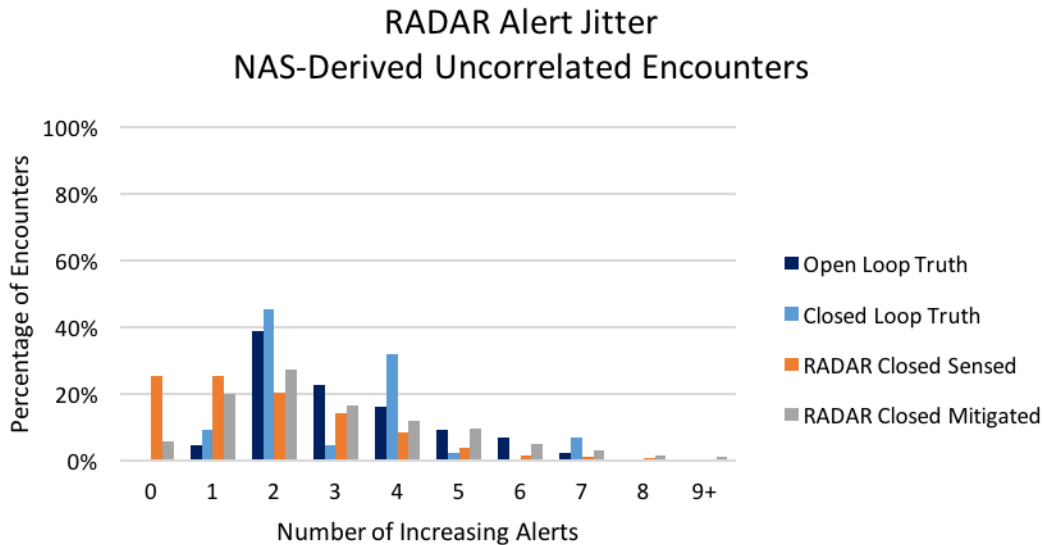

Figure 26. Radar Alert Jitter for NAS-Derived Uncorrelated Encounters

Results for the AST sensor (Figure 27) and ADS-B sensor (Figure 28) show that using unmitigated sensor data for guidance pulls the distribution generally to the right, indicating more maneuvering by the ownship. As with SLoWC, using the SUM approach worsened the AST alert jitter results, but seems to slightly flatten the distribution for ADS-B.

American Institute of Aeronautics and Astronautics

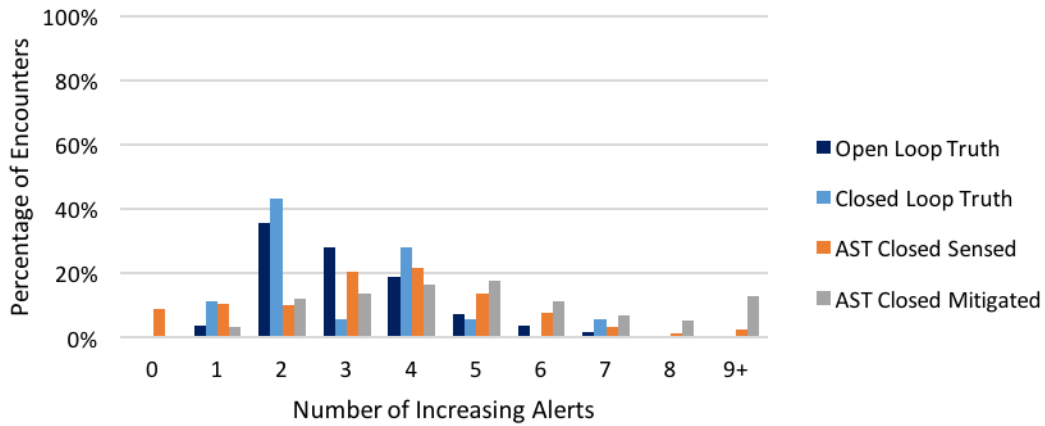*Figure 27. AST Alert Jitter for NAS-Derived Uncorrelated Encounters*

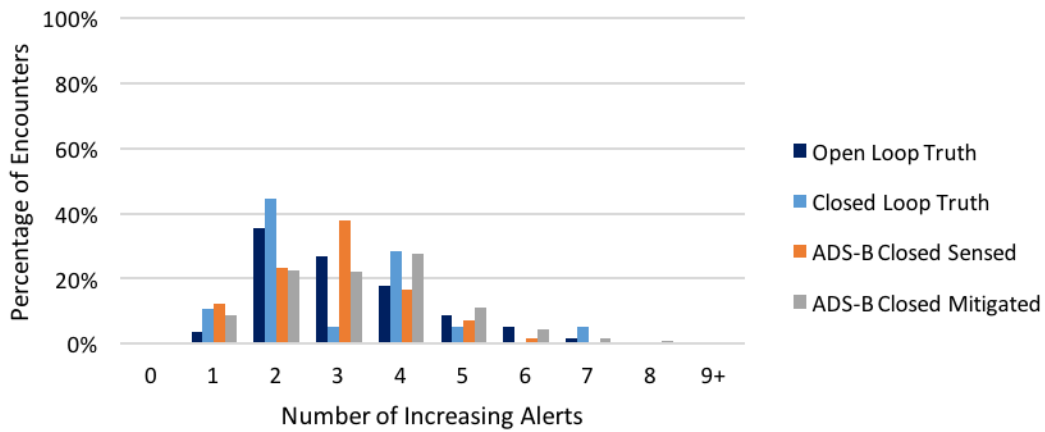Figure 28. ADS-B Alert Jitter for NAS-Derived Uncorrelated Encounters

American Institute of Aeronautics and Astronautics

VII. Discussion

The demand for unmanned aircraft in mainstream aviation operations continues to grow. Understanding key detect and avoid system performance capabilities and limitations are essential to developing rules and regulations that allow routine UAS operations but maintain the safety of the National Airspace System. To understand these capabilities and limitations, as part of on-going RTCA SC-228 efforts, NASA Langley Research Center evaluated the Phase I DAA MOPS requirements with end-to-end functionality over a specific set of encounters, in a variety of geometries, and with specific surveillance sensor performance, to verify and validate that a MOPS-representative DAA system performs acceptably.

Evaluation results showed that, overall, a MOPS-representative DAA system performed within acceptable ranges with few limitations. Values greater than 50% for severity of loss of well clear (SLoWC) occurred in less than 1.5% of total encounters. Results for alert scoring and alert jitter were similar. Losses of well clear and poor alert performance were mainly due to late maneuvers made by the intruder aircraft that the DAA system could not guard against and shortcomings of the surveillance data available to the DAA system.

Results suggest that slow moving aircraft should not depend solely on the AST sensor for lateral maneuvers. It should be noted that all three surveillance sensors (ADS-B, Phase I air-to-air radar, and AST) were modeled to produce data at the minimum specified quality, and can be expected to perform better in the field on average. As expected, the DAA system performed better with ADS-B than with radar or AST. Two other factors affecting DAA system behavior were observed in the pilot model. In some cases, the pilot model abandoned the initial avoidance maneuver in conditions where a human pilot may have continued or even increased the avoidance margins. Also, in some encounters with high uncertainty about the intruder's position and velocity, the SUM approach used in this study could cause erroneous guidance and alerting. Taken all together, none of the results of this study revealed surprising or serious problems with a Phase I DAA MOPS-compliant system.

References

Ghatas, R. W., Jack, D. P., Tsakpinis, D., Vincent, M. J., Sturdy, J. L., Muñoz, C., Hoffler, K. D., Dutle, A., Myers, R., DeHaven, A. M., Lewis, T., Arthur, K. E. (2017). Unmanned Aircraft Systems Minimum Operational Performance Standards End-to-End Verification and Validation (E2-V2) Simulation. NASA Technical Memorandum 2017-219598, Hampton, VA.

Jack, D., Hoffler, K., Sturdy, J. (2017) Mitigating the Impact of Sensor Uncertainty on Unmanned Aircraft Operations. NASA CR 2017, Hampton, VA.

Kochenderfer, M.J., Espindle, L.P., Kuchar, J.K., Griffith, J.D. (2008). Correlated Encounter Model for Cooperative Aircraft in the National Airspace System, Version 1.0. Massachusetts Institute of Technology Lincoln Laboratory, Lexington, MA. October 2008.

Kochenderfer, M.J., Espindle, L.P., Kuchar, J.K., Griffith, J.D. (2008). Uncorrelated Encounter Model of the National Airspace System, Version 1.0. Massachusetts Institute of Technology Lincoln Laboratory, Lexington, MA. November 2008.

RTCA, Inc. (2016). DRAFT Detect and Avoid (DAA) Minimum Operational Performance Standards (MOPS) for Verification and Validation, Version 3.6. RTCA Paper No. 261-15/PMC-1400. RTCA, Inc., Washington, DC. In Press.