NASA-TM-2017-219598

Unmanned Aircraft Systems Minimum Operational Performance Standards End-to-End Verification and Validation (E2-V2) Simulation

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April 2017

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List of Acronyms

2PAIRS	2 degrees-of-freedom Prototyping Aircraft Interaction Research Simulation
ADS-B	Automatic Dependent Surveillance – Broadcast
AGL	Above Ground Level
AST	Active Surveillance Transponder
ATC	Air Traffic Control
CPA	Closest Point of Approach
DAA	Detect and Avoid
DAAET	DAA Execution Threshold
DAAWC	DAA Well Clear
DAIDALUS	Detect and Avoid Alerting Logic for Unmanned Systems
E2-V2	End-to-End Verification and Validation
EKF	Extended Kalman Filter
FAA	Federal Aviation Administration
GA-ASI	General Atomics Aeronautical Systems Inc.
GPS	Global Positioning System
HAZ	Hazard Zone
HAZNot	Non-Hazard Zone
ICAO	International Civil Aviation Organization
LaRC	Langley Research Center
LoWC	Loss of Well Clear
MAZ	May Alert Zone
MIT/LL	Massachusetts Institute of Technology's Lincoln Laboratory
MOPS	Minimum Operational Performance Standards
msec	Millisecond
NACp	Navigation Accuracy Category Position
NACv	Navigation Accuracy Category Velocity
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NMAC	Near Mid-Air Collision
nmi	Nautical Mile
RTCA	Radio Technical Commission for Aeronautics, Inc.
SARP	Science and Research Panel
sec	Seconds
SLoWC	Severity of Loss of Well Clear
SUM	Sensor Uncertainty Mitigation
TCOA	Time to Co-Altitude
UA	Unmanned Aircraft
UAS	Unmanned Aircraft Systems
UAT	Universal Access Transceiver
WC	Well Clear

Abstract

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 (CFR 14 91.113) of other aircraft. RTCA SC-228 has defined DAA Well Clear (DAAWC) to provide a quantified Well Clear volume to allow systems to be designed and measured against. Extended research efforts have been conducted to understand and quantify system requirements needed to support a UAS pilot's ability 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 develop 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 maneuvers the ownship aircraft to remain well clear from intruder aircraft, having received collective input from the previous modules of the system. LaRC developed a functioning batch simulation and added a sensor/tracker model from the Federal Aviation Administration (FAA) William J. Hughes Technical Center, an in-house developed sensor uncertainty mitigation strategy, and implemented a pilot model similar to one from the Massachusetts Institute of Technology's Lincoln Laboratory (MIT/LL). The resulting simulation provides the following key parameters, among others, to evaluate the effectiveness of the MOPS DAA system: severity of loss of well clear (SLoWC), alert scoring, and number of increasing alerts (alert jitter). The technique, 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 this paper.

Introduction

As the number of Unmanned Aircraft (UA) continues to increase, the demand to allow them routine access to the nation's airspace drives research into methods and technologies to ensure that their integration into the National Airspace System (NAS) is done in a safe and efficient manner. One of the main challenges to safe integration is development of a capability for the unmanned aircraft system (UAS) to detect and avoid other air traffic. A Detect and Avoid (DAA) system would overcome the UAS's lack of "eyes in the sky." Understanding key DAA system performance capabilities and limitations is essential to developing rules and regulations that prioritize safety as UASs are integrated into routine NAS operations.

To date, DAA research has focused on sensors to detect other aircraft, algorithms to help make avoidance determinations, and displays to help the operator remain well clear of other aircraft (as required by CFR 14 91.113). To enable a DAA capability, a mathematical definition of DAA Well Clear (DAAWC) has been developed that provides a minimum separation volume for large UA operating in the NAS. A federal working group known as a Science and Research Panel (SARP) on UAS that consists of representatives from the Department of Defense, Department of Homeland Security, the Federal Aviation Administration (FAA), and the National Aeronautics and Space Administration (NASA) developed the DAAWC definition at the request of RTCA Special Committee 228 (SC228). RTCA "functions as a Federal D Committee and develops consensus-based recommendations on contemporary aviation issues" (RTCA, Inc., In Press). SC-228 consists of government, private, industry representatives, and other interested parties who are working to develop the Phase I Minimum Operational Performance Standards (MOPS) for DAA equipment. The initial phase of standards development (Phase I) focused on civil UAS "transitioning to and from Class A or special use airspace" (above 500 feet Above Ground Level (AGL)), and "traversing Class D, E, and G airspace" in the NAS (RTCA, Inc., In Press). Phase I DAA MOPS are to be published in early 2017 as an RTCA DO publication.

SC-228 members have conducted extensive research efforts to understand and quantify DAA system requirements needed to support a UAS pilot's need to remain well clear. With proper design, these systems "could provide an additional layer of protection that maintains or even enhances the current exceptional level of aviation safety" (Kochenderfer, Espindle, Kuchar, Griffith, October 2008). The safety-critical nature of a DAA system requires a robust and rigorous assessment before confidence can exist to certify a system for operational use. Research efforts have included developing and testing sensor, algorithm, alerting, and display requirements. Recently, an evaluation was conducted on sensor uncertainty and a mitigation strategy has been developed and assessed (Jack, In Press).

However, to understand these capabilities and limitations in a wider scope, NASA Langley Research Center (LaRC) evaluated the Phase I DAA MOPS requirements with end-to-end DAA functionality in order to verify and validate that a representative MOPS-DAA system performed acceptably. The End-to-End Verification and Validation (E2-V2) simulation study included the use of sensor and tracker models, a sensor uncertainty mitigation model, DAA algorithmic guidance in horizontal maneuvering, and a pilot model that commanded the ownship aircraft's heading in response to the DAA algorithm's maneuver guidance to remain well clear from other aircraft (i.e., an intruder). The MOPS-representative DAA system was evaluated over an extensive set of encounters representative of flight operations in the NAS, as well as several encounters designed to invoke specific system responses. The resulting simulation provided the following key parameters, and many more, to evaluate the effectiveness of the MOPS DAA system: severity of loss of well clear (SLoWC), alert scoring, and number of increasing alerts (alert jitter). The technique, 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 this paper.

1. General Information

1.1 Approach and Objective

The primary focus of the End-to-End Verification and Validation (E2-V2) simulation study was to show, through detailed examination of specific test vectors and encounter cases, whether a MOPS-representative DAA system behaved acceptably. System performance with, and without, sensor uncertainty mitigation (see Section 2.4) was investigated so that relative system benefits may be quantified. E2-V2 served as an additional validation of a MOPS-representative DAA system in a closed-loop fast-time simulation environment along with a limited number of open loop trials.

2. Simulation Environment

An end-to-end fast-time simulation tool was developed to model simplified unmanned aircraft (UA) operations. All DAA system components were also modeled, including: an aircraft performance model referred to as 2PAIRS (2 degrees-of-freedom Prototyping Aircraft Interaction Research Simulation), various sensor models, a DAA tracker model, a deterministic pilot model, a sensor uncertainty mitigation approach, and a representative DAA algorithm, known as DAIDALUS (Detect and AvoID Alerting Logic for Unmanned Aircraft Systems).

2.1 E2-V2 Architecture

A notional depiction of the E2-V2 simulation architecture is shown in Figure 1. There are three paths for data flow within the simulation tool:

The first path, labeled "Truth" in Figure 1, provides true (i.e., perfect) state data as output by the simulation tool 2PAIRS (see Section 2.2) to the DAIDALUS software (see Section 2.5), which outputs guidance bands to the pilot model. The pilot model then determines a heading change command with respect to the truth-based guidance bands.

The second path, labeled "Sensed" in Figure 1, provides true state data to the Sensor/Tracker suite (see Section 2.3) which degrades the state data using sensor accuracy assumptions. After degradation, the state data is then provided to DAIDALUS which outputs guidance bands based on the degraded state data of the ownship and intruder. The pilot model (see Section 2.6) then determines a heading change command with respect to the degraded state based guidance bands.

The third path, labeled "Mitigated" in Figure 1, provides true state data to the Sensor/Tracker suite which degrades the state data using sensor accuracy assumptions. After degradation, the state data is then provided to the Sensor Uncertainty Mitigation (SUM) software (see Section 2.4), which acts as a wrapper around DAIDALUS (i.e., the DAIDALUS algorithm is embedded within the mitigation model, which determines the positions and velocities of the aircraft). The SUM wrapper determines the positions and velocities of the 'phantom' intruder aircraft and provides the additional state data to DAIDALUS. DAIDALUS then outputs guidance bands based on the degraded state data of the ownship, the sensed intruder aircraft, and all 'phantom' intruder aircraft.

The pilot model then determines a heading change command with respect to the resulting guidance bands.

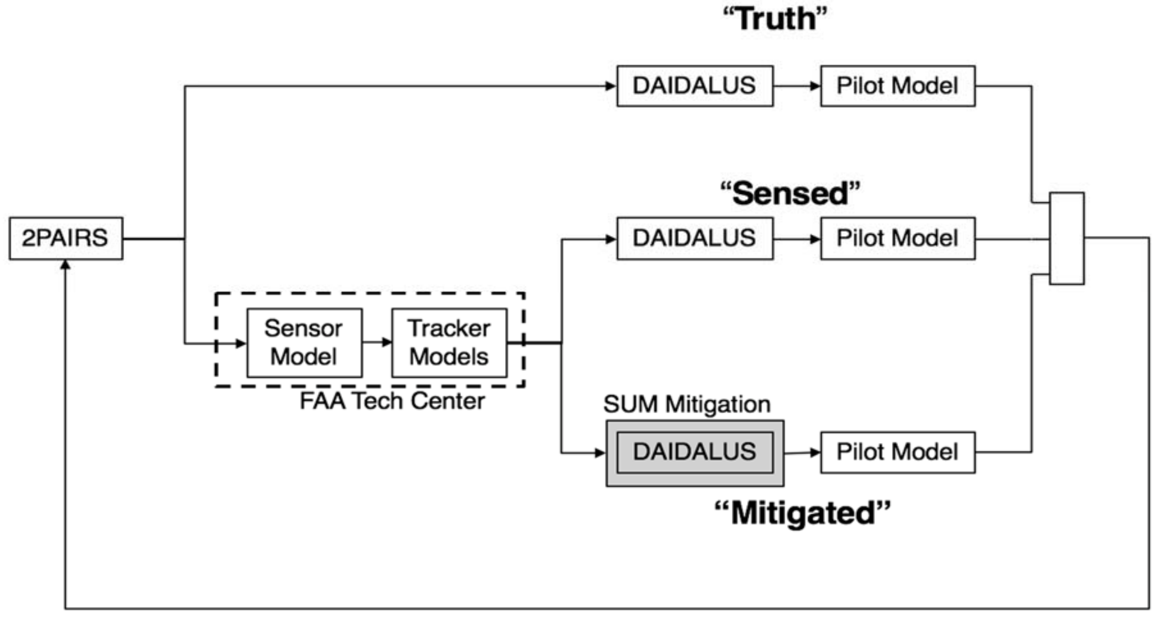

Figure 1. E2-V2 Architecture for Unmanned Aircraft Batch Simulation

2.2 Aircraft Flight Dynamics

An aircraft performance model, 2PAIRS, was used to model the UA's dynamics throughout the encounter and simulated lateral maneuvers and various ground speeds. 2PAIRS consists of a library that ingests either initial position and velocity or a time-sequence of positions for one ownship and one or more intruders. Ownship and intruder data is propagated in time according to these inputs until the Pilot Model (see Section 2.6) begins to output heading commands to resolve conflicts. At that time, ownship lateral motion is modeled using a simple 2 degree-of-freedom (bank and heading) model; the aircraft initiates a 3 degrees/sec turn with a 5 degrees/sec roll-in and roll-out rate. The library tool can capture and store key data about the encounter for further investigation and analysis, which is referenced at run time as a JAR (Java Archive) during batch simulation execution. The assumed maneuver rates and accelerations of this study did not stress the performance model.

2.3 Sensor/Tracker Suite

The E2-V2 simulation contained a version of the FAA's reference sensor and tracker models developed by the FAA's William J. Hughes Technical Center as reference models for the SC-228 DAA MOPS. The models, written in the Java programming language, were modified to replace the inter-process communication between the position model and standalone sensor and tracker models with direct function call/return semantics for processing efficiency. The sensor model accepts aircraft truth-state data for ownship and intruder(s) and returns degraded ownship state as well as intruder target reports for specific sensor configurations. This study considered each sensor (ADS-B, AST, or RADAR) in isolation and did not consider multi-sensor scenarios. The tracker model accepts sensed ownship state and target reports and produces the final degraded track information needed for the system to use as input to the DAA algorithm.

The sensor software model contains sensor emulators to perform internal detection, correlation, and error modeling for ownship and each intruder using truth data as input and generating sensor reports appropriate for each sensor type that include both the measured quantities and estimates of their uncertainty. The emulators for the three sensors (ADS-B, AST, and RADAR) are described on the following pages.

The ownship state emulator uses a Global Positioning System (GPS) error model, shown in Table 1, (Calhoun, 2016) to generate navigational information for position and velocity with correlated noise and barometric altitude. Correlated noise is generated based on the specified Navigation Accuracy Category for Position (NACp) and Navigation Accuracy Category for Velocity (NACv) values using a first order Gauss-Markov process and barometric altitude using a Laplacian error model.

- Navigation Accuracy Category for Position (NACp): Parameter that "describes the accuracy region about the reported position within which the true position of the surveillance position reference point is assured to lie with a 95% probability at the report time of applicability" (RTCA DO-317B, 2014).

- Navigation Accuracy Category for Velocity (NACv): Parameter that "describes the accuracy about the reported velocity vector within which the true velocity vector is assured to be with a 95% probability at the reported time of applicability" (RTCA DO-317B, 2014).

Table 1. Ownship GPS Error Model Parameters

<table>
<tr><th colspan="4">Navigation Accuracy Category for Position (NACp) = 7</th></tr>
<tr><th>State</th><th>Absolute Error (per aircraft) 1-sig</th><th>Bias</th><th>Time Correlation</th></tr>
<tr><td>Horizontal Position</td><td>75.6m</td><td>0</td><td>300 seconds</td></tr>
<tr><td>Baro Altitude</td><td>0</td><td>Per Traffic Situational Awareness with Alerts (TSAA) Model</td><td>---</td></tr>
<tr><th colspan="4">Navigation Accuracy Category for Velocity (NACv) = 1</th></tr>
<tr><th>State</th><th>Absolute Error (per aircraft) 1-sig</th><th>Bias</th><th>Time Correlation</th></tr>
<tr><td>Horizontal Velocity</td><td>4m/s</td><td>0</td><td>300 seconds</td></tr>
<tr><td>Vertical Velocity</td><td>1.707m/s (95%)</td><td>---</td><td>---</td></tr>
<tr><td>Attitude</td><td>[0.2, 0.2, 0.4] degrees</td><td>---</td><td>---</td></tr>
</table>

The radar emulator (Table 2) (Calhoun, 2016) uses a single beam to search and track as it scans the field of view at +/- 110 degrees in bearing and +/- 15 degrees in elevation, using a specified pattern to generate raw measurements that include appropriate measurement noise. These measurements are correlated scan-to-scan to produce sensor reports.

Table 2. Radar Emulator Model Parameters

State	**Relative Error (1-sig)**	**Bias**
Range	15.24m (50 feet)	15.24m (50 feet)
Bearing	3.0m/s (10 feet/second)	2.4m/s (8 feet/second)
Altitude	1-degree	0.5-degree

Radar Emulator Model Parameters

State	**Value**	
Update Rate	1 second	
Tracking Range	5 nmi (< 100kts. Intruder) 6.5 nmi (100-300kts. Intruder) 8 nmi (> 130kts. Intruder)	Detection Range Scale Factor Az: [0, 30], 1.0 Az: [30, 60], 0.84 Az: [60, 90], 0.46 Az: [90, 110], 0.45
Field of Regard	+/- 15 Elevation (Stabilized with respect to velocity vector) +/- 110 Azimuth	
Probability of Track	Pr(Track) = 1	

The Active Surveillance Transponder (AST) emulator (Table 3) (Calhoun, 2016) models either one of two interrogation modes: Mode S (with 25 feet altitude resolution) and Mode C (with 100-foot altitude resolution). It receives true ownship and intruder position from the true source and generates the AST measurements at a computed rate based on the intruder's estimated closing rate. Mode S maximum detection range is configured at 35 nmi with probability of detection at 95%, while Mode C detection is configured at 15 nmi with probability of detection at 90%. The field of regard in elevation is [-15, +20] degrees.

Table 3. AST Emulator Model Parameters

State	Relative Error (1-sig)	Bias	Quantization
Range	15.24m (50 feet)	38.1m (125 feet)	---
Bearing	[-10, 10 degrees]: 9 degrees RMS; maximum 27 degrees [-15, -10] or [10, 20 degrees): 15 degrees RMS; maximum 45 degrees	---	---
Altitude	0	Per TSAA Model	Quantization 25 ft. / 100 ft. (Intruder Aircraft) / 1 ft. (Ownship Aircraft)

AST Emulator Model Parameters

State	Value
Update Rate	1 second
Detection Range	Mode C = 15 nmi Mode S = 35 nmi
Probability of Reception/Detection	Mode C = 0.90 Mode S = 0.95
Field of Regard	[-15, +20 degrees) Elevation

The Automatic Dependent Surveillance – Broadcast (ADS-B) emulator (Table 4) (Calhoun, 2016) models either one of two transmission modes: 1090 MHz Extended Squitter (1090ES) and Universal Access Transceiver (UAT). It uses a similar error model to the ownship state emulator.

Table 4. ADS-B Emulator Model Parameters

Navigation Accuracy Category for Position (NACp) = 7			
State	**Absolute Error (per aircraft) 1-sig**	**Bias**	**Time Correlation**
Horizontal Position	75.6m	0	300 seconds
Baro Altitude	0	Per TSAA Model	---
Navigation Accuracy Category for Velocity (NACv) = 1			
State	**Absolute Error (per aircraft) 1-sig**	**Bias**	**Time Correlation**
Horizontal Velocity	4m/s	0	300 seconds
Vertical Velocity	1.707m/s (95%)	---	---
ADS-B Emulator Model Parameters			
State	**Value**		
Update Rate	1 second		
Latency Effects (Uncompensated)	< 0.4 seconds		
Detection Range	< 20 nmi		
Probability of Reception/Detection	0.95		

The tracker software model contains emulators to perform radar, ADS-B, and AST correlation, sensor selection, and track smoothing. It produces filtered, geo-referenced track data and track uncertainty.

- The Radar Tracker uses a three-dimensional filter to estimate intruder track states in the ownship reference frame.

- The ADS-B Tracker includes position and velocity, barometric altitude, and the International Civil Aviation Organization (ICAO) address with time of applicability. It is the most stable and most accurate sensor of the three.

- The AST Tracker uses an Extended Kalman Filter (EKF) and a polar-beta tracker to estimate intruder track states from AST sensor measurements.

- Linking multiple sensor tracks into a single central/fused track for the same intruder is performed based on the nearest neighbor paradigm by the use of the following parameters: ICAO address, time-aligned sensor track positions and time-aligned sensor measurements. The central tracker performs a preferred sensor selection based on the propagated uncertainty (circular error bound computed from the elliptical track propagated covariance) at the time of linking.

- The Track Manager within the Tracker outputs a track message at each one second epoch for each intruder and includes the linearly extrapolated central/fused track state from the preferred sensor track. The estimated ownship state is also output.

2.4 Sensor Uncertainty Mitigation Approach

Sensor errors impose a need for a DAA system to take account of the imprecision of sensed intruder states when providing alerts and maneuver guidance to the UAS operator. An approach to account for sensor errors has been developed; the methodology is referred to as the Sensor Uncertainty Mitigation (SUM) model approach. The SUM model approach uses the horizontal and vertical position, and velocity standard deviations provided by the tracker to augment the sensed position of each intruder with additional 'phantom' intruders. This approach presents the DAA algorithm with a block of intruders that span a sigma-multiple of the possible intruder location and velocity arrayed around the sensed position and velocity, as depicted in Figure 2.

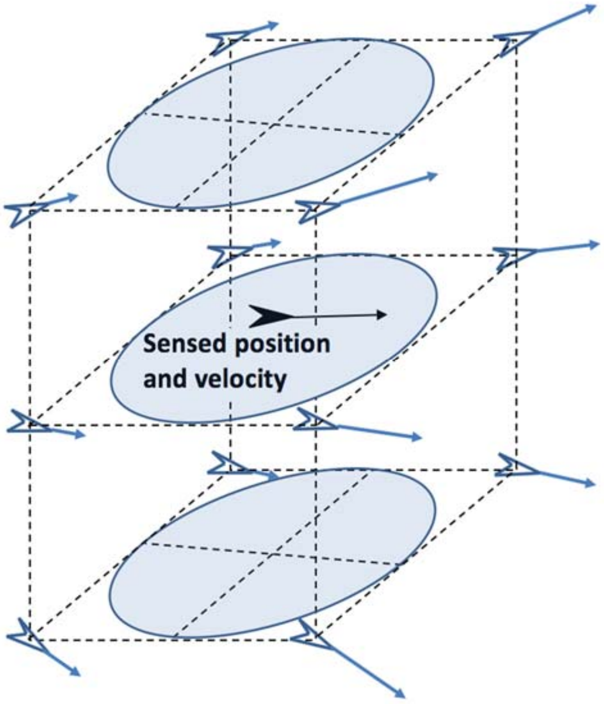

Figure 2. Notional Depiction of Sensor Uncertainty Mitigation Approach

The SUM wrapper determines the positions and velocities of the ‘phantom’ intruder aircraft. This is achieved by using constant scaling factors to multiply the estimated horizontal and vertical position and velocity standard deviations provided by the tracker model. Scaling factors with the SUM approach were optimized to reduce frequency and severity of losses of well clear and to increase probability of correct alerts:

- Horizontal Position Uncertainty = 0.5σ
- Horizontal Velocity Uncertainty = 1.5σ
- Vertical Position Uncertainty = 1.0σ
- Vertical Velocity Uncertainty = 1.0σ

2.5 Detect and Avoid Alerting Logic for Unmanned Systems

The E2-2V study relied on the DAIDALUS[1] software library to compute maneuver guidance that satisfies RTCA SC-228 DAA requirements (Munoz et al, 2015). DAIDALUS functional specification is described in Appendix G of the Phase I DAA MOPS. The top-level functionality of DAIDALUS provides traffic awareness and maneuver guidance supporting UAS operators' ability to detect and avoid other aircraft having the potential to cause Loss of Well Clear (LoWC). This functionality is intended to aid the pilot in command (PIC) in order to perform a safe maneuver to maintain DAA Well Clear, or regain DAA Well Clear, if a LoWC has already occurred (or is unavoidable). Traffic awareness is achieved through increasing alert levels, which correspond to increasing potential for LoWC. Maneuver guidance is provided in the form of ranges of maneuvers, which the pilot in command may execute to avoid or recover from LoWC.

DAIDALUS algorithms are memoryless and were designed using truth input/output data. Further, the algorithms do not track or filter the aircraft input state information and do not apply time delays or hysteresis to the output data. Therefore, all pre-processing of surveillance input data and all post-processing of computed date interface is performed by external modules such as the E2-V2 infrastructure. Under these assumptions, DAIDALUS algorithms have been formally verified for logical correctness (i.e., algorithms satisfy their functional requirements) and the software implementation has been validated against the formal algorithmic models, i.e., given a set of stressing scenarios, the outputs computed by the software implementation coincide to the expected algorithmic outputs modulo numerical imprecisions due to computer arithmetic (Munoz et al, 2016).

Because of the scope of the study presented in this paper, E2-V2 only exercises the maneuver guidance logic, the alerting logic, and the calculation of DAA Execution Threshold (DAAET) provided by DAIDALUS. The maneuver guidance logic in E2-V2 is configured for the class of aircraft that are able to perform a turn rate of 3.0 degrees/sec. In this configuration, maneuver guidance is computed when the current ownship state is predicted to violate, within the next 60s, a buffered DAAWC as defined in Table 5. Traffic aircraft are assumed to fly straight line trajectories. Furthermore, maneuver guidance is computed for a look-ahead time of 75s.

The recovery guidance logic is exercised when, assuming a turn rate of 3.0 degrees/min, the ownship cannot avoid a violation of the buffered DAAWC with traffic aircraft. In this case, guidance is computed that exits the buffered DAAWC while maintaining a minimum separation distance of at least D-Threshold (DMOD*) horizontally and Z-Threshold (ZTHR*) vertically with traffic aircraft. If maintaining this separation is not possible, for example because of aircraft performance limits, the separation is dynamically reduced by 20% until the Near Mid-Air Collision (NMAC) volume. If the NMAC volume cannot be avoided, the recovery guidance logic does not return any guidance.

The DAAET value is calculated when the linear projection of the ownship current state is predicted to violate the buffered DAAWC. In this case, DAAET is the predicted time to recovery guidance. In E2-V2, the DAAET is used as the time that the ownship has to avoid a LoWC assuming its performance limits.

Table 5. DAIDALUS Buffered Well Clear Definition

DAIDALUS Configuration	**Buffered Well Clear Volume**	**Preventive**	**Corrective**	**Warning**
D-Threshold (nmi)	1.0	1.0	1.0	1.0
Z-Threshold (feet)	450	750	450	450
T-Threshold (seconds)	35	35	35	35
TCOA (seconds)	20	20	20	20
Look-Ahead Time (seconds)	75	---	---	---
Alerting Time (seconds)	60	60	60	30

2.6 Pilot Model

The pilot model was derived from the Massachusetts Institute of Technology's Lincoln Laboratory's (MIT/LL) UAS Pilot Model Release 3.0. The pilot model was originally written in MATLAB/Simulink but converted to Java for this study. The Java version implements only the "Deterministic" mode of the model and excludes the "Stochastic" mode. The pilot model is implemented as a simple state machine whose states, transitions, and transition-processing elements are depicted in the following figure. The state transitions are triggered by timers and/or alert level thresholds.

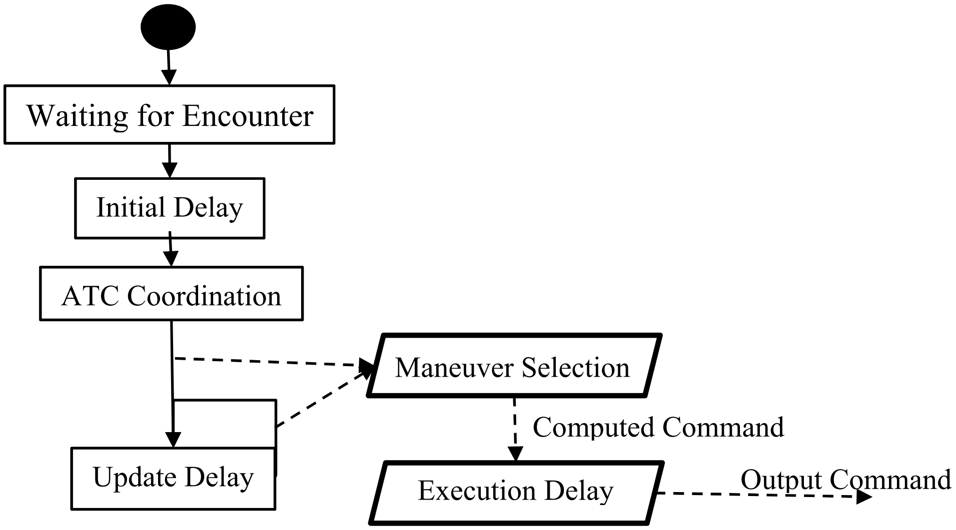

Figure 3. E2-V2 Pilot Model

The pilot model incorporates the following states:

- The pilot model initializes in the Waiting for Encounter state. It remains in that state until the first update cycle in which the alert level reaches or exceeds 2 (Preventive).

- The Initial Delay state implements a fixed (5 second) delay starting when the alert level first reaches 2 (Preventive) or higher, implemented using a simple cycle counter.

- The Air Traffic Control (ATC) Coordination state is a constant (11 second) delay starting when the Initial Delay is satisfied, implemented using a simple cycle counter. An alternative transition out of the ATC Coordination state occurs if the alert level reaches 4 (Warning) or higher.

- The Update Delay state is a delay whose exit transition criteria is a function of the current alert level. It starts when the ATC Coordination Delay is satisfied and restarts each time it is satisfied. Maneuver Selection is performed each time the Update Delay state is re-entered.

- Maneuver Selection function assesses the band data (heading) and current heading to determine the maneuver command. It executes on each entry into the Update Delay state and completes its processing within the cycle that it is activated. Maneuver Selection first determines the minimal left and right heading deviation required to achieve the minimum band value (None, Recovery, Near) available in that direction. Heading changes are limited to 135 degrees in the MIT/LL model, but this limitation is not included in the LaRC implementation. Once this heading pair is determined, the logic proceeds to pick between the two options by first picking based on lower band value, then based on lower deviation magnitude, and finally picking left. Once selected, the maneuver value and selection time is retained until the process is re-evaluated. The vertical maneuver selection logic in the MIT/LL model was not implemented for this study. The LaRC implementation includes provision for specification of a heading band buffer that specifies how far beyond the band-edge the commanded heading should be selected. When the buffer is applied, logic ensures that if there is another band beyond the band edge, the buffer will not push the commanded heading beyond the midpoint of the band gap. For this study, a buffer of 5 degrees was used.

- The Execution Delay function implements a constant 3-second delay starting when the maneuver is selected. Once the execution delay is satisfied, the maneuver selection is passed out of the pilot model. Note that this delay is intended to represent the time it takes the pilot to input a command in the ground control station once a maneuver decision has been made, and is not related to any C2 link delay.

2.7 UAS Performance Assumptions

Table 6 provides the performance assumptions that were used in the E2-V2 simulation to represent what the UA initial state (speed) and maneuverability, in response to pilot commands, would be within the NAS. The model allowed the UA to instantaneously (one simulation time step) achieve or return to zero from the roll rate and maneuvering load factor.

Table 6. Unmanned Aircraft Performance Assumptions

UA Performance Capability	**Assumption**
Turn Rate	3.0 degrees/second
Airspeed	40 – 600 KTAS at appropriate altitudes
Maneuvering Load Factor Increment	0.25g
Roll Rate	5 degrees/second
Command and Non-Payload Control Link	400 msec delay – each way

3. Method

3.1 Scenarios

Multiple encounters were utilized to show whether a MOPS-representative DAA system behaved acceptability. Encounters were run in a closed loop simulation environment in order to mimic maneuvering behaviors of a human pilot in addition to 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. Each closed loop encounter was run one time through the Truth mode and fifty times through the Sensed and Mitigated modes (see Figure 1) for replication purposes to verify and validate the output data. Each open loop encounter was run one time through the Truth mode and ten times through the Sensed and Mitigated modes.

Encounters originated from two main categories: NAS-Derived Encounter Sets (Section 3.1.1) and MOPS Requirements-Derived Test Vectors (Section 3.1.2).

3.1.1 National Airspace System (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.

3.1.2 MOPS Requirements-Derived Test Vectors

The MOPS requirements-derived test vectors will be included as supplement to the Phase I DAA MOPS. Each test vector, or track, was placed in one of two categories: alerted or non-alerted. For the E2-V2 simulation study, only alerted tracks were utilized for data collection. "Alerted tracks test the alerting capabilities of a DAA system for a range of aircraft encounters that have either occurred historically in the en-route environment, or have been identified through flight test or the design of prototype DAA systems to stress the performance of a DAA system" (RTCA, Inc., In Press).

The tracks were derived from multiple sources, including:

- A review of mid-air collisions that occurred between January 2000 and June 2010
- 95 Stressing Cases used by the Science and Research Panel (SARP) for the derivation of the DAAWC boundaries
- Flight Test 4 conducted by NASA in support of DAA MOPS development
- Test Vectors used in RTCA DO-317B for testing of the Airborne Surveillance and Separation Assurance Processing tracker and TSAA

Test vectors describe cases that are representative of encounters observed during routine operations and categorized as Head-On, Converging, Overtake, and Maneuvering encounters. Additionally, test vectors also described encounters that are considered to be "corner cases" that stressed the performance of the system, such as High Speed encounters (RTCA, Inc., In Press).

Table 7 shows the final 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.

Several test vectors were designed such that a loss of well clear would be unavoidable. These test vectors were removed from aggregate statistics. Additionally, through open loop data analysis, additional test vectors were removed from aggregate statistics in the following cases: 1) non-cooperative intruder violated operational assumptions associated with a DAA radar (RTCA, Inc., In Press), 2) intruder was outside of the radar or AST sensor field-of-view, and/or 3) the encounter's maneuver guidance was inconsistent with lateral maneuver constraint. Appendix A contains notional depictions of three of the five types of encounters derived from the MOPS requirements.

Table 7. Final E2-V2 Test Vectors Set

	E2-V2 Test Vectors (based on Truth Tracks)			
Category Description	**Total**	**Radar**	**AST**	**ADS-B**
NAS-Derived: Correlated	120	72	100	119
NAS-Derived: Uncorrelated	60	44	53	56
MOPS: Head-On	15	3	14	15
MOPS: Converging	20	10	13	20
MOPS: High Speed	4	0	4	4
MOPS: Maneuvering	15	2	14	15
MOPS: Overtake	16	3	15	16
Total	250	134	213	245

3.2 Metrics

3.2.1 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).

3.2.2 Alert Scoring

Another metric used to analyze the large data set was Alert Scoring. In order 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 4 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 5 quantifies an alerting system's performance. The Hazard Zone is based on the DAA Well Clear volume (Table 5), 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 5 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 5, the green region indicates where truth data is used, while the purple represents degraded alert timing information.

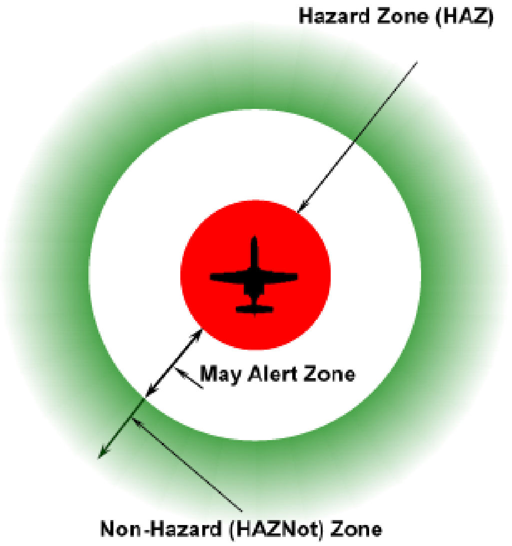

Figure 4. Notional Depiction of Hazard, May Alert, and Non-Hazard Zones

Table 8. 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

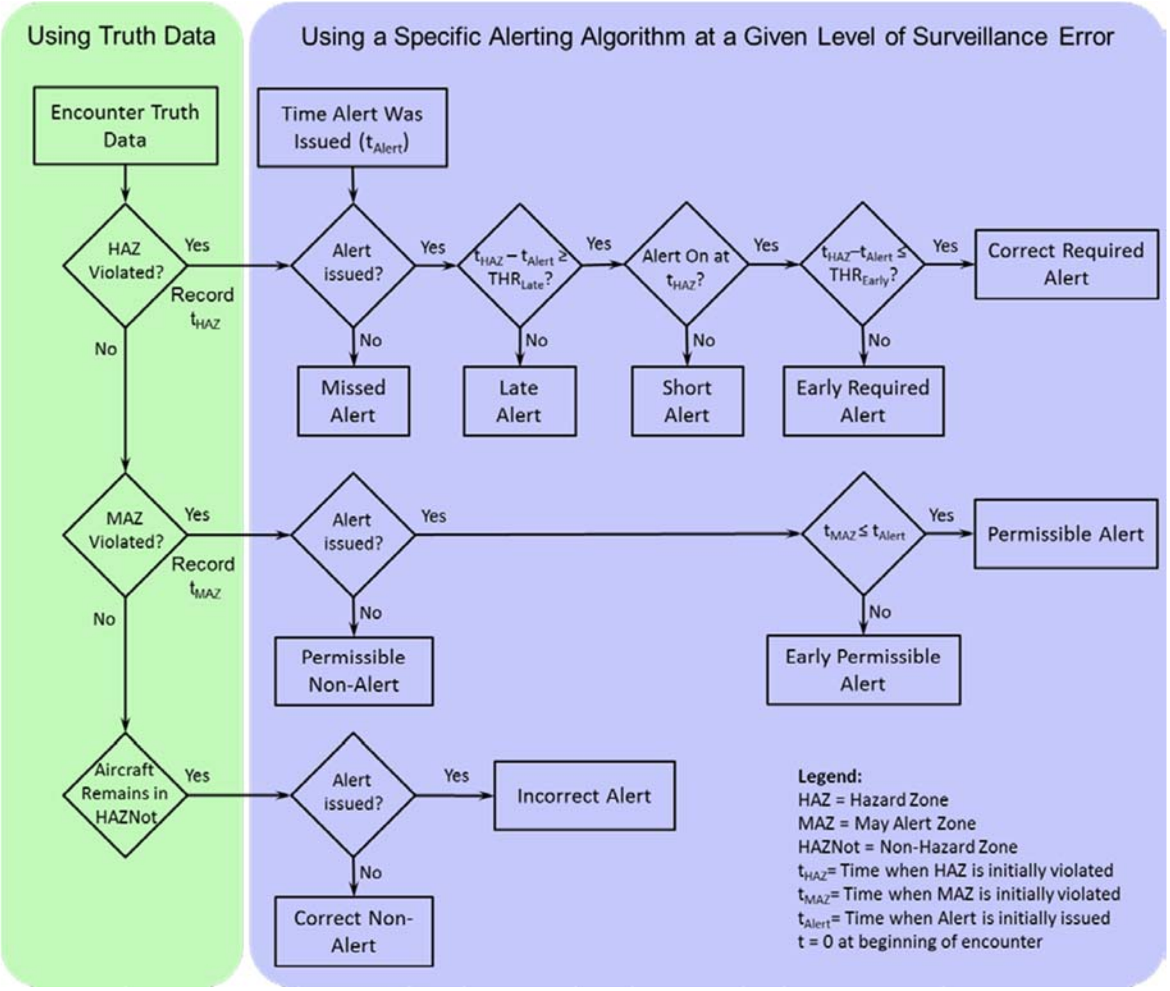

Figure 5. Alert Scoring Process

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

3.2.2.1 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.

3.2.3 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 manually control 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).

4. Summary of Results

To concisely present the data, the following section provides figures and discussion considering all encounter sets together. Focused analysis on specific encounter sets is provided in Sections 5 and 6. The summarizing figures in this section show normalized distributions of SLoWC, Alert Scoring, and Alert Jitter for all encounter sets. In all figures, open loop runs are shown in black to show the response with no input from the pilot model. Truth runs in which the pilot model follows guidance based on perfect state data are shown in Blue. Runs with DAA guidance based on sensor-degraded state data with (Mitigated) and without (Sensed) the SUM mitigation approach in place are shown in Green and Red, respectively.

4.1 Severity of Loss of Well Clear (SLoWC)

SLoWC is a metric that quantifies the severity of the loss of separation between two aircraft. Figures 6, 8, and 10 show normalized distributions of SLoWC for radar, AST, and ADS-B, respectively. Each SLOWC distribution shown in Figure 6, 8, and 10 are with active pilot model response to DAA Guidance resulting in many of the encounters remaining well-clear. To provide further insight in the distribution of LoWC, Figures 7, 9, and 11 show normalized distributions of runs where LoWC occur for each sensor. The percentage of runs shown in the distribution of the LoWC-only figures is a function of all runs, therefore the distributions in these figures do not amount to 100%.

Results for normalized SLoWC distribution for radar equipped runs (Figures 6 and 7) show that nearly 70% of all mitigated runs with the SUM approach incorporated results in no LoWC. Relying solely on sensed data without compensation for uncertainty reduces the percentage of runs that maintain DAAWC to less than 40%. Guidance based on truth data results in more than 80% of runs maintaining DAAWC, which indicates that the encounter set contains scenarios in which the DAA system could not maintain DAA Well Clear given ideal conditions.

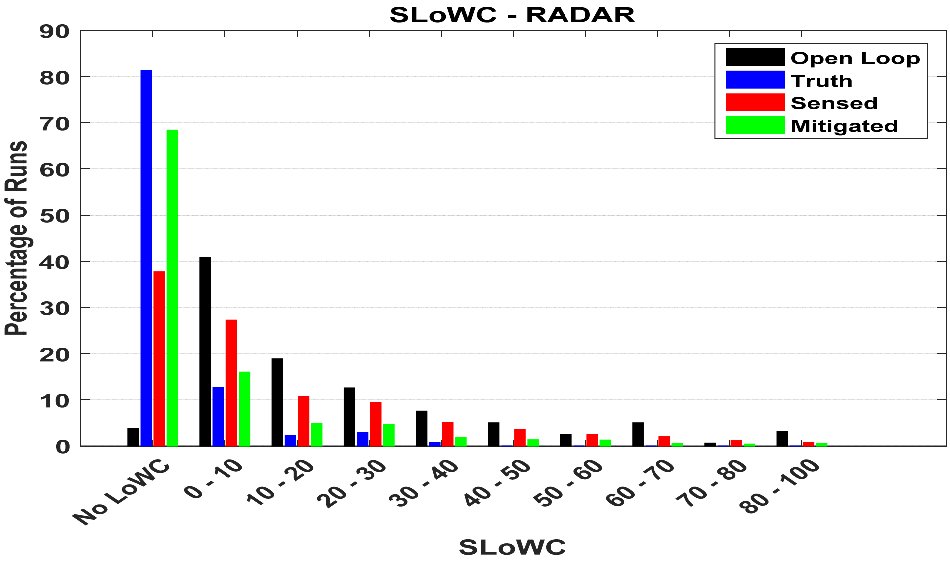

Figure 6. Radar SLoWC for Combined Encounters

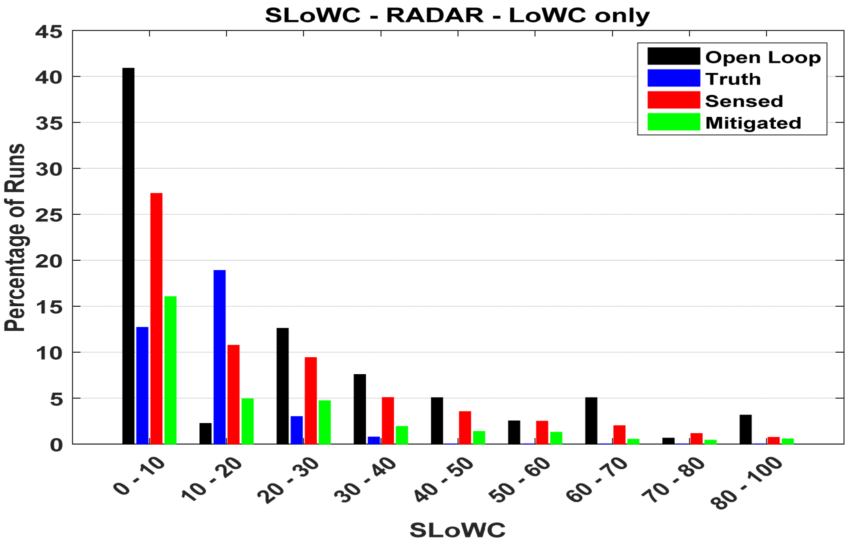

Figure 7. Radar SLoWC for Combined Encounters that Lost Well Clear

Figures 8 and 9 show the normalized distribution of SLoWC with AST equipped. In Figure 8, it is clear that the SUM mitigation approach improves the achieved SLoWC when compared to sensor degraded tracks only. Due to the large variations in the bearing measurement of the AST sensor model, the commanded heading can alternate across ownship heading. These variations in bearing can result in the pilot model beginning an initial turn to the left followed by a turn to the right. The resulting trajectory fails to achieve the required deviation from initial trajectory, which results in a large SLoWC values. This changing ownship course, as well as blundering intruders, accounts for a large proportion of the encounters with high SLoWC values in Figures 8 and 9.

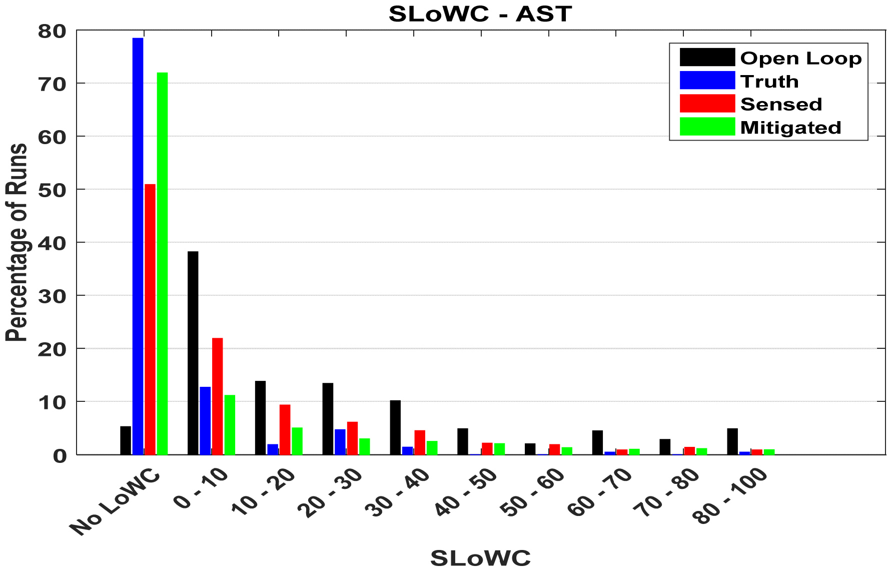

Figure 8. AST SLoWC for Combined Encounters

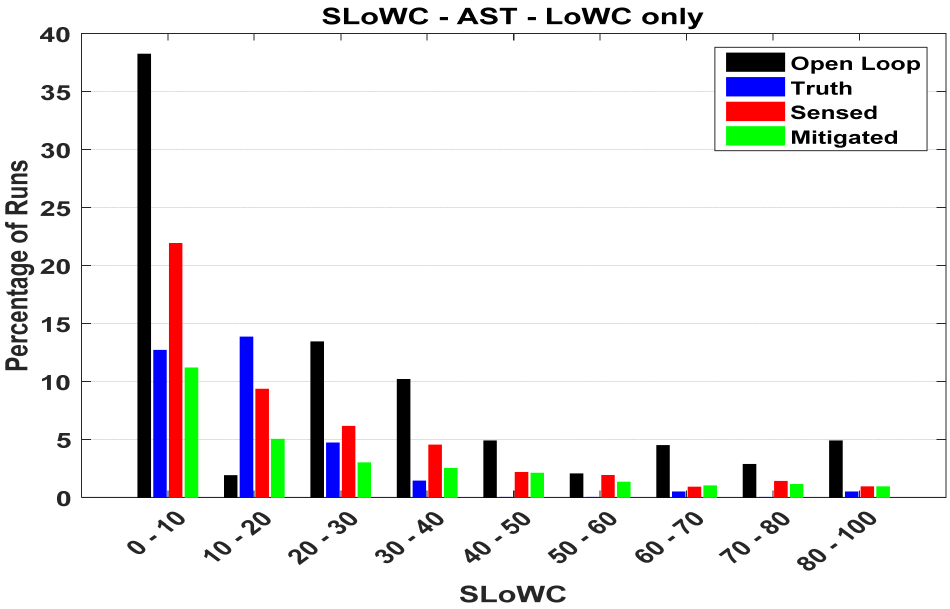

Figure 9. AST SLoWC for Combined Encounters that Lost Well Clear

Figures 10 and 11 show the achieved SLoWC distribution for ADS-B equipped runs. Figure 10 shows the SUM approach resulted in fewer runs with LoWC occurrences than in Truth-based runs. This implies that the SUM approach adds an additional buffer within the avoidance region which resulted in a larger achieved separation between the ownship and intruder. Even with the decrease in the number of LoWC occurrences, runs with SLoWC values greater than 80% still occurred. Although these runs represent a small proportion of total runs (<1% of the runs using Sensed and Mitigated guidance), they are realistic occurrences and cannot be ignored. Beyond featuring blundering intruders or ownship maneuvers, these encounters are characterized by combined sensor-degraded state information for the ownship and intruder. The degradation of each aircraft's state information can result in the DAA system sensing safe separation when in fact there is a LoWC (e.g., in a pair-wise encounter with the two aircraft head-on at the same altitude). The sensed ownship position is 200 feet above the actual ownship position while the intruder's sensed position is 250 feet below the actual intruder position. The sensed vertical separation is roughly 450 feet which may result in no alert being issued and a direct collision between the aircraft.

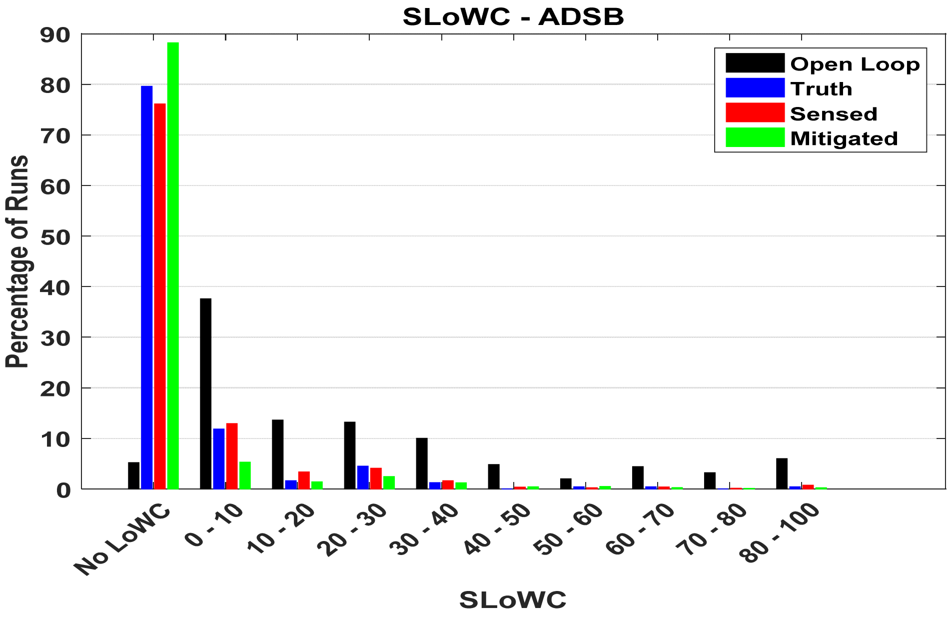

Figure 10. ADS-B SLoWC for Combined Encounters

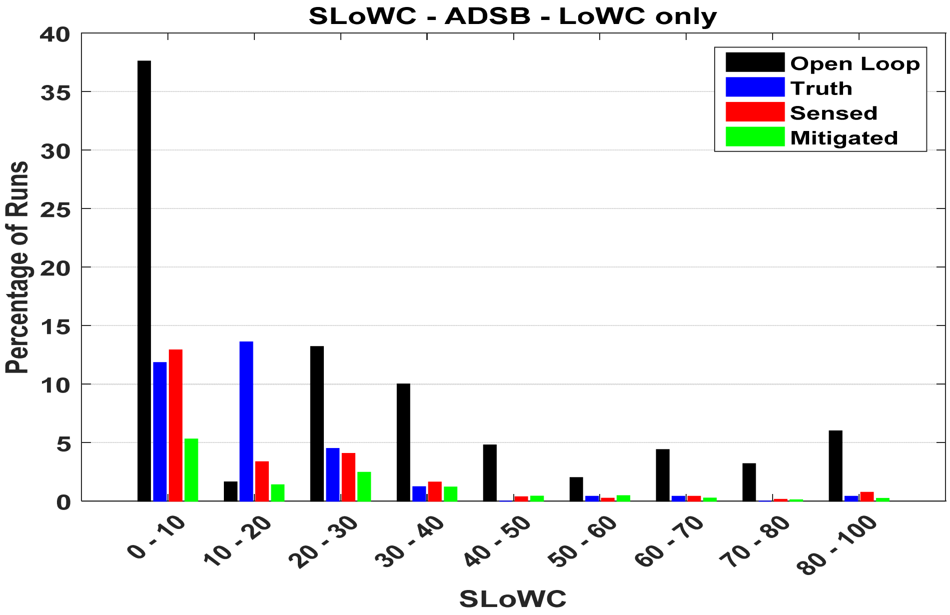

Figure 11. ADS-B SLoWC for Combined Encounters that Lost Well Clear

4.2 Alert Scoring

This subsection presents results showing the distribution of the categorical alert scoring outlined in Section 3.2.2. While the categorical alert scoring does not represent a continuum from poor to good performance, Figures 12 through 17 notionally order the categories from desirable performance to undesirable performance. The first six categories are considered desirable: Correct Required Alert through Early Permissible Alert. The last four are undesirable: Short, Late, Incorrect, and Missed Alerts. Open loop runs – runs that did not include the pilot model (i.e., did not "close the loop") and therefore had no avoidance maneuvers – are shown in black for comparison to the closed-loop runs. Closed loop runs with Truth-based guidance and alerting are shown in blue, runs with sensed only alerting guidance are shown in red, and runs with the SUM approach are shown in green.

Since the pilot model is responding to the DAA guidance to avoid a LoWC, the closed loop nature of these runs introduces an interdependency between the alert scoring of the Corrective Alert level and the Warning Alert level. For instance, in the following figures there is an increase in incorrect alerts when utilizing the SUM approach to compensate for sensor uncertainty. While this is undesirable behavior, there is no loss of well clear. The "Incorrect Alert" results when an alert is issued while still in the HAZNot zone, but the pilot model responds to this early non-permissible alert and commands the UA to maneuver away from the intruder. Based solely on alert scoring, this encounter would be viewed negatively; however, safe separation was achieved. Further, the Corrective and Warning HAZ zones are identical. If a blundering intruder enters the HAZ zone with insufficient time to allow for the DAA system to progress through the hierarchy of alert levels, then a Warning Alert will be issued. In the same example, the Corrective Alert will be scored as a "Missed Alert" due to the intruder's blunder. Although having a "Missed Alert" is an undesirable behavior, the alerting system does correctly prioritize the Warning Alert over the Corrective Alert. In all figures below, given Truth-based guidance the pilot model responds to the alerts and is able to avoid entering the Corrective HAZ zone. Therefore, the provided alert is considered a "Permissible Alert" rather than a "Required Alert."

4.2.1 Corrective Alert Scoring

Figures 12 through 14 show the normalized distribution of the categorical alert scoring for Corrective Alerts for radar-only, AST-only, and ADS-only equipped runs.

Analyzing the Truth-based open loop runs equipped with radar only, shown in black on Figure 12, reveals that the majority (>85%) of the runs had a "Correct Required Alert." Of note, there were approximately 10% of runs that had a "Missed Alert." Comparing Sensed runs to Mitigated runs with radar-quality source data, the SUM approach increased the number of permissible alerts and permissible non-alerts, while decreasing the short, late, and missed alerts. Undesirably, the SUM approach also increased the early alerts and incorrect alerts. The increase in incorrect alerts can be attributed to runs in which an alert was issued, but the intruder remained in the HAZNot zone due to ownship maneuvering. The slight increase in early and incorrect alerts was expected as the SUM approach introduced 'phantom' intruder aircraft that were perceived to be closer than the sensed position of the intruder.

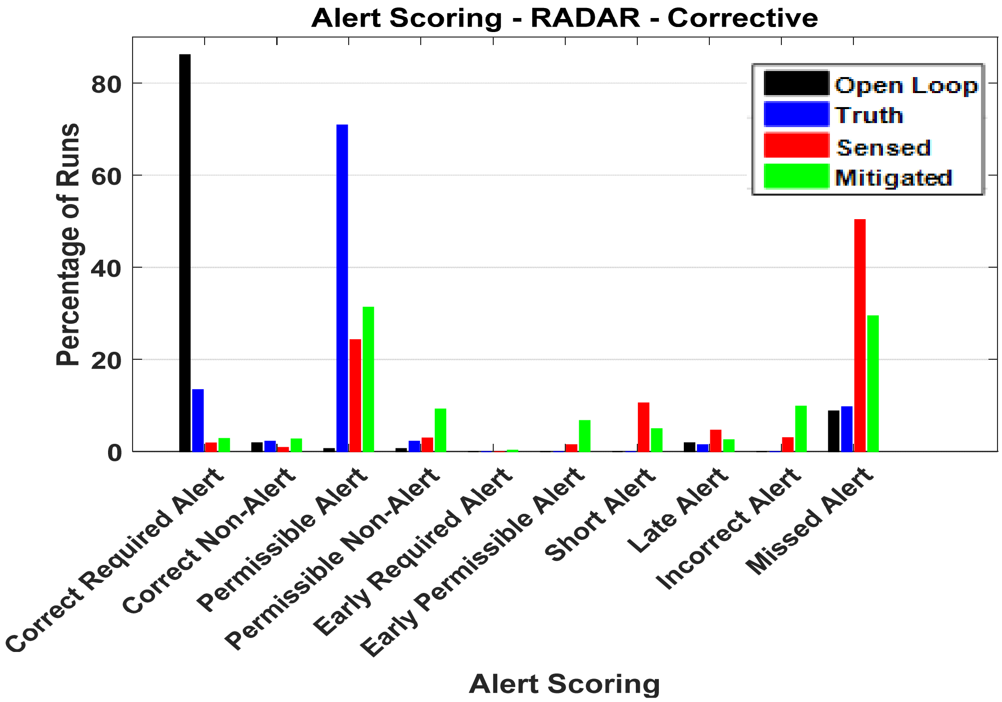

Figure 12. Radar Corrective Alert Scoring for Combined Encounters

Figure 13 shows the normalized distribution of alert scoring for AST-equipped runs. Similar to the radar-only alert scoring response, the SUM approach improved the response of short, late, and missed alerts. Additionally, the SUM approach greatly increased percentage of runs within the "Early Permissible Alert" and "Incorrect Alert." The early permissible alerts can be attributed to the expansion of the avoidance volume caused by the introduction of the 'phantom' intruders. The incorrect alerts were caused by the unmanned aircraft's ability to achieve separation following the DAA guidance. The SUM approach also shifted the number of "Correct Required Alert" to "Permissible Alert" due to the increase in the avoidance region beyond the DAAWC volume.

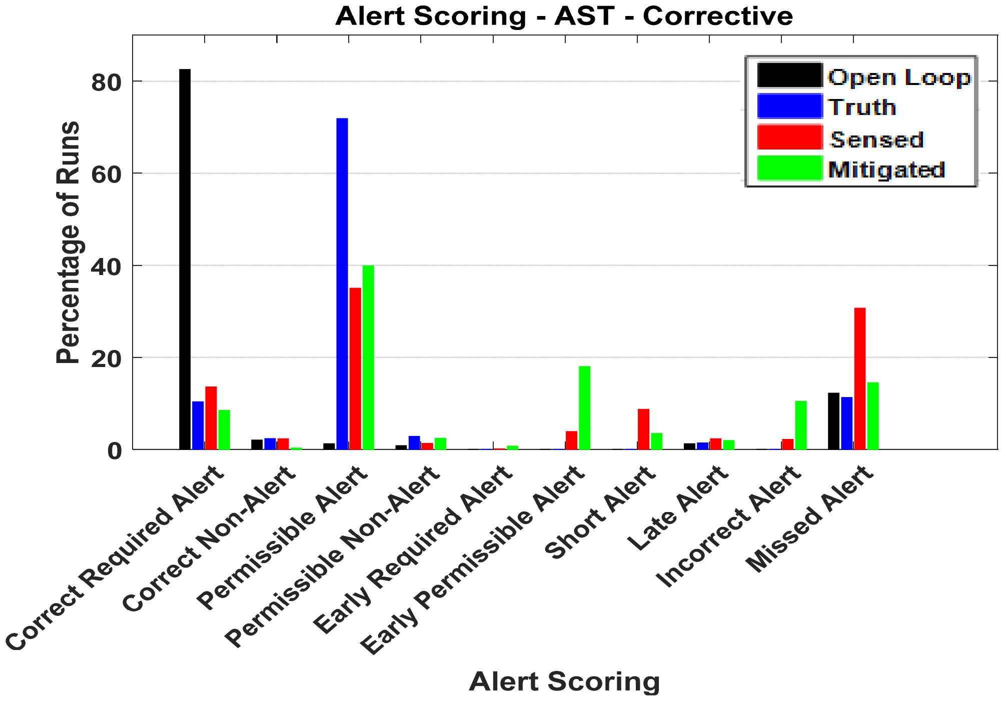

Figure 13. AST Corrective Alert Scoring for Combined Encounters

Figure 14 shows the normalized alert scoring distribution for ADS-B only runs. Similar to the other two sensors, the SUM approach increased the number of early permissible alerts and incorrect alerts. Interestingly, the SUM approach appeared to have no effect on the "Late Alert," the "Permissible Non-Alert," and the "Correct Non-Alert" responses.

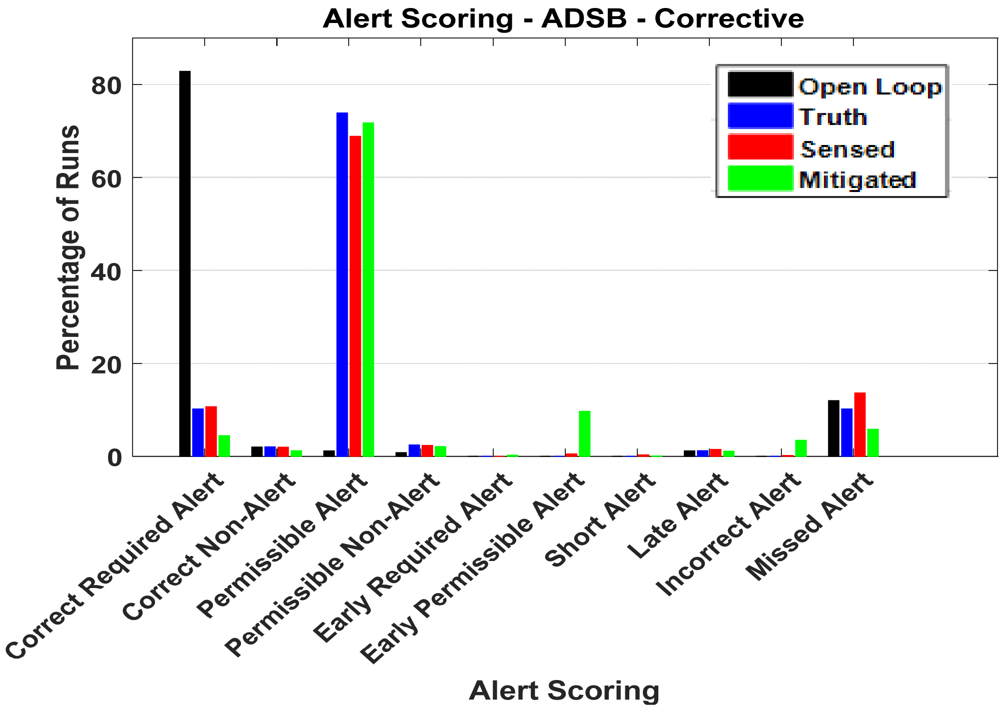

Figure 14. ADS-B Corrective Alert Scoring for Combined Encounters

4.2.2 Warning Alert Scoring

The following subsection contains figures with the normalized distribution of alert scoring for Warning Alerts for each single sensor configuration. In the majority of encounters a Corrective Alert was issued prior to the Warning Alert, Warning Alert being the highest level. Given sufficient time to respond, the pilot model will maneuver the ownship and avoid entering the HAZ zone of the Warning Alert. This behavior is presented in the following figures as the high percentage of correct non-alerts and permissible non-alerts, particularly the runs with Truth-based guidance and alerting.

Figure 15 shows the normalized distribution of alert scoring for radar-only runs for the Warning Alert level. Comparing Truth and Sensed distributions in Figure 15, sensed tracks resulted in 30% more missed alerts. Using the SUM approach, the missed alerts were reduced to below 20% of the runs. The SUM approach effectively increased the size of the avoidance region, which resulted in an increase in the number of incorrect alerts (i.e., the alerts provided to the pilot model even though the intruder remains in the HAZNot zone). The number of late alerts and short alerts were also reduced, while correct, permissible, and early permissible alerts increased as a result of the SUM approach.

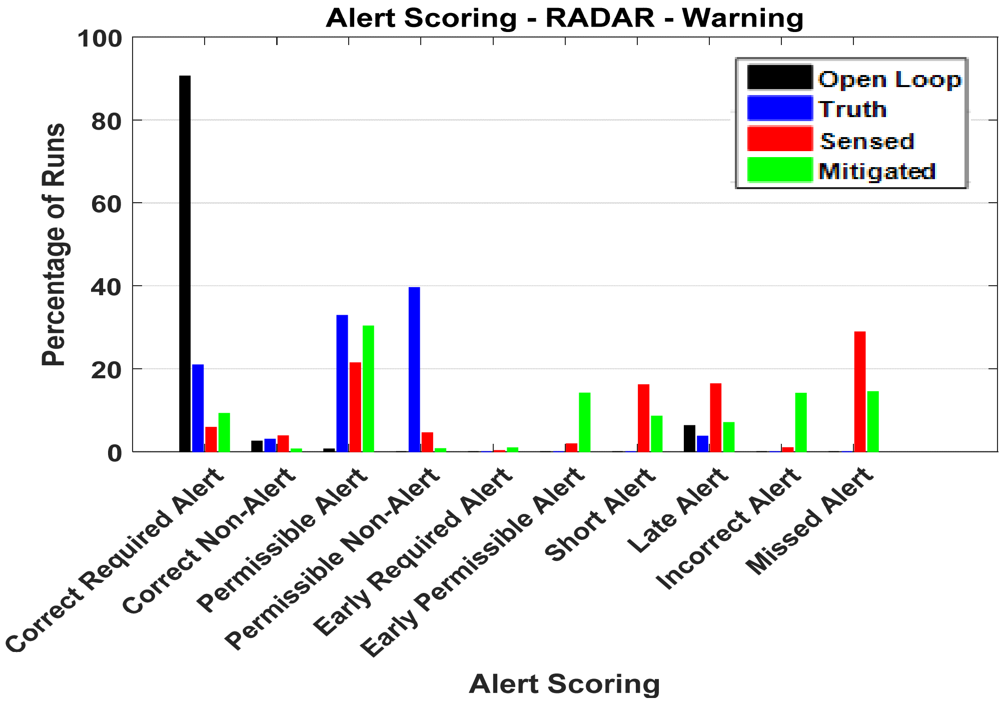

Figure 15. Radar Warning Alert Scoring for Combined Encounters

The Warning Alert scoring distribution is shown for AST equipped runs in Figure 16. Similar behavior can be seen in comparison to the radar results (Figure 15).

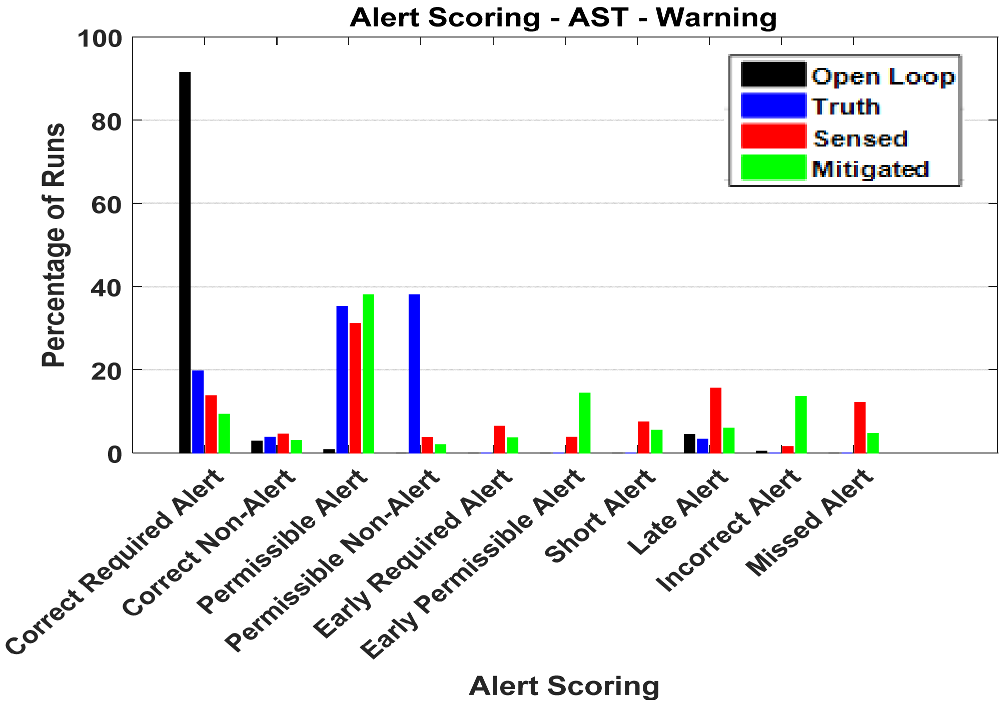

Figure 16. AST Warning Alert Scoring for Combined Encounters

Figure 17 shows results for the normalized distribution of Warning Alert scoring for the ADS-B-equipped runs. More than 80% of runs resulted in a Correct or Permissible Alert or Non-Alert, which are the most favorable alert scoring behaviors.

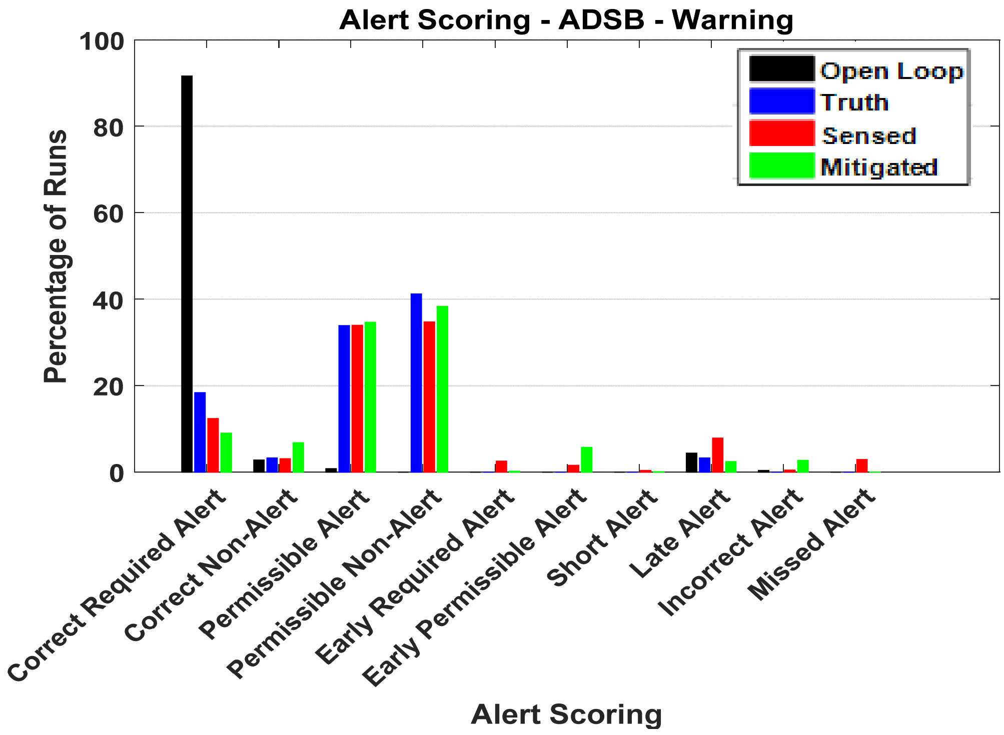

Figure 17. ADS-B Warning Alert Scoring for Combined Encounters

4.3 Alert Jitter – Open Loop

To determine the effect of sensor uncertainty and the SUM uncertainty mitigation approach on alert jitter, open loop distributions of alert jitter were analyzed and are presented in Figures 18, 19, and 20 for radar, AST, and ADS-B, respectively. Each figure in this subsection shows alert jitter as a function of the data source provided to the DAA guidance system with Truth runs shown in blue, Sensed runs shown in red, and Mitigated runs shown in green. The Alert Jitter measure is the number of increasing alert transitions experienced during an encounter scenario. For an encounter in which both aircraft are in steady flight conditions, the ideal alert jitter value is "2." An alert jitter value of "2" represents a transition from an initial alert state from <No Alert> to <Corrective Alert> to <Warning Alert>. High levels of alert jitter are considered a nuisance to the pilot in command, which may result in a lack of trust in the DAA system. There are no requirements associated with alert jitter presented in the DAA MOPS document, however consideration of this metric is important to the design of DAA systems.

In Figure 18 the alert jitter distribution of radar-based runs is shown. There are a large number of Truth runs (i.e., runs with guidance based on perfect state data) with an alert jitter of "2," as expected. There were a substantial number of Sensed runs with alert jitter of zero indicating that no alert was issued to the pilot-in-command (i.e., the pilot model) during the encounter, meaning the pilot model was given no cues indicating that there was a potential loss of separation. Compensating for sensor uncertainty using the SUM approach reduced the percentage of runs with no alert (alert jitter = 0) from 25% to 15%, while increasing the percentage of runs with the ideal alert jitter of "2" from 15% to 28%. Overall, the SUM approach is shown to change the sensed alert jitter distribution to be somewhat closer to the truth alert jitter distribution.

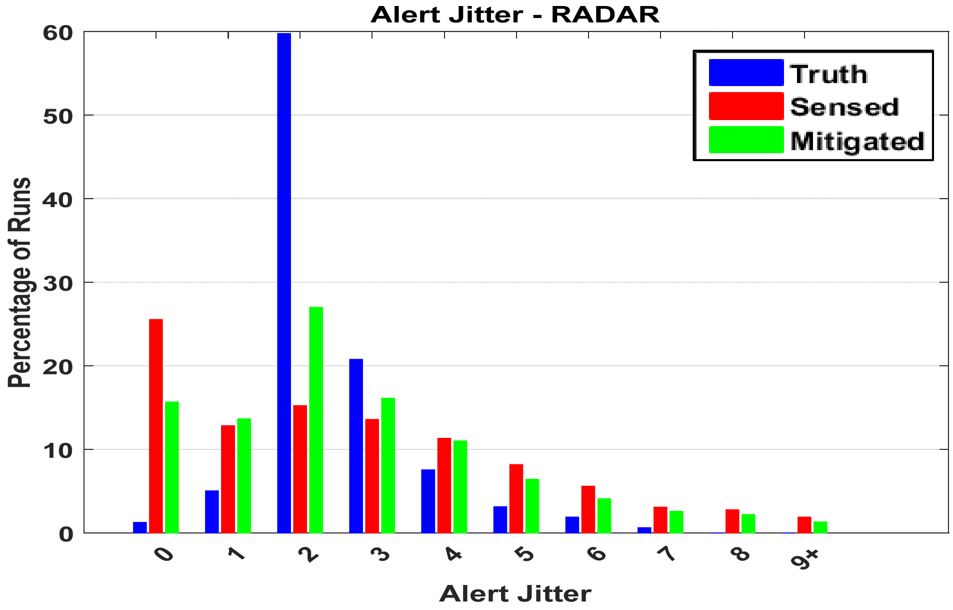

Figure 18. Open Loop Radar Alert Jitter for Combined Encounters

Figure 19 shows the normalized distribution of alert jitter for AST-equipped simulation runs. As previously discussed, a large proportion of Truth runs resulted in an alert jitter of "2." Relying on

AST as the only DAA sensor results in a wider range of alert jitter values. The SUM approach did not improve the distribution. It should be noted that the SUM approach was intended to address frequency and severity of losses of well clear, and a different approach to address alert jitter may be needed.

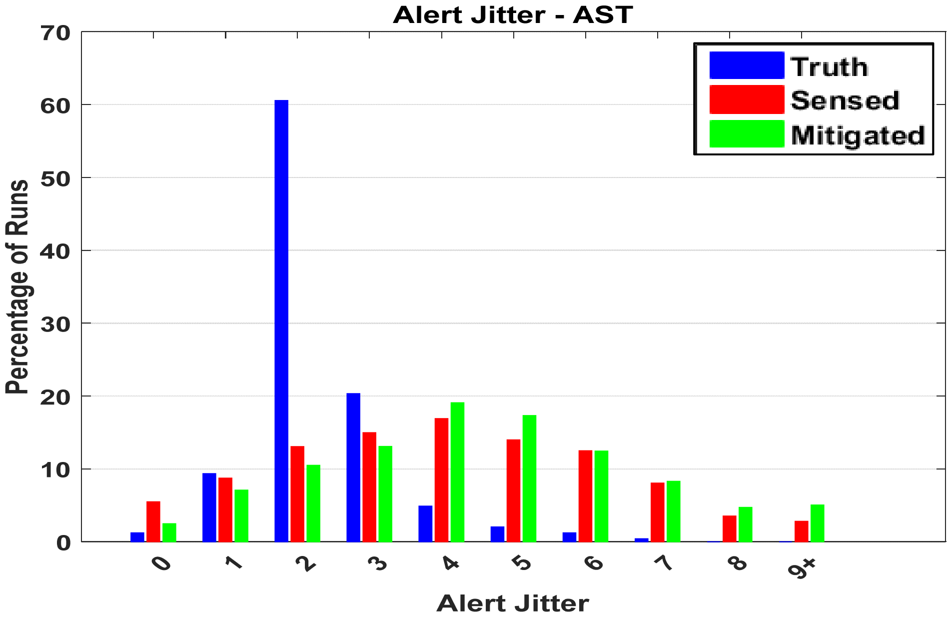

Figure 19. Open Loop AST Alert Jitter for Combined Encounters

The normalized alert jitter distribution for runs with ADS-B equipped is presented in Figure 20. This figure shows a tightly bound alert jitter distribution not only for truth but also for both sensed and mitigated ADS-B data sources provided to the DAA system. Although the ADS-B system is able to provide more accurate sensed intruder position and velocity information to the DAA system, there are still occurrences of alert jitter greater than “7” for the Mitigated runs. These high values of alert jitter are associated with perturbations in the vertical rate of ‘phantom’ intruders. Further filtering of the vertical rate covariance term may help to reduce the alert jitter in these cases.

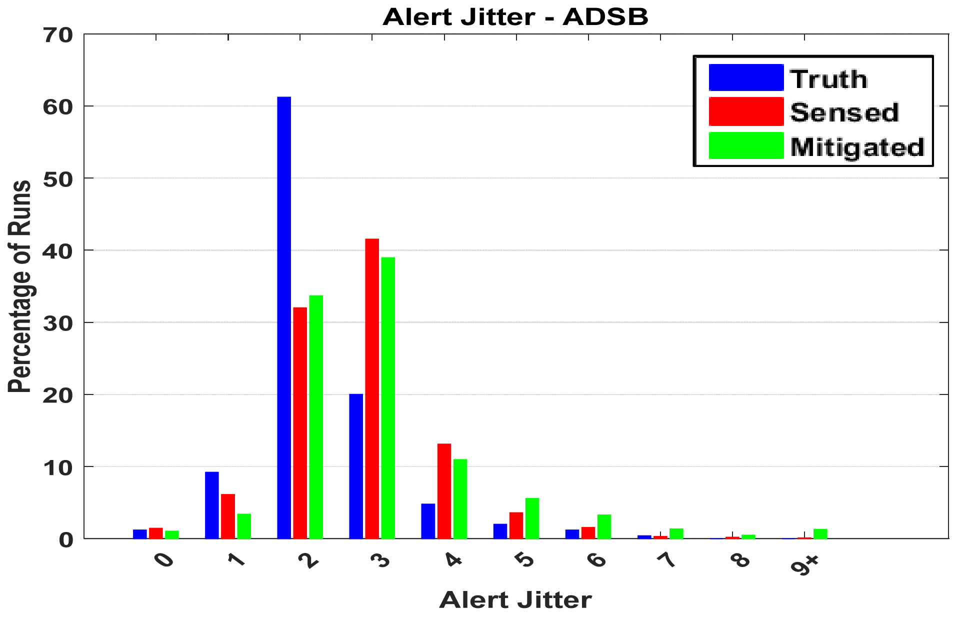

Figure 20. Open Loop ADS-B Alert Jitter for Combined Encounters

5. National Airspace System (NAS)-Derived Encounter Set Results

5.1 Correlated Encounters

5.1.1 Severity of Loss of Well Clear (SLoWC)

Figure 21 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.

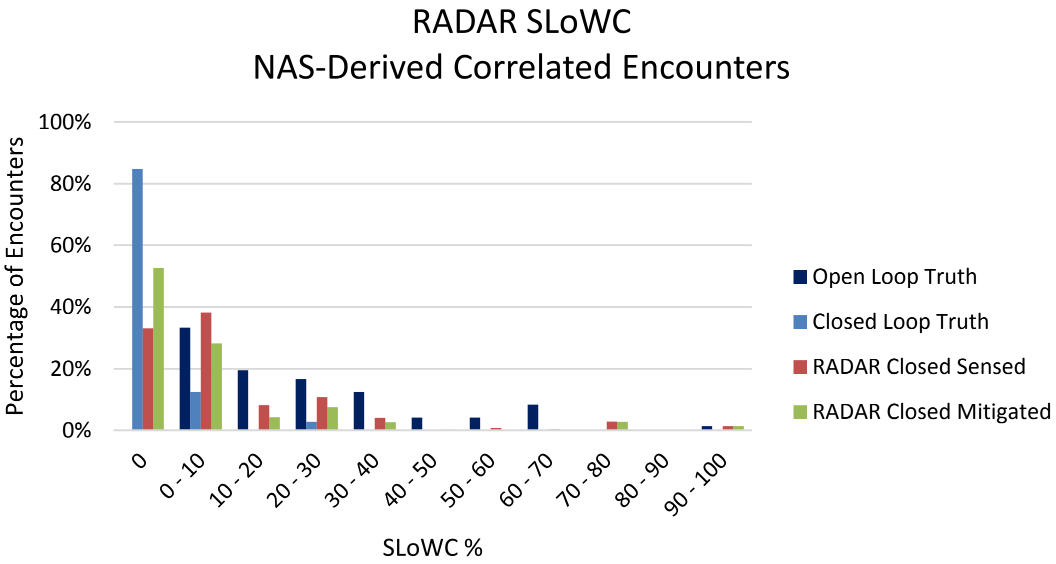

Figure 21. Radar SLoWC for NAS-Derived Correlated Encounters

Figure 22 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 23 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.

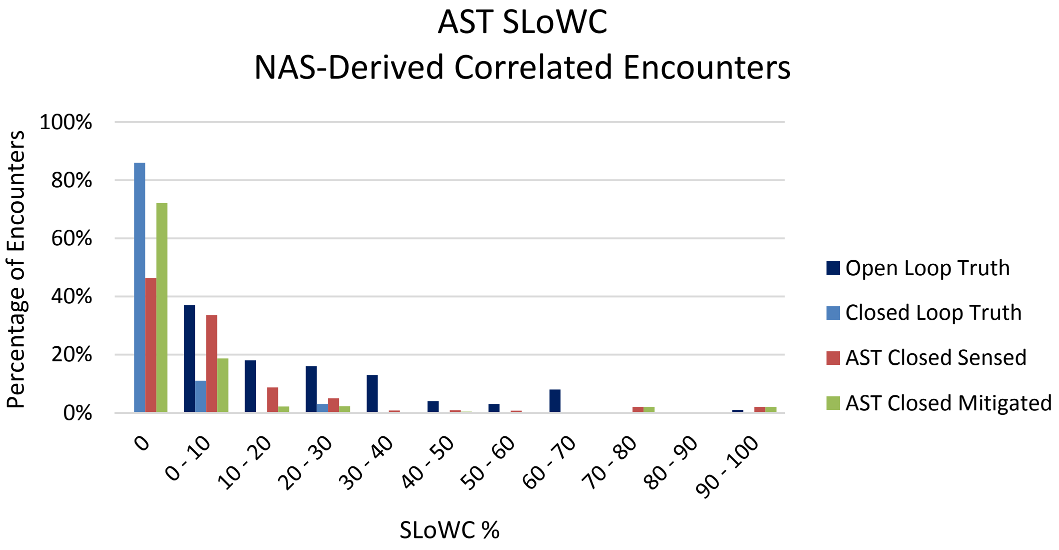

Figure 22. AST SLoWC for NAS-Derived Correlated Encounters

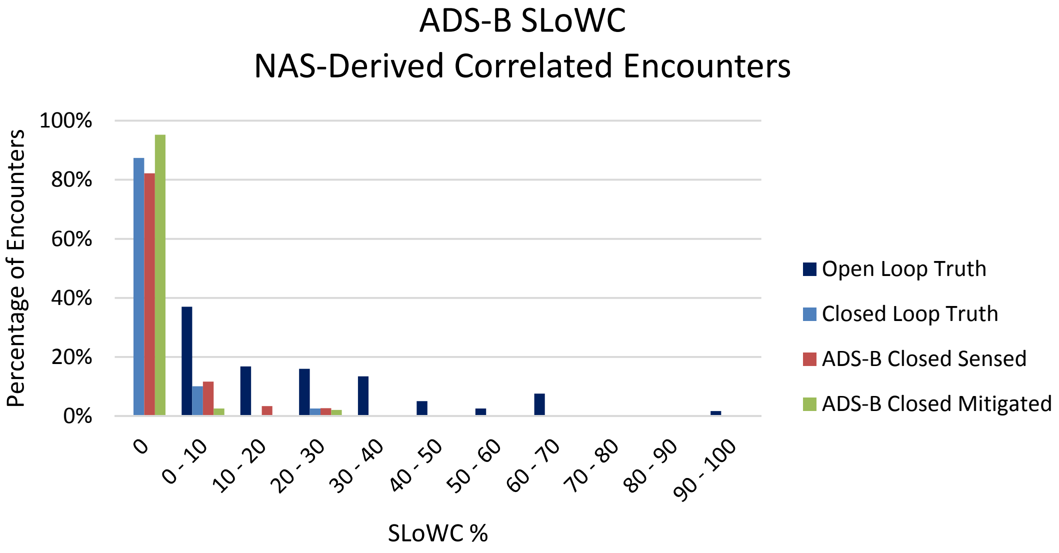

Figure 23. ADS-B SLoWC for NAS-Derived Correlated Encounters

5.1.2 Alert Scoring

5.1.2.1 Corrective Alert Scoring

Figure 24 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 25). Results for the ADS-B sensor (Figure 26) show that more than 80% of closed loop encounters were within the “Permissible Alert” criteria signifying better performance by the ADS-B sensor.

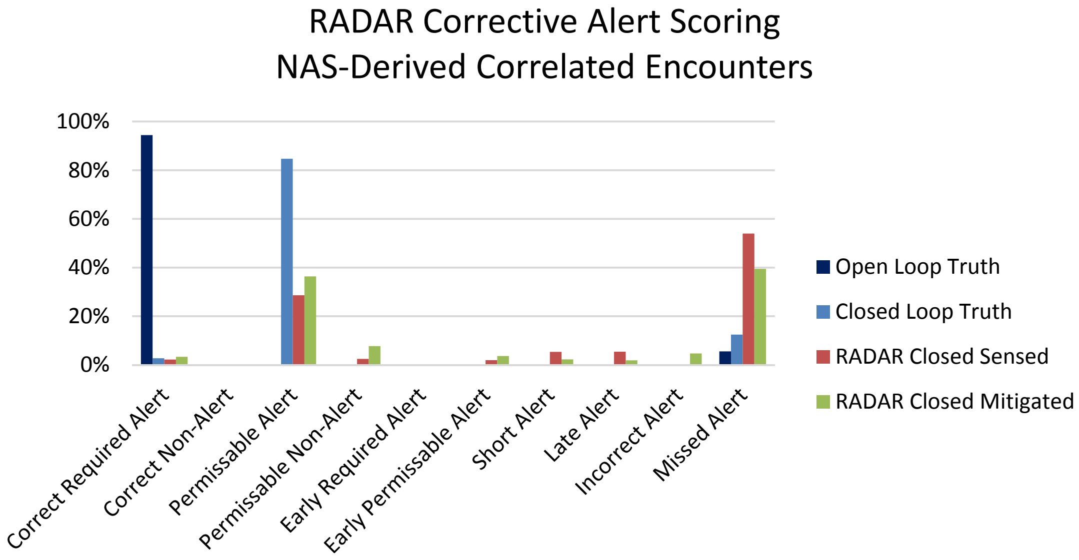

Figure 24. Radar Corrective Alert Scoring for NAS-Derived Correlated Encounters

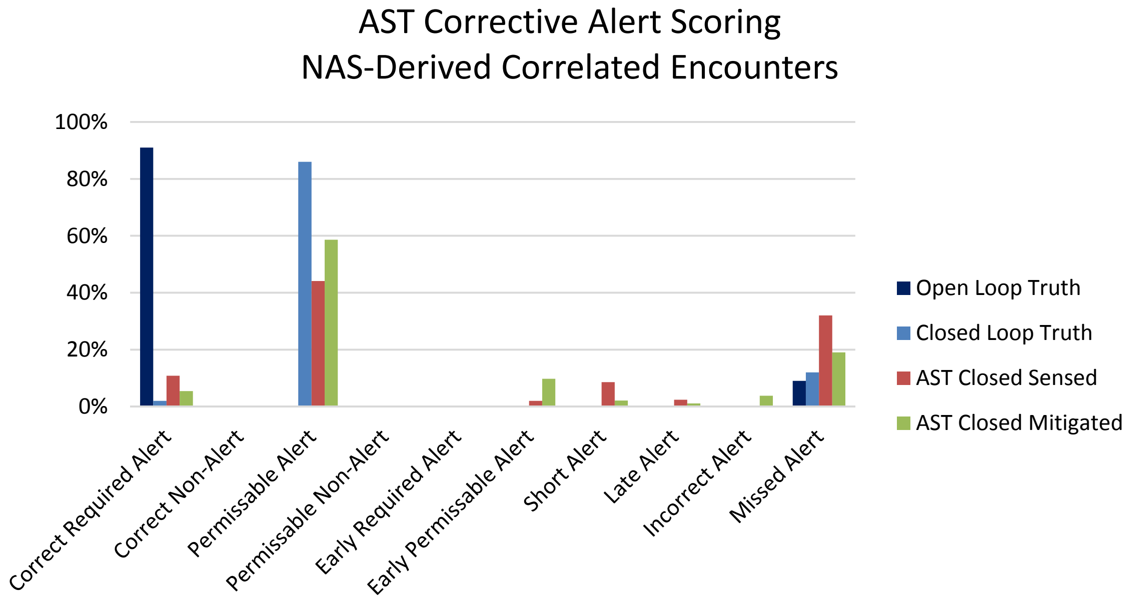

Figure 25. AST Corrective Alert Scoring for NAS-Derived Correlated Encounters

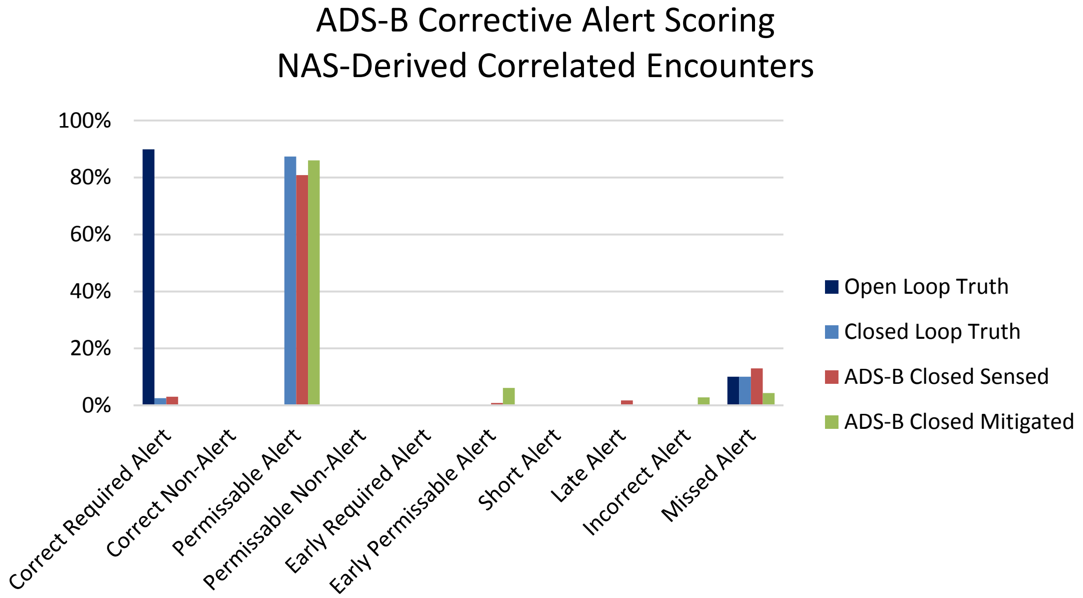

Figure 26. ADS-B Corrective Alert Scoring for NAS-Derived Correlated Encounters

5.1.2.2 Warning Alert Scoring

A histogram of the warning alert scoring as a function of the radar sensor is shown in Figure 27. 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.

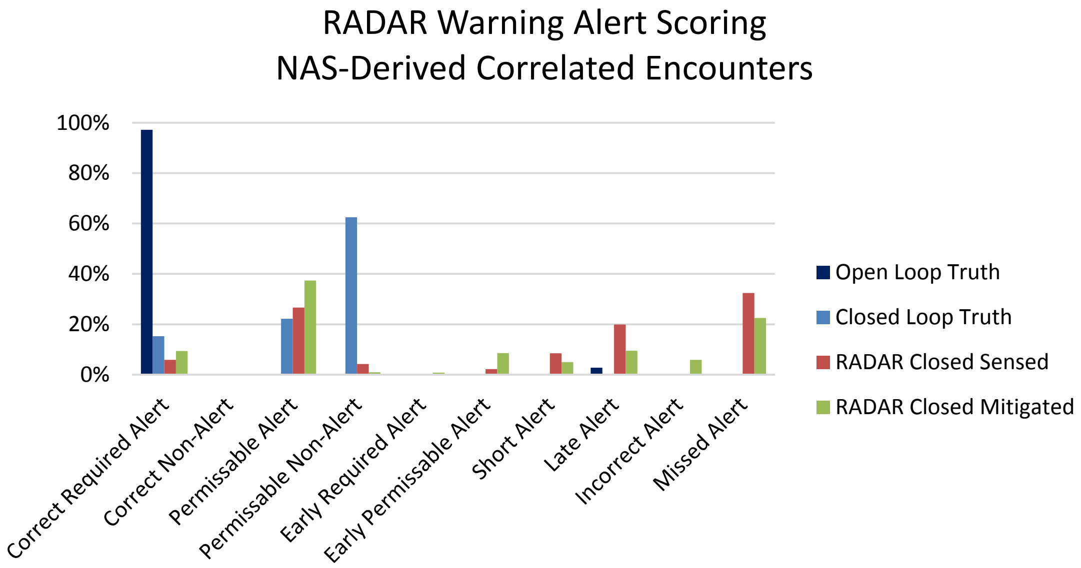

Figure 27. Radar Warning Alert Scoring for NAS-Derived Correlated Encounters

Result trends for encounters using the AST sensor (Figure 28) were similar to the radar sensor results.

Results 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.

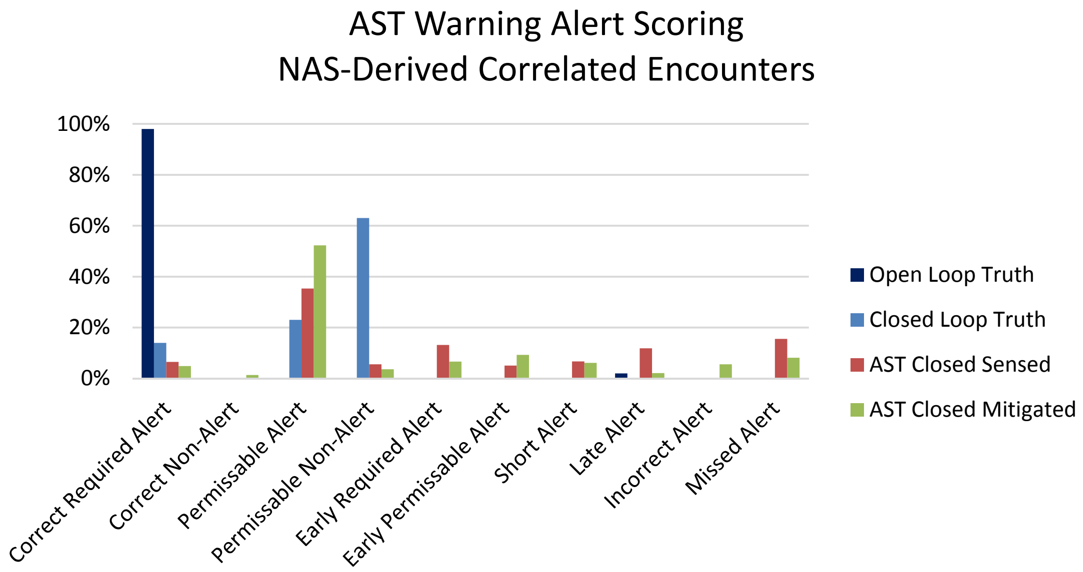

Figure 28. AST Warning Alert Scoring for NAS-Derived Correlated Encounters

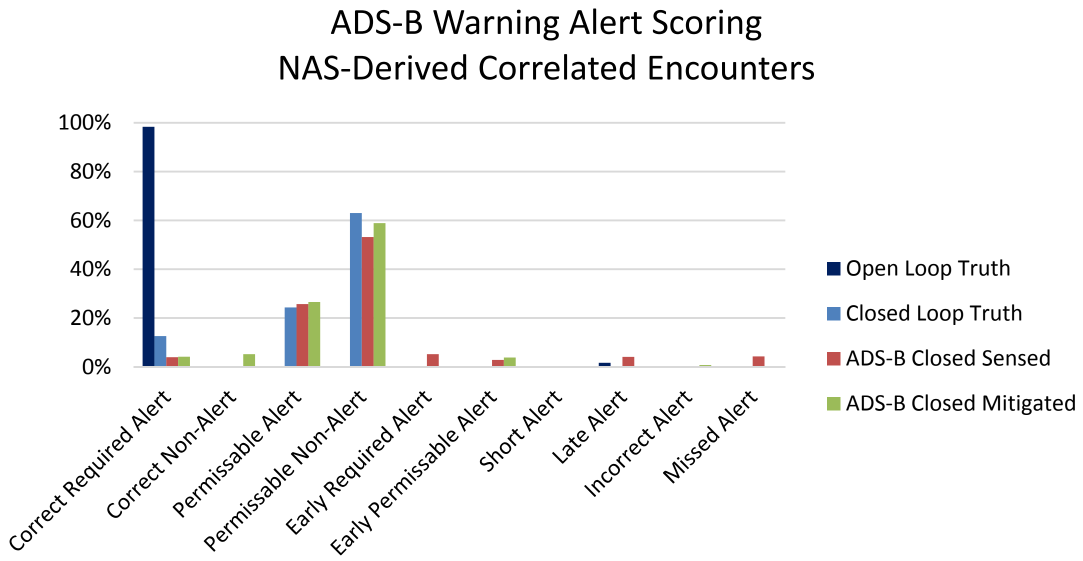

Figure 29. ADS-B Warning Alert Scoring for NAS-Derived Correlated Encounters

5.1.3 Alert Jitter

An alert jitter histogram is shown in Figure 30 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.

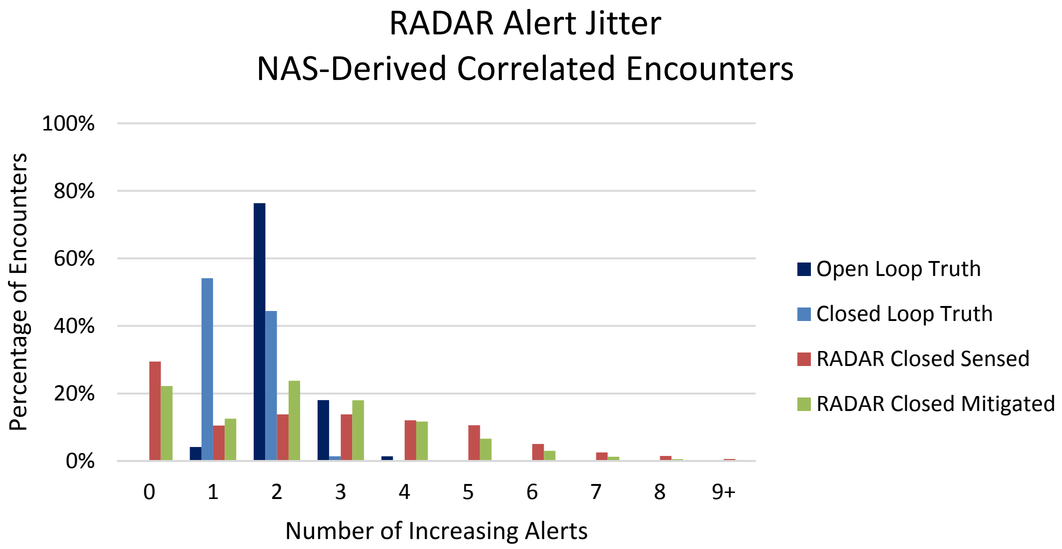

Figure 30. Radar Alert Jitter for NAS-Derived Correlated Encounters

Findings for encounters using the AST sensor (Figure 31) shows that Sensed and Mitigated guidance performed at comparable percentages among all the alert jitter values.

Results for the ADS-B sensor (Figure 32) 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.

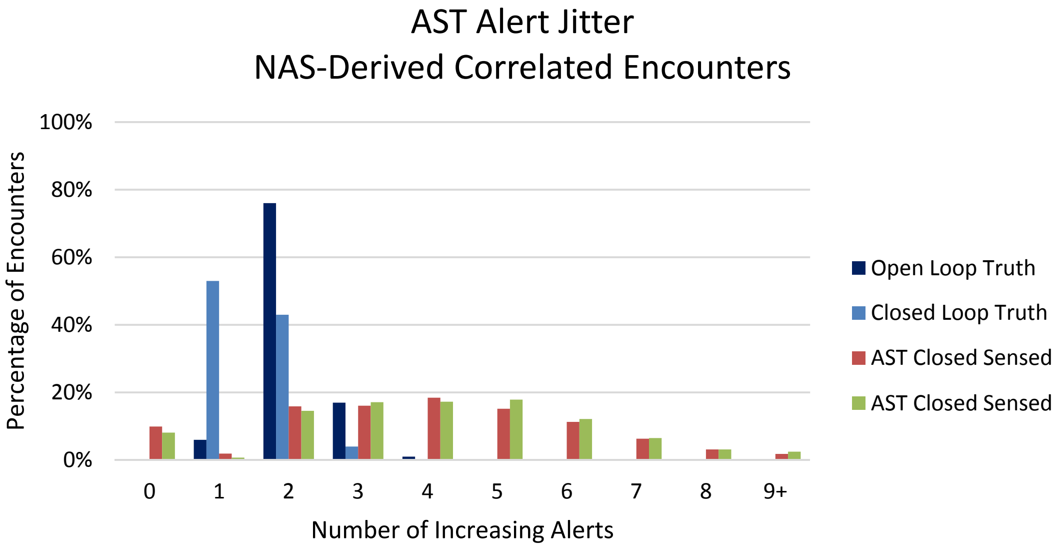

Figure 31. AST Alert Jitter for NAS-Derived Correlated Encounters

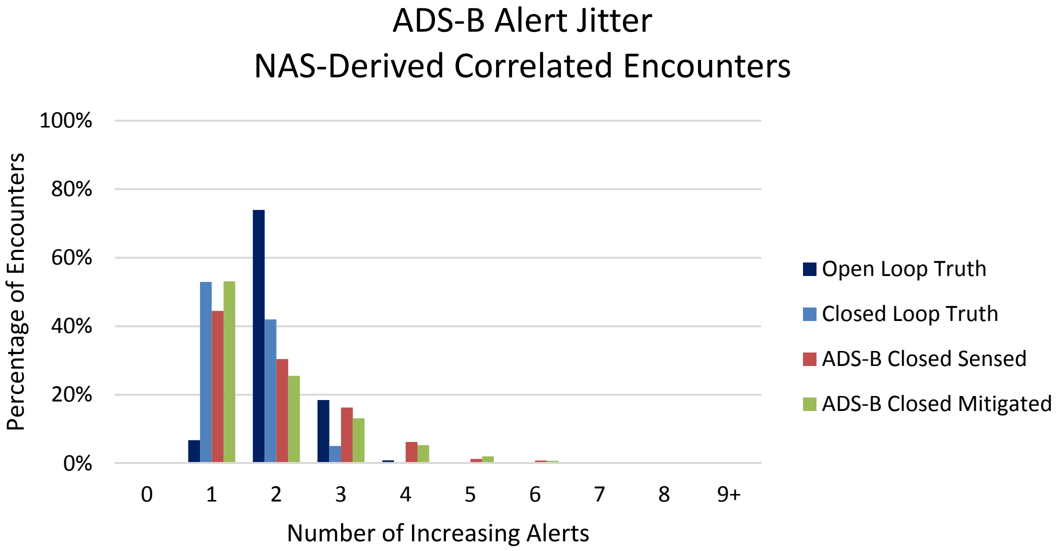

Figure 32. ADS-B Alert Jitter for NAS-Derived Correlated Encounters

5.2 Uncorrelated Encounters

5.2.1 Severity of Loss of Well Clear (SLoWC)

Figure 33 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.

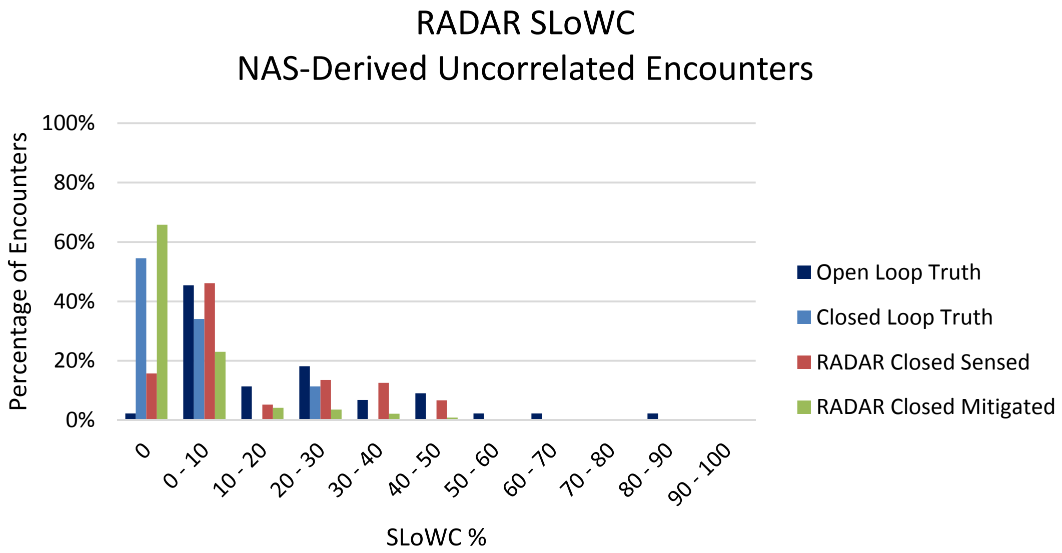

Figure 33. Radar SLoWC for NAS-Derived Uncorrelated Encounters

Figure 34 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.

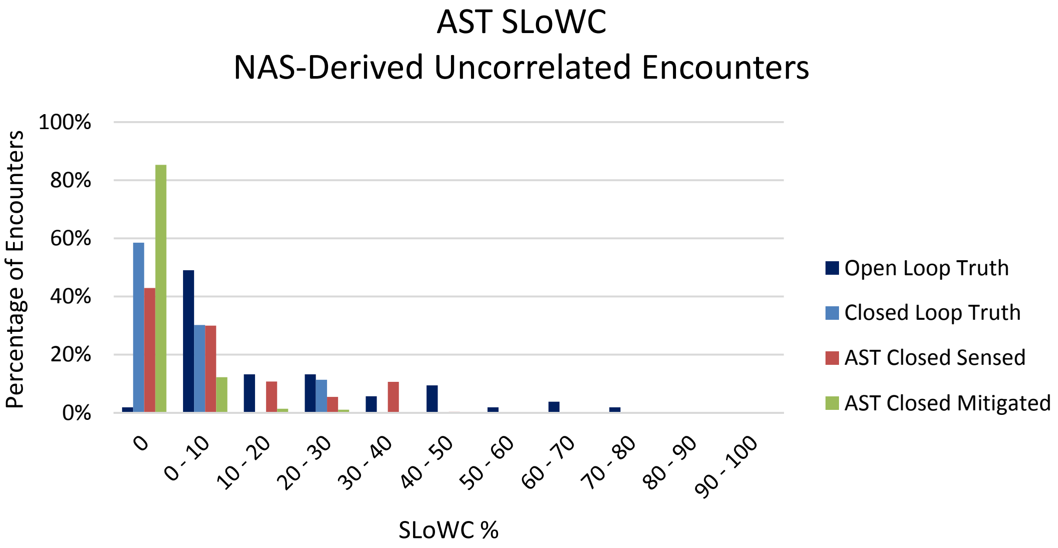

Figure 34. AST SLoWC for NAS-Derived Uncorrelated Encounters

Figure 35 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.

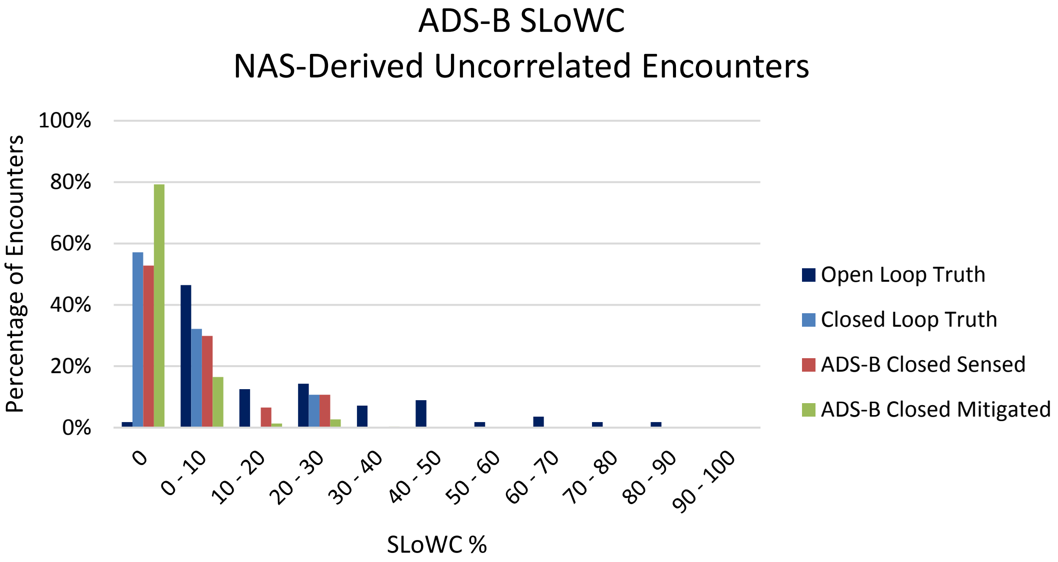

Figure 35. ADS-B SLoWC for NAS-Derived Uncorrelated Encounters

5.2.2 Alert Scoring

5.2.2.1 Corrective Alert Scoring

Figure 36 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%.

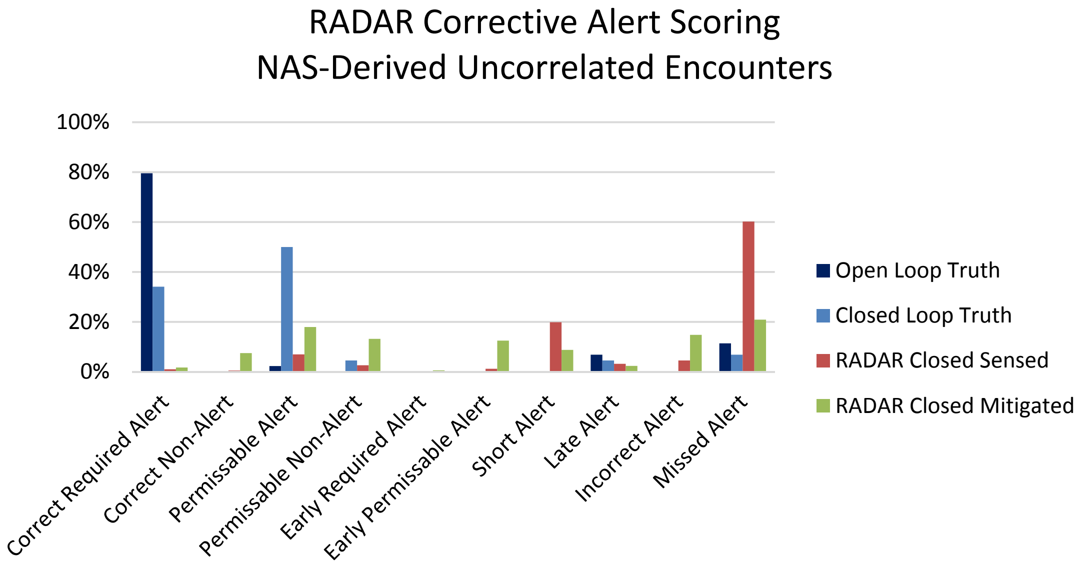

Figure 36. Radar Corrective Alert Scoring for NAS-Derived Uncorrelated Encounters

Figure 37 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.

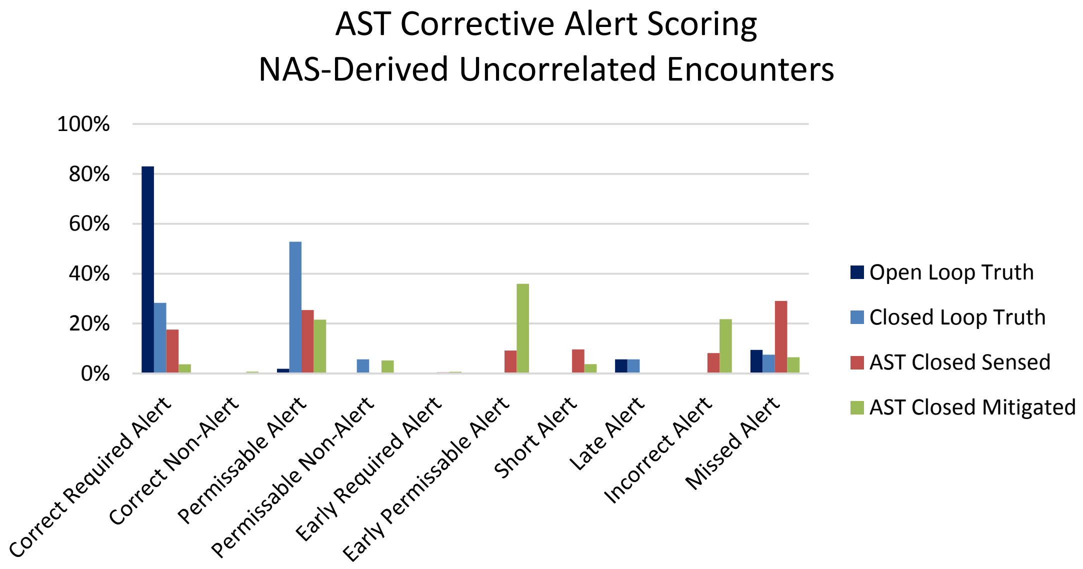

Figure 37. AST Corrective Alert Scoring for NAS-Derived Uncorrelated Encounters

Results for the ADS-B sensor are shown in Figure 38. 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.

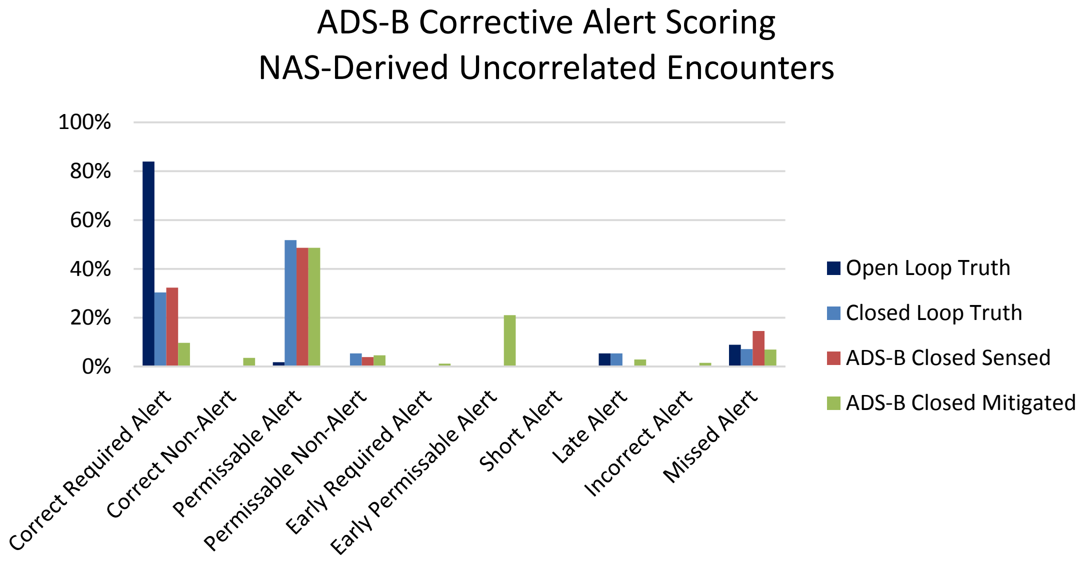

Figure 38. ADS-B Corrective Alert Scoring for NAS-Derived Uncorrelated Encounters

5.2.2.2 Warning Alert Scoring

Figure 39 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.

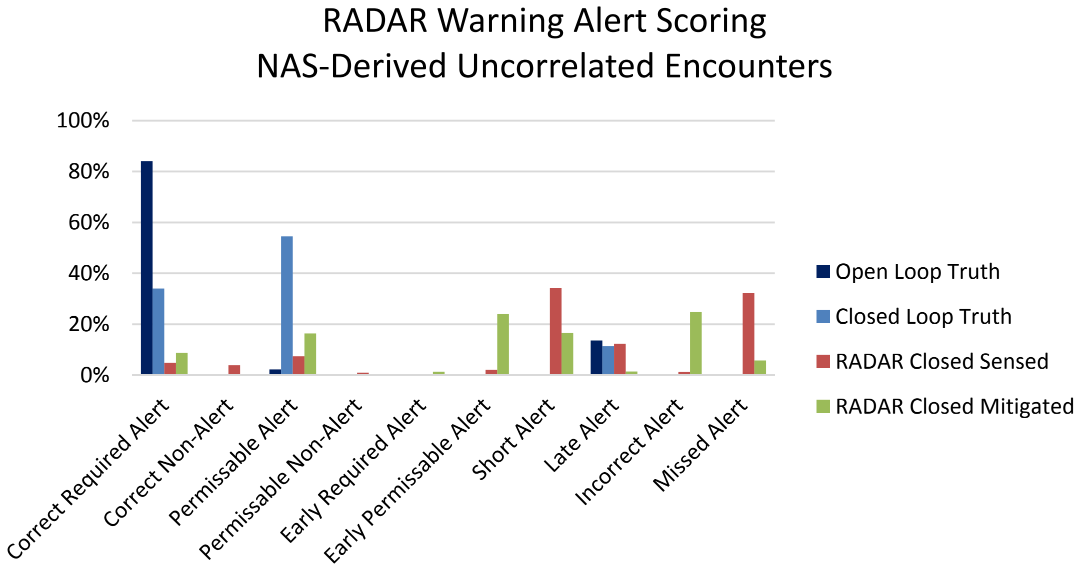

Figure 39. Radar Warning Alert Scoring for NAS-Derived Uncorrelated Encounters

Figure 40 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.

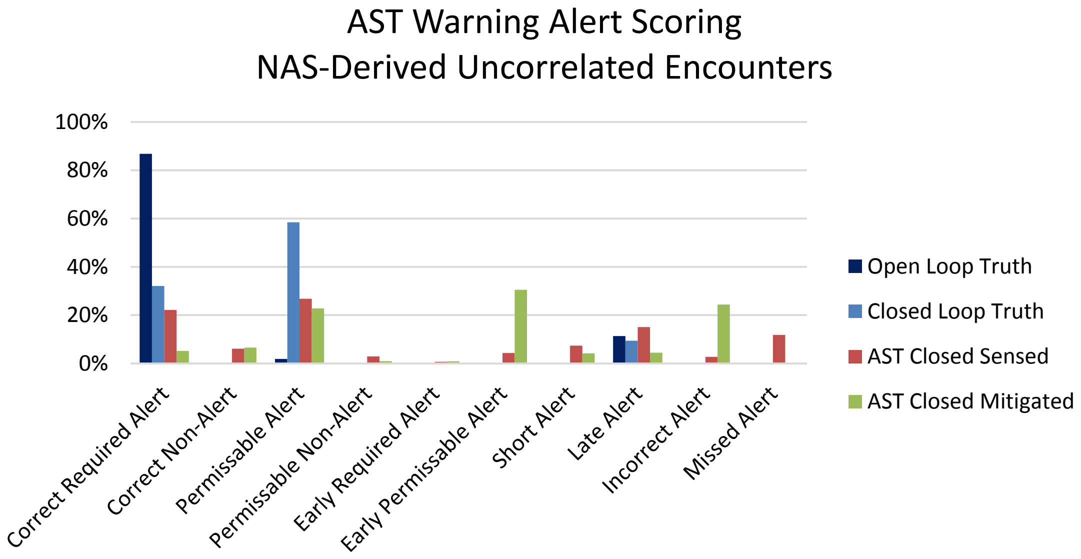

Figure 40. AST Warning Alert Scoring for NAS-Derived Uncorrelated Encounters

Results for the ADS-B sensor are shown in Figure 41. 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.

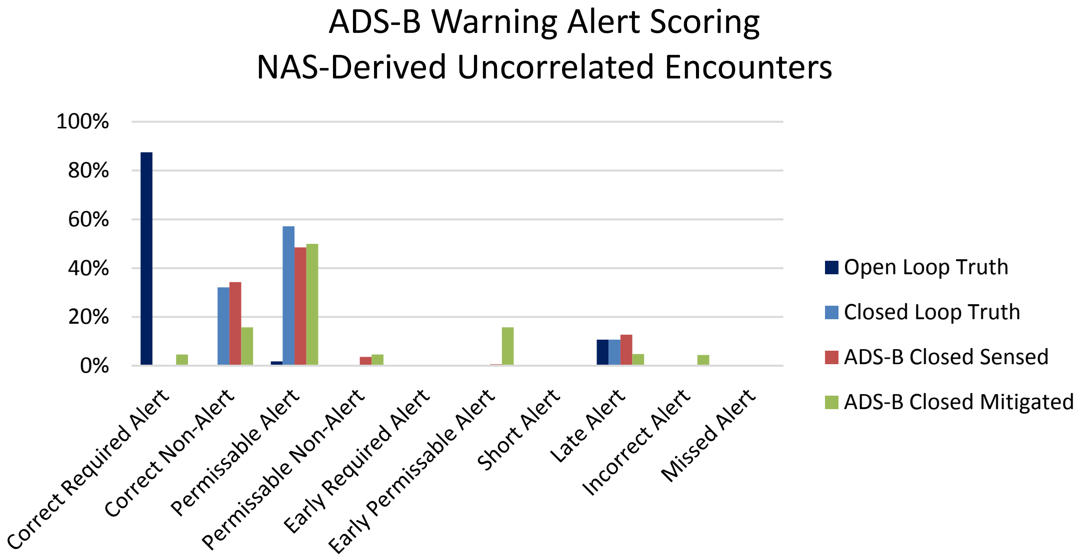

Figure 41. ADS-B Warning Alert Scoring for NAS-Derived Uncorrelated Encounters

5.2.3 Alert Jitter

Figures 42 through 44 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 more in Section 3.2.3 and at the beginning of Section 4.3.

Figure 42 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.

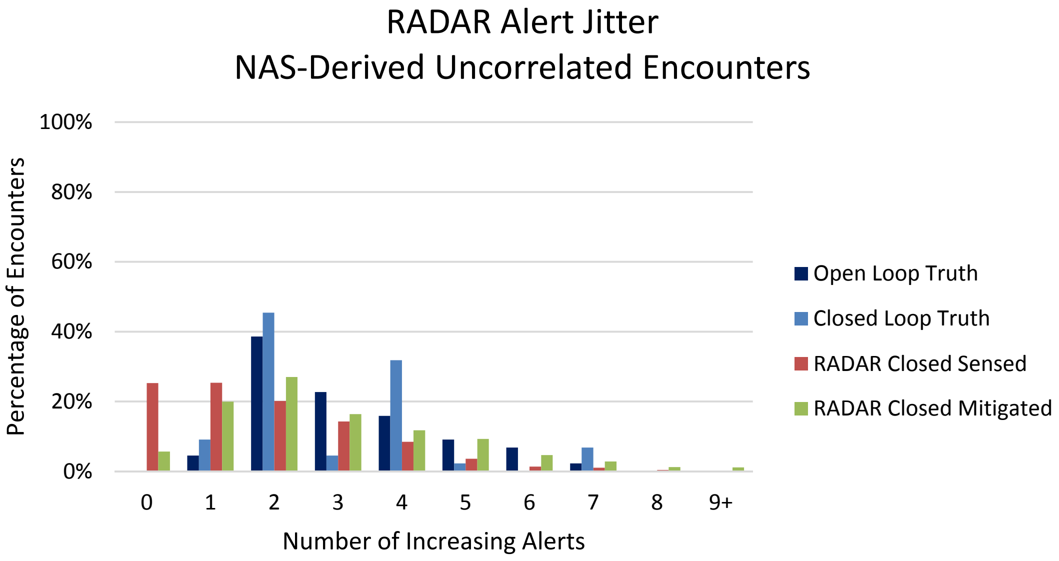

Figure 42. Radar Alert Jitter for NAS-Derived Uncorrelated Encounters

Results for the AST sensor (Figure 43) and ADS-B sensor (Figure 44) 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.

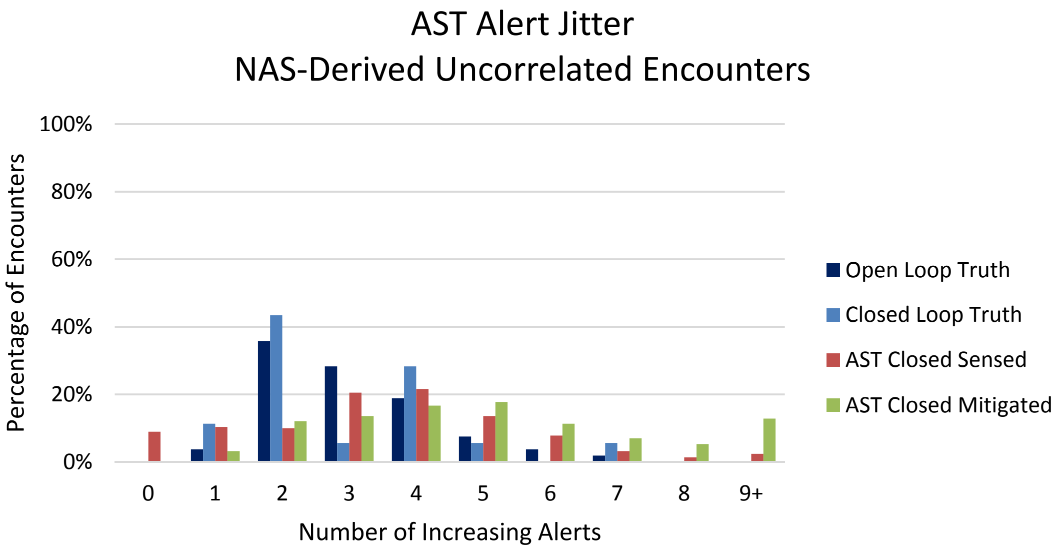

Figure 43. AST Alert Jitter for NAS-Derived Uncorrelated Encounters

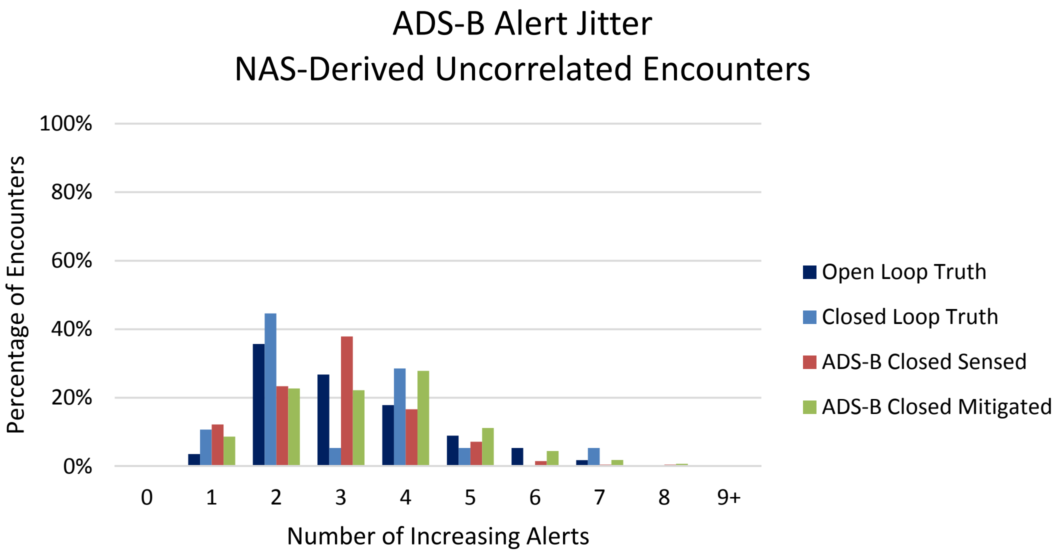

Figure 44. ADS-B Alert Jitter for NAS-Derived Uncorrelated Encounters

6. MOPS Requirement-Derived Test Vectors Results

As expected, overall performance of the MOPS-representative DAA system in both the Sensed and Mitigated cases was similar to the closed-loop Truth cases. For comparison, results of open loop runs – with no avoidance maneuvers – are also shown alongside the closed loop results. See Section 3.1.2 for an explanation of the MOPS requirement-derived test vectors.

6.1 Severity of Loss of Well Clear (SLoWC)

6.1.1 Radar SLoWC

Figures 45 through 48 show SLoWC histograms for the radar guidance source in a closed loop simulation using MOPS Requirement-Derived test vectors.

Results for Head-On test vectors (Figure 45) show that in cases using Truth closed loop data for guidance, the ownship was always able to remain well clear from other aircraft (0% SLoWC). However, 1/3 of those same cases would have resulted in a mid-air collision (MAC) or near mid-air collision (NMAC) without the DAA system and pilot maneuvers (Open Loop Truth, 90-100% SLoWC). SLoWC performance for closed loop Sensed radar guidance was similar to closed loop Mitigated guidance, both of which are not far from performance for Truth data.

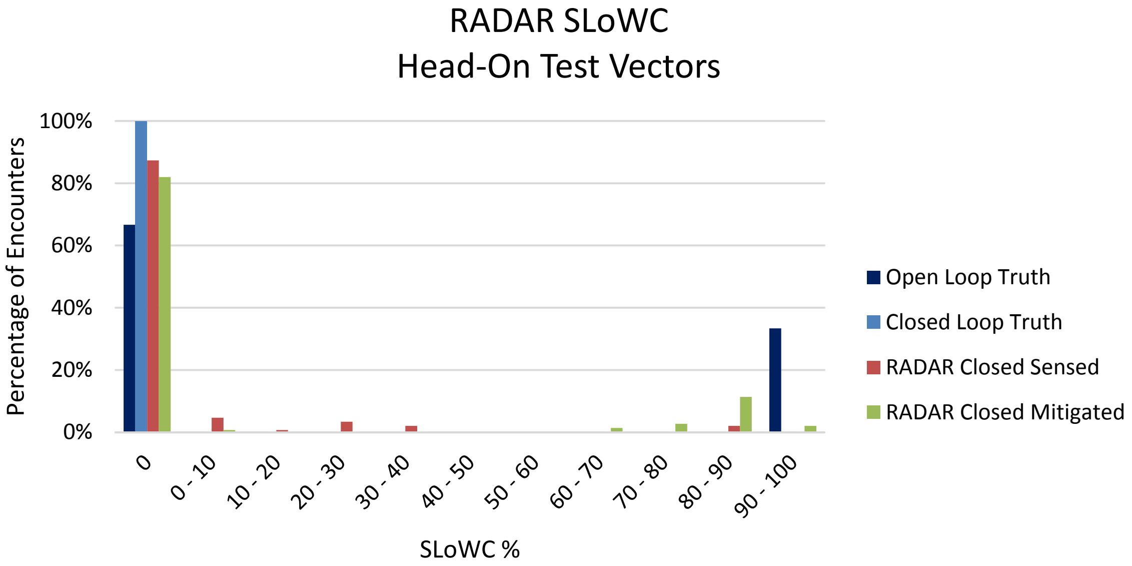

Figure 45. Radar SLoWC for Head-On MOPS Requirement-Derived Test Vectors

Similarly, results for Converging test vectors (Figure 46) show that in cases using closed loop Truth data for guidance, the ownship was always able to remain well clear from other aircraft (0% SLoWC). One-third of those same cases, though, would have resulted in a MAC or NMAC without the DAA system and pilot maneuvers (Open Loop Truth, 90-100% SLoWC). Also, as with the Head-On Test Vectors, for the Converging Test Vectors performance with Sensed and Mitigated guidance spread out the distribution somewhat, slightly reducing the number of encounters remaining well clear (0% SLoWC) and slightly increasing those with values between 0 and 60.

Note that the DAA system was able to keep all Converging encounters using Sensed or Mitigated guidance below 60% SLoWC.

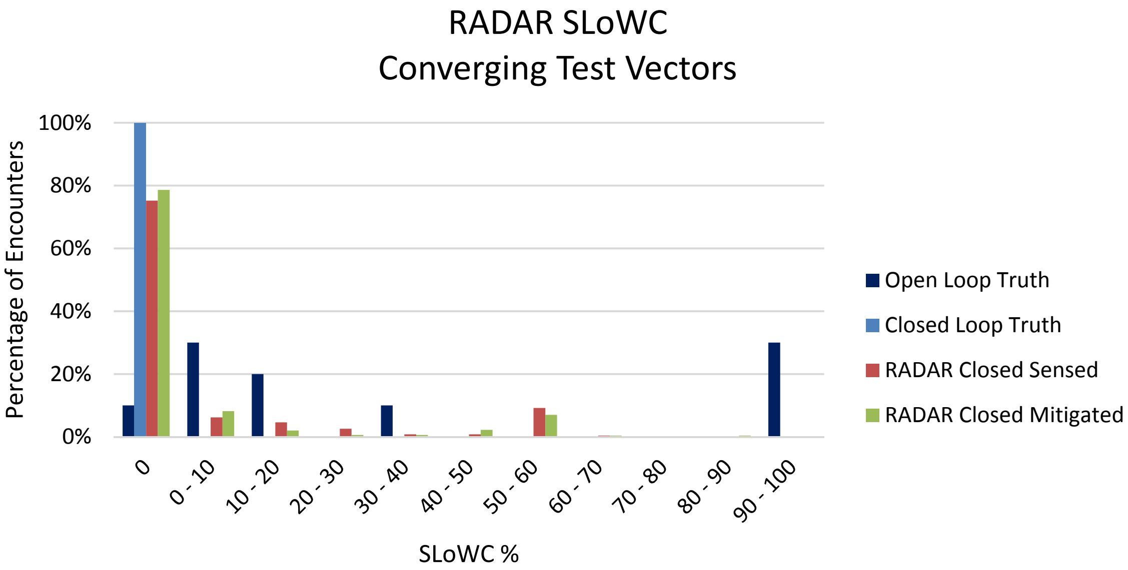

Figure 46. Radar SLoWC for Converging MOPS Requirement-Derived Test Vectors

Results for Maneuvering test vectors (Figure 47) show that the ownship lost DAAWC in all encounters, regardless of the source of guidance data, even Truth. Performance remained consistent across all four cases (open Truth, closed Truth, Sensed, and Mitigated) with 50% of encounters having a SLoWC between 0% and 10%. The other half of the closed loop Truth encounters resulted in a 30-40% SLoWC. Note that the other half of both the Sensed and Mitigated encounters resulted in lower severity scores (10%-20%), likely because the sensor uncertainty caused the pilot model to maneuver earlier than when using Truth guidance.

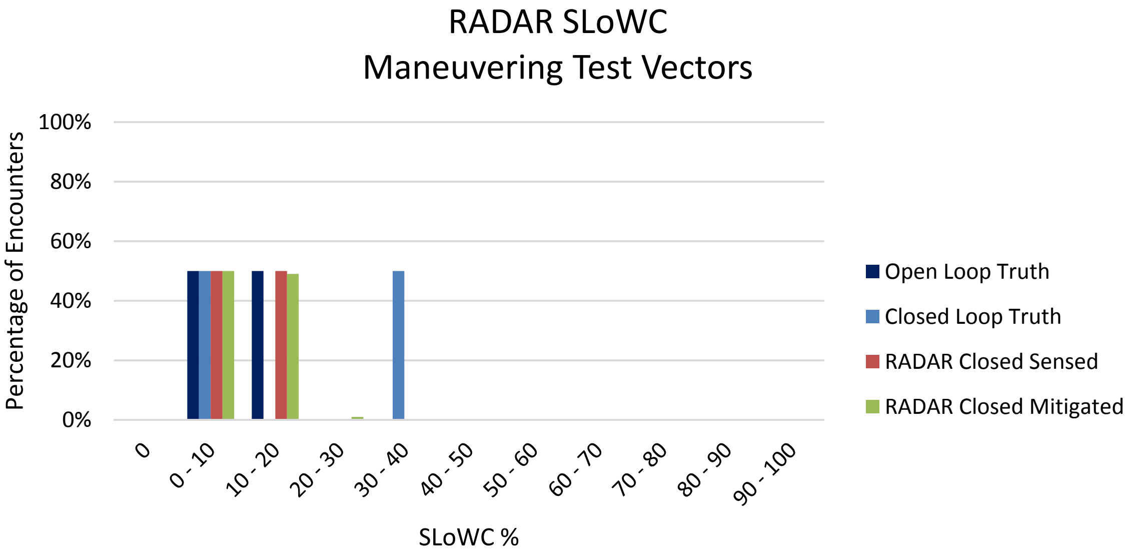

Figure 47. Radar SLoWC for Maneuvering MOPS Requirement-Derived Test Vectors

Figure 48 shows results for Overtake test vectors using radar data for guidance. The closed loop system resulted in 100% of encounters being within the 0% SLoWC range when Truth guidance was used. Open loop Truth results show 67% of encounters were within this SLoWC range and the remaining 33% of encounters were within the 20-30% SLoWC range. Overtake encounters using the radar sensor scored better in comparison to the other encounter geometries, which can be attributed to the radar's field of regard specifications enabling it to always detect the intruder because the ownship is overtaking, or approaching, the other aircraft from behind.

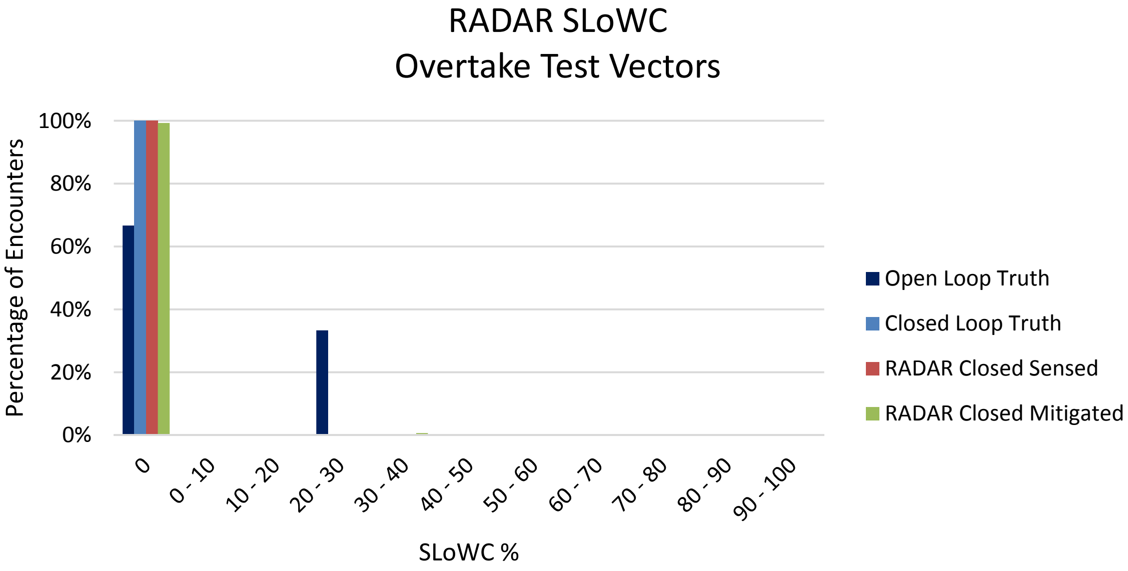

Figure 48. Radar SLoWC for Overtake MOPS Requirement-Derived Test Vectors

6.1.2 Active Surveillance Transponder (AST) SLoWC

Figures 49 through 53 show SLoWC histograms for the AST guidance source used in a closed loop simulation for MOPS Requirement-Derived test vectors.

Results for Head-On test vectors (Figure 49) show that the DAA system resulted in no losses of well clear for all encounters using Truth guidance. Sensed and Mitigated guidance encounters, however, were spread out across the entire range of SLoWC values, with performance similar to each other and to the open loop Truth results.

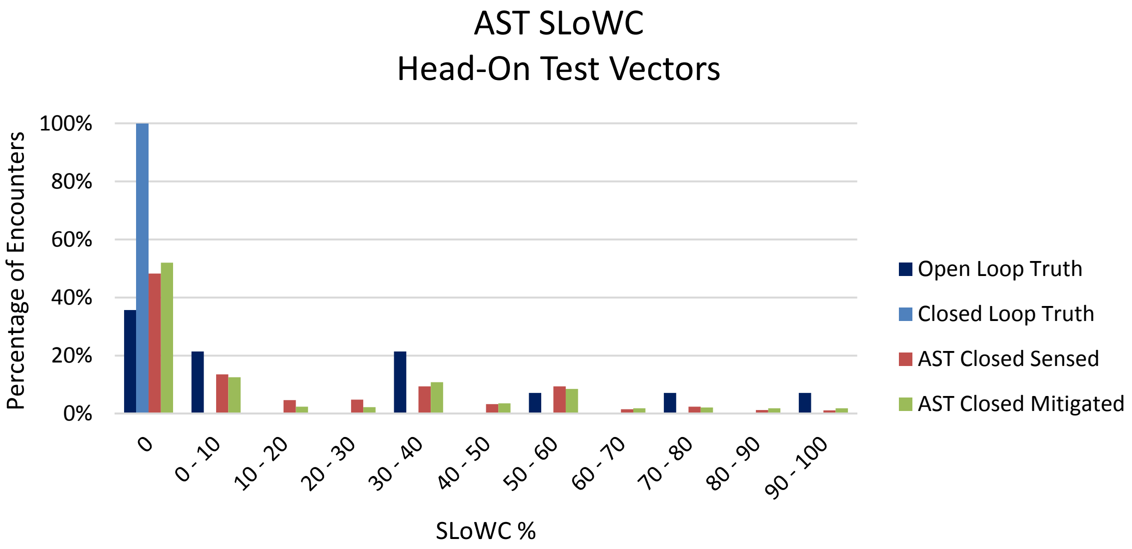

Figure 49. AST SLoWC for Head-On MOPS Requirement-Derived Test Vectors

Similarly, results for Converging test vectors (Figure 50) show that the DAA system resulted in 0% SLoWC for all encounters using Truth guidance. Sensed and Mitigated results were also spread out, but to only part of the SLoWC range. The SUM approach enabled the DAA system to pull the distribution to the left, eliminating all SLoWC values above 50% and increasing the number of well clear encounters to 79%.

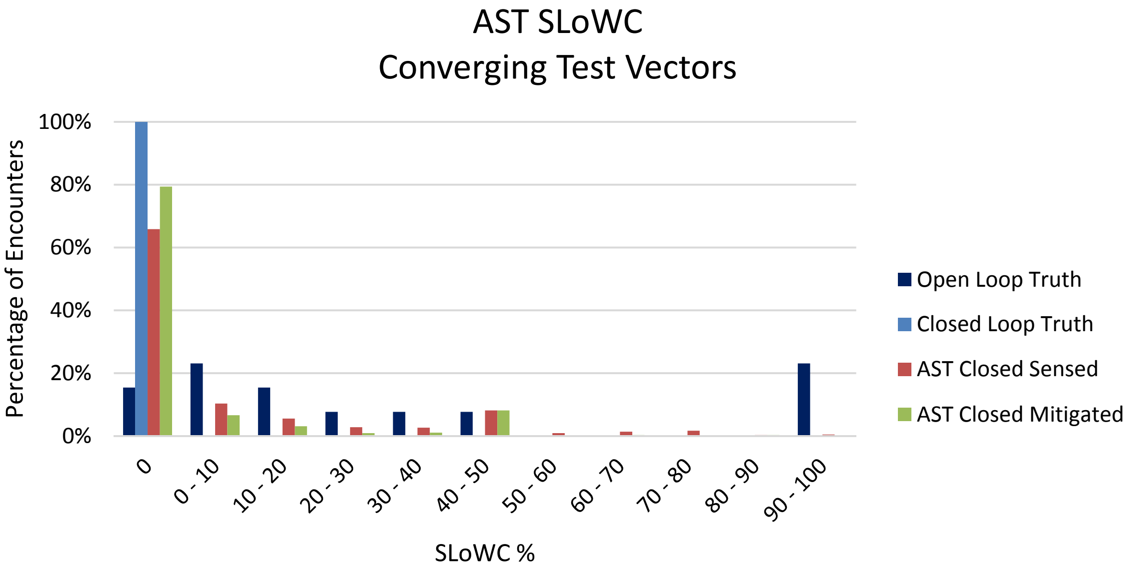

Figure 50. AST SLoWC for Converging MOPS Requirement-Derived Test Vectors

Figure 51 shows results for High Speed test vectors. Open loop Truth results show that all of these High Speed encounters would have some loss of well clear without any maneuvering to avoid it, including a significant portion (25%) having a SLoWC value close to 100%. Truth guidance in the closed loop system resulted in all encounters having 0% SLoWC. Both Sensed and Mitigated guidance spread the distribution out across essentially the entire range of SLoWC, but Mitigated guidance shows the SUM approach was able to keep 80% of the encounters well clear (SLoWC of 0%), and increase of 17% over Sensed guidance.

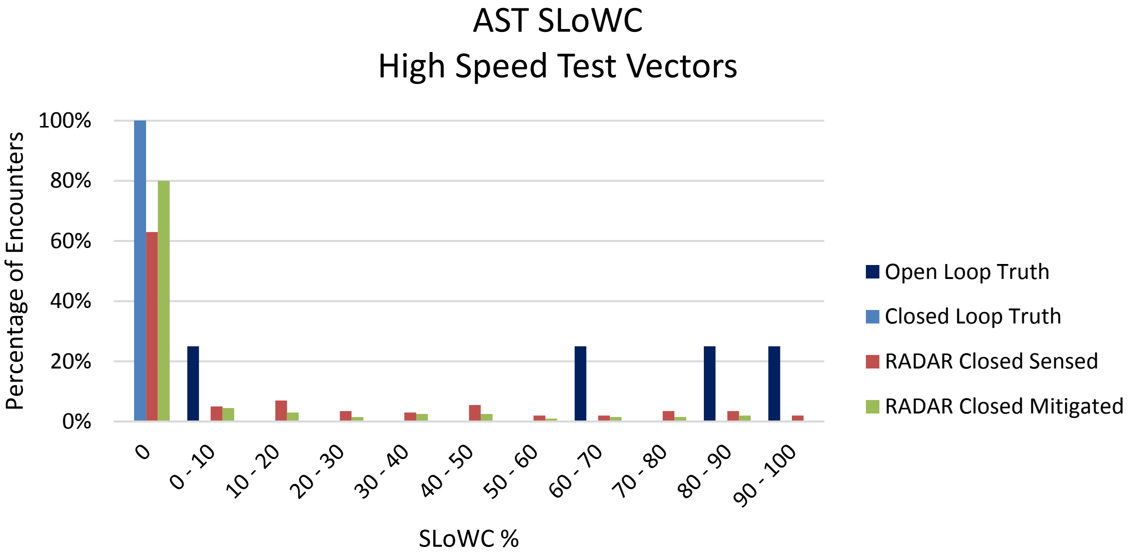

Figure 51. AST SLoWC for High-Speed MOPS Requirement-Derived Test Vectors

Figure 52 shows results for Maneuvering test vectors using the AST sensor. Open loop Truth results show that all of the encounters would result in some loss of well clear, and the DAA system was able to prevent loss of well clear in only small portions of all maneuvering (closed loop) cases. However, the Mitigated approach had the highest percentage of encounters with no loss of well clear (33.86%). Overall, the DAA system performed least favorably in the Maneuvering encounters using the AST sensor in comparison to the other encounter geometries and sensors.

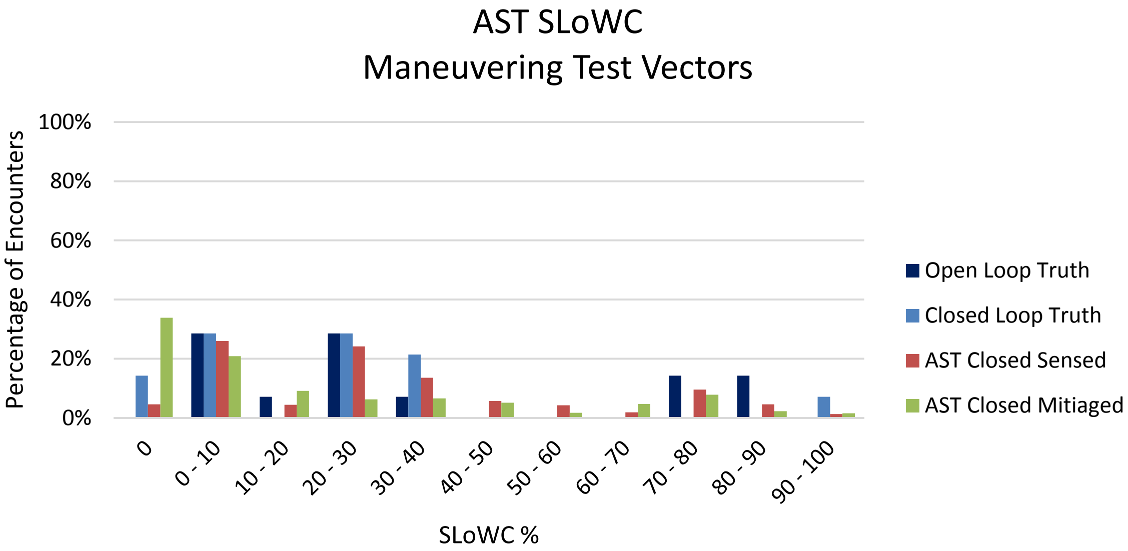

Figure 52. AST SLoWC for Maneuvering MOPS Requirement-Derived Test Vectors

Figure 53 shows results for Overtake test vectors. Similar to the radar Overtake results, the closed loop system resulted in 100% of encounters having a 0% SLoWC when Truth guidance was used, but with some distribution over the SLoWC range with no maneuvers (Open Loop Truth). Both Sensed and Mitigated guidance results are very similar, avoiding loss of well clear in most encounters.

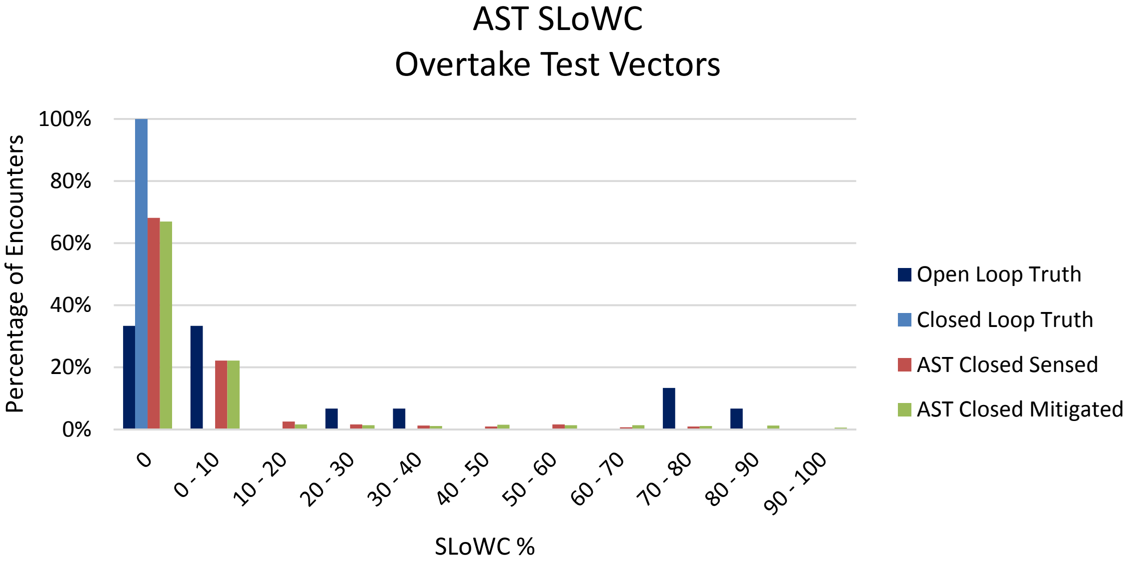

Figure 53. AST SLoWC for Overtake MOPS Requirement-Derived Test Vectors

6.1.3 Automatic Dependent Surveillance – Broadcast (ADS-B) SLoWC

Figures 54 through 58 show SLoWC histograms for ADS-B guidance source used in a closed loop simulation for MOPS Requirement-Derived test vectors. ADS-B data is by far less noisy and uncertain than radar and AST; the figures show that the DAA system performs very close to the way it would with perfect (Truth) data.

Results for Head-On test vectors (Figure 54) show that the DAA system resulted in no loss of well clear for all of the encounters using Truth guidance, whereas open loop Truth results show a 0% SLoWC value for only 33% of encounters. Essentially all the encounters using both Sensed and Mitigated guidance had a SLoWC of 0% (96% for closed loop Sensed and 97% for closed loop Mitigated.

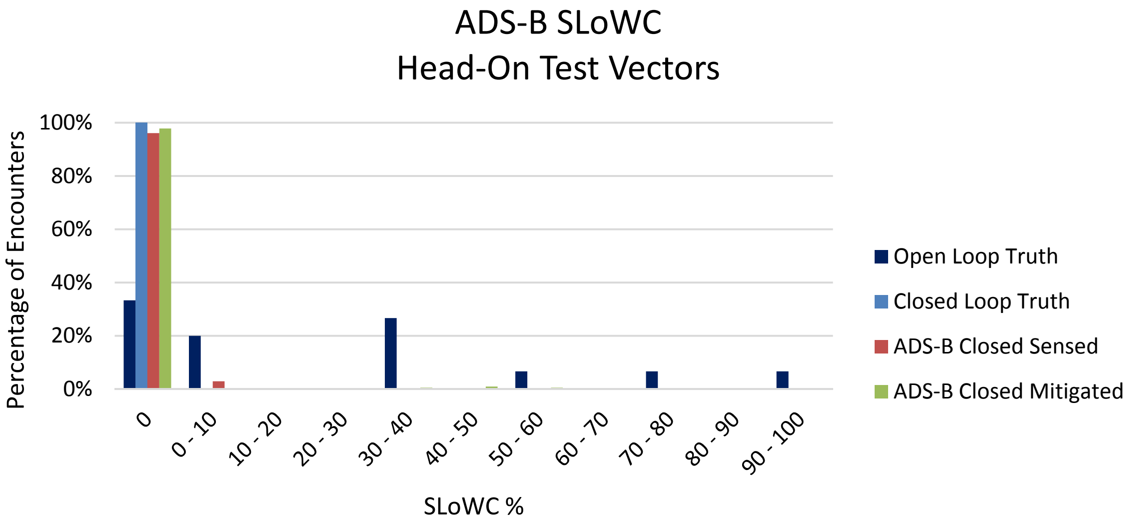

Figure 54. ADS-B SLoWC for Head-On MOPS Requirement-Derived Test Vectors

Results for Converging test vectors using ADS-B (Figure 55) are almost identical to the Head-On results. The DAA system was able to keep 99% of the encounters well clear using Sensed ADS-B guidance and 100% of encounters well clear using Mitigated guidance.

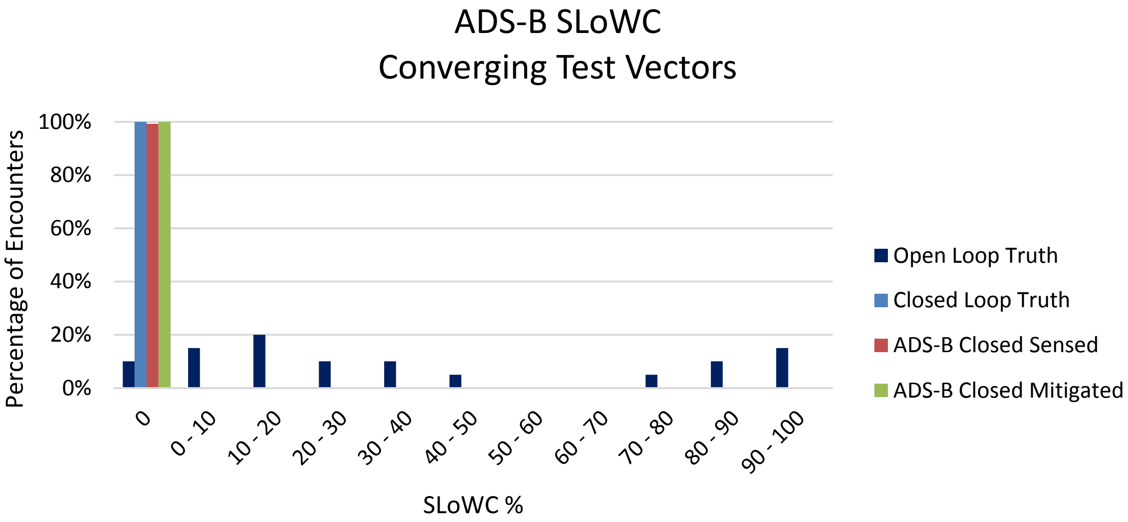

Figure 55. ADS-B SLoWC for Converging MOPS Requirement-Derived Test Vectors

Figure 56 shows results for High Speed test vectors. Closed loop results show 100% of encounters remained well clear when any of the three guidance sources were used (Truth, Sensed, and Mitigated).

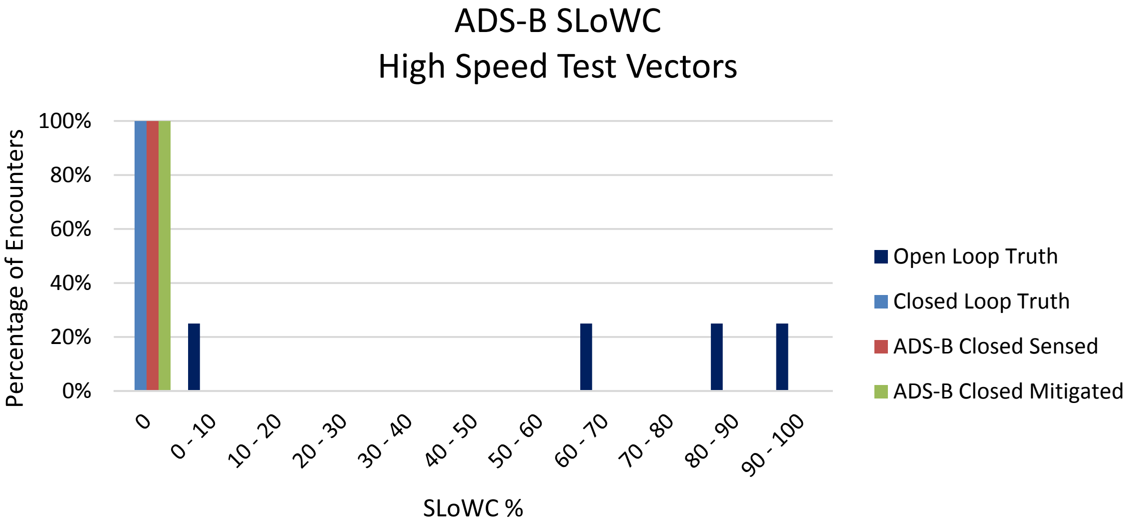

Figure 56. ADS-B SLoWC for High Speed MOPS Requirement-Derived Test Vectors

Figure 57 shows results for Maneuvering test vectors. As with AST and radar, the Maneuvering encounters for MOPS requirements testing proved very difficult, even for ADS-B. Only 13% of encounters had 0% SLoWC using Truth guidance and Sensed guidance results show only 12% of encounters maintained well clear; however, the Mitigated (SUM) approach more than doubled that (32% remained well clear). Overall, the DAA system performed least favorably in the Maneuvering encounters in comparison to the other MOPS requirements-derived encounter geometries.

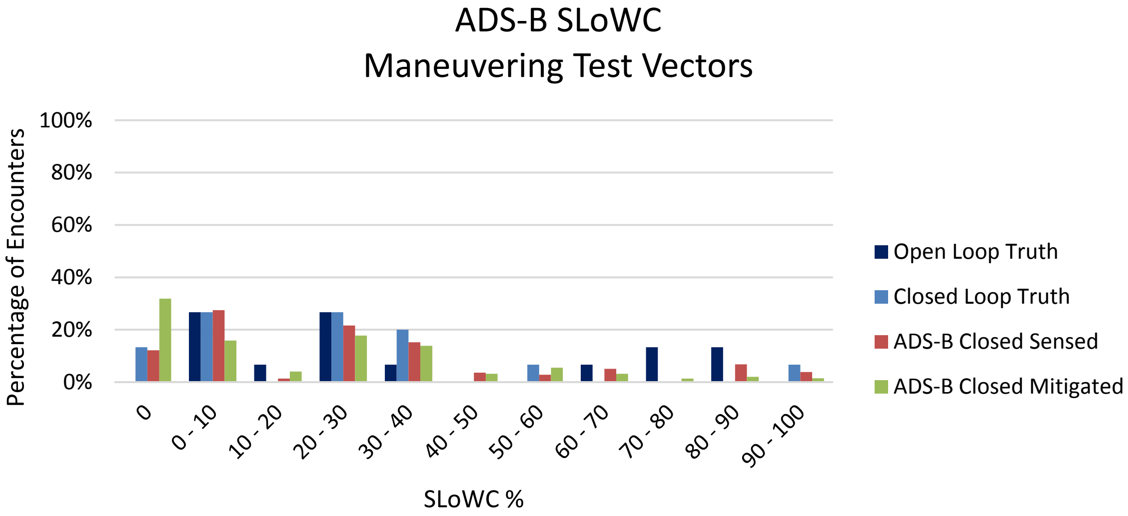

Figure 57. ADS-B SLoWC for Maneuvering MOPS Requirement-Derived Test Vectors

Figure 58 shows results for Overtake test vectors. The DAA system was able to keep 97% of encounters well clear using Sensed guidance and 100% of encounters well clear using Mitigated guidance.

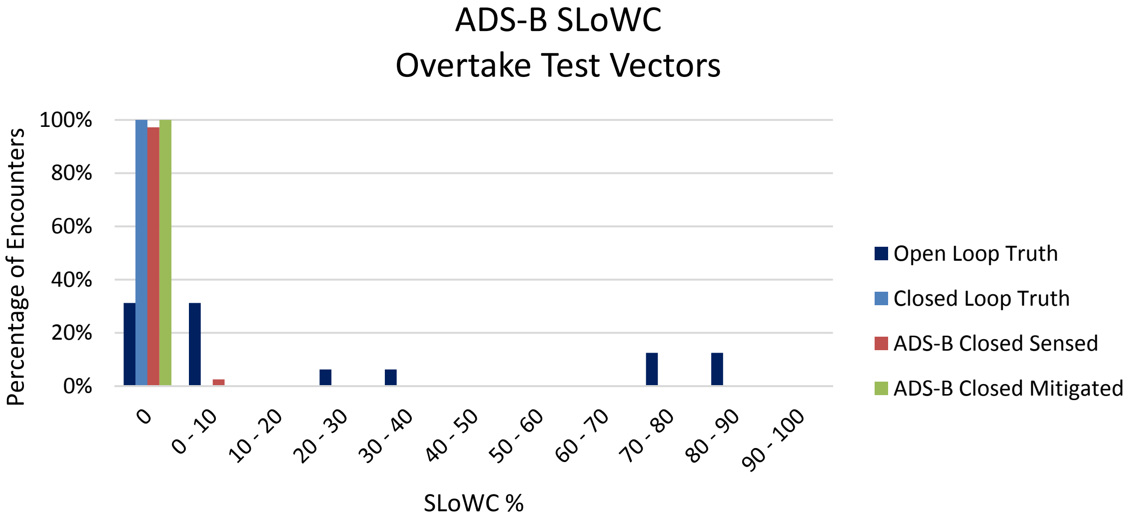

Figure 58. ADS-B SLoWC for Overtake MOPS Requirement-Derived Test Vectors

6.2 Alert Scoring

Traffic alerts and their scoring methodology are explained in Section 3.2.2.

6.2.1 Corrective Alert Scoring

Figures 59 through 72 show corrective alert scoring histograms for radar, AST, and ADS-B guidance sources used in a closed loop simulation for MOPS Requirement-Derived test vectors.

6.2.1.1 Radar Corrective Alerts

Figure 59 shows corrective alert results for Head-On test vectors using the radar sensor for closed loop testing. Closed loop Truth guidance shows 67% of encounters were within the "Correct Non-Alert" scoring criteria, which matches the open loop Truth results. The remaining 33% of closed loop Truth encounters were within the "Permissible Alert" scoring criteria. Using Sensed guidance decreased all desirable alerts and drastically increased incorrect alerts (45% of encounters). Mitigated guidance using the SUM approach worsened the situation, further decreasing desirable alerts and further increasing incorrect alerts (67% of encounters).

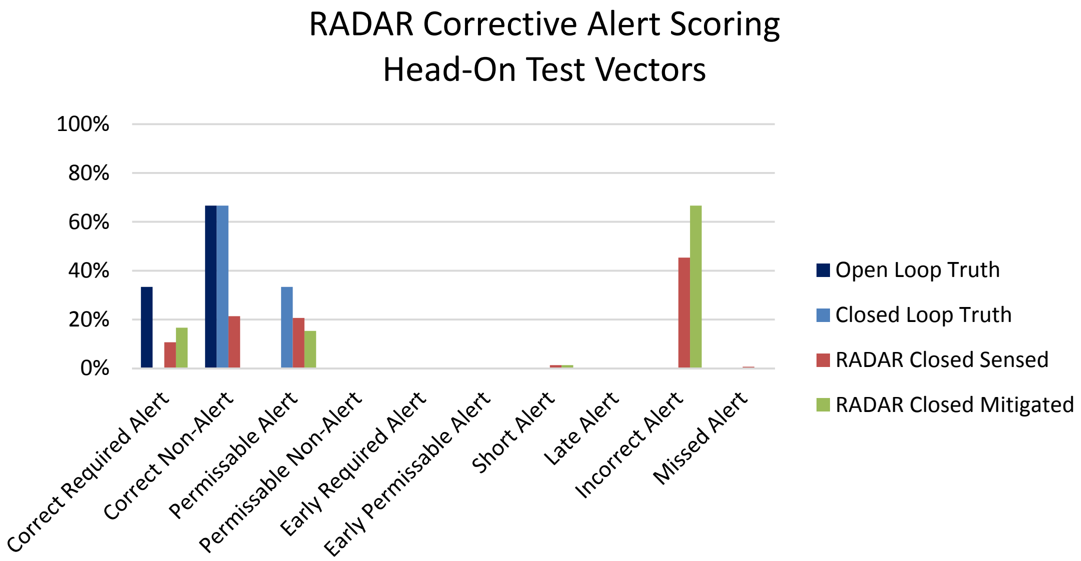

Figure 59. Radar Corrective Alert Scoring for Head-On MOPS Requirement-Derived Test Vectors

Figure 60 shows results for Converging test vectors using the radar sensor. Closed loop Truth guidance shows 90% of encounters were within the "Permissible Alert" scoring criteria while the remaining 10% of encounters experienced permissible non-alerts. Using Sensed guidance decreases permissible alerts by 25%. Mitigated guidance using the SUM approach shows 57% of encounters received permissible alerts. Both Sensed and Mitigated shift a few of the encounters into the undesirable alert categories, with the mitigation approach making very little difference overall.

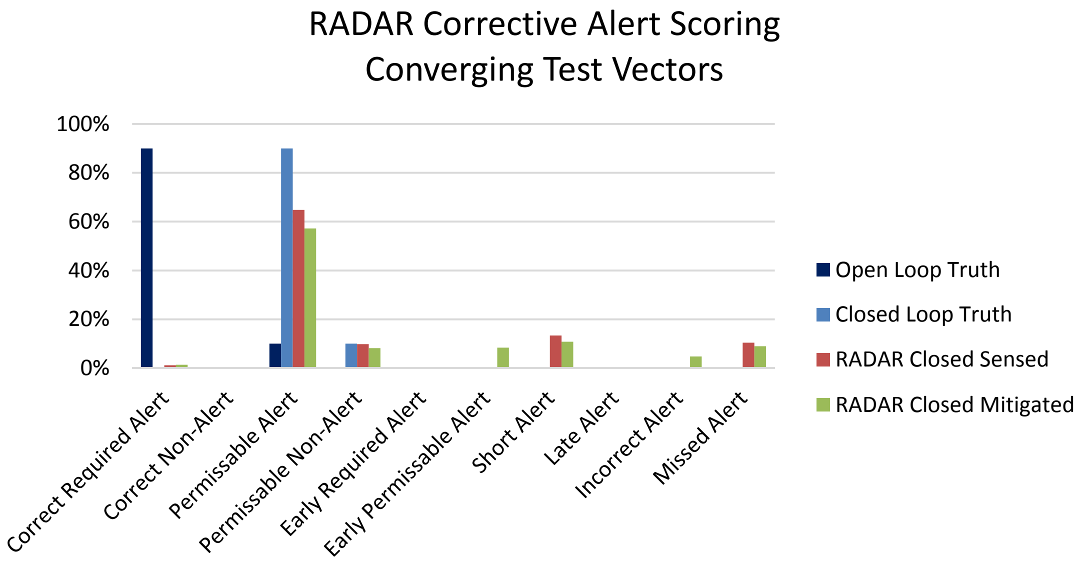

Figure 60. Radar Corrective Alert Scoring for Converging MOPS Requirement-Derived Test Vectors

Findings from Maneuvering test vectors using the radar sensor are shown in Figure 61. Truth guidance in both open loop and closed loop shows 50% of encounters were within the “Correct Required Alert” scoring criteria while the remaining 50% never received a corrective alert. When Sensed and Mitigated guidance were used, no encounters received correct required alerts, nor any desired alerts. Sensed guidance shows 45% of test vectors encountered late alerts and 55% were within the “Missed Alert” scoring criteria. The SUM approach enabled the DAA system to alert on a few more encounters, but they were late.

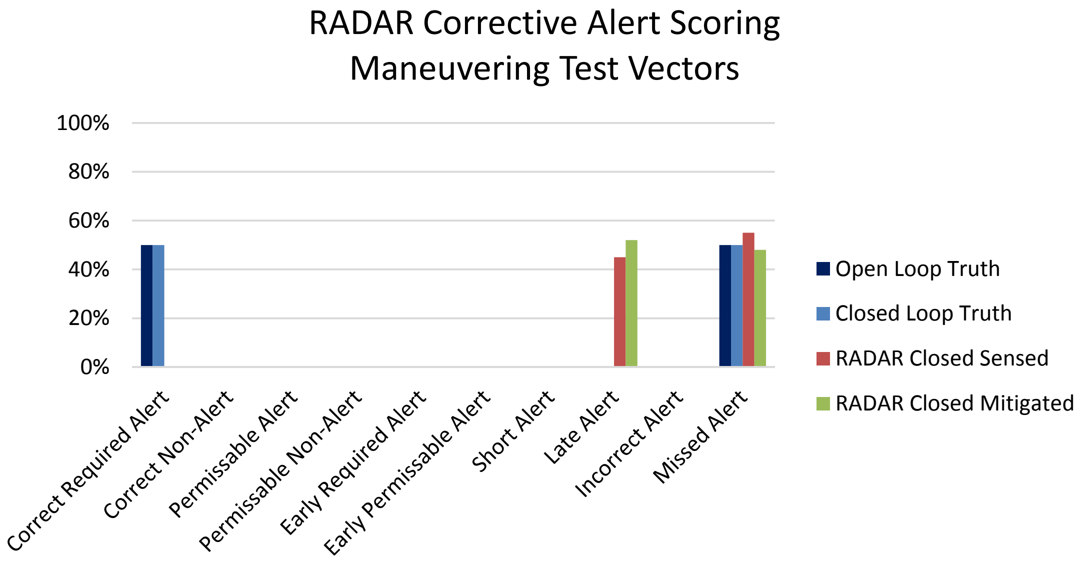

Figure 61. Radar Corrective Alert Scoring for Maneuvering MOPS Requirement-Derived Test Vectors

Results for Overtake test vectors in a closed loop simulation and using the radar sensor are shown in Figure 62. Truth guidance shows 33% of encounters were within the "Correct Non-Alert" scoring criteria while the remaining 67% received permissible alerts. Using Sensed guidance decreased the number of encounters in both of those desirable categories, and shifted most of them to undesirable categories (22% incorrect alerts). Mitigated guidance made the alerting slightly worse (28% were within the "Incorrect Alert" scoring criteria).

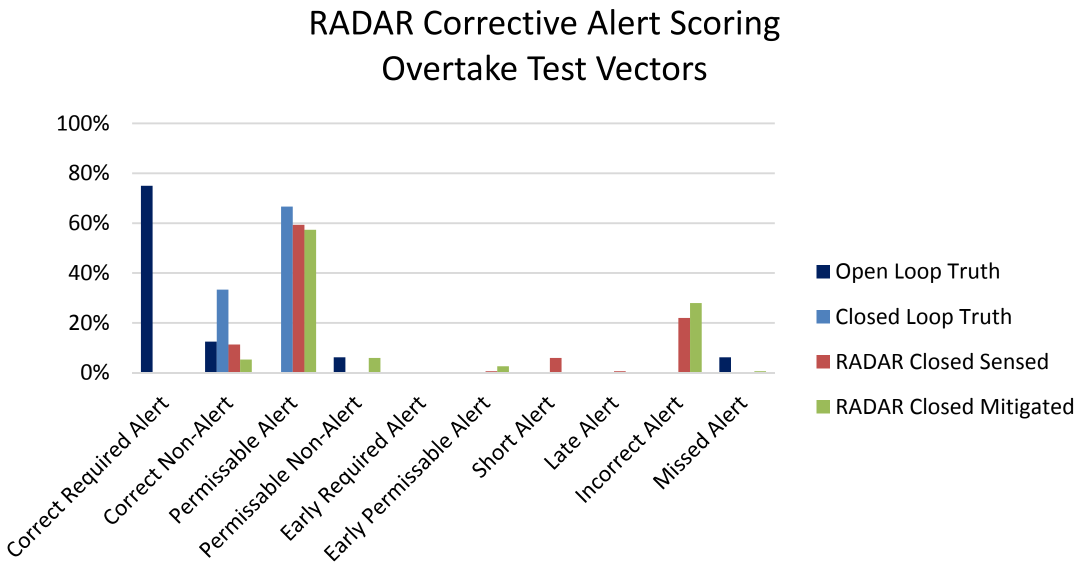

Figure 62. Radar Corrective Alert Scoring for Overtake MOPS Requirement-Derived Test Vectors

6.2.1.2 Active Surveillance Transponder (AST) Corrective Alerts

Figure 63 shows corrective alert results for Head-On test vectors using the AST sensor for closed loop testing. Truth guidance shows 21% of encounters were within the "Correct Non-Alert" scoring criteria while the remaining 79% were within the "Permissible Alert" scoring criteria. Surprisingly, using Sensed guidance shifts 25% of the encounters from Permissible Alerts to Correct Required Alerts, but also shifts encounters to Short (9%) and Missed Alerts (27%). Mitigated guidance using the SUM approach shows a decrease of 10% of the encounters that received missed alerts in comparison to Sensed guidance.

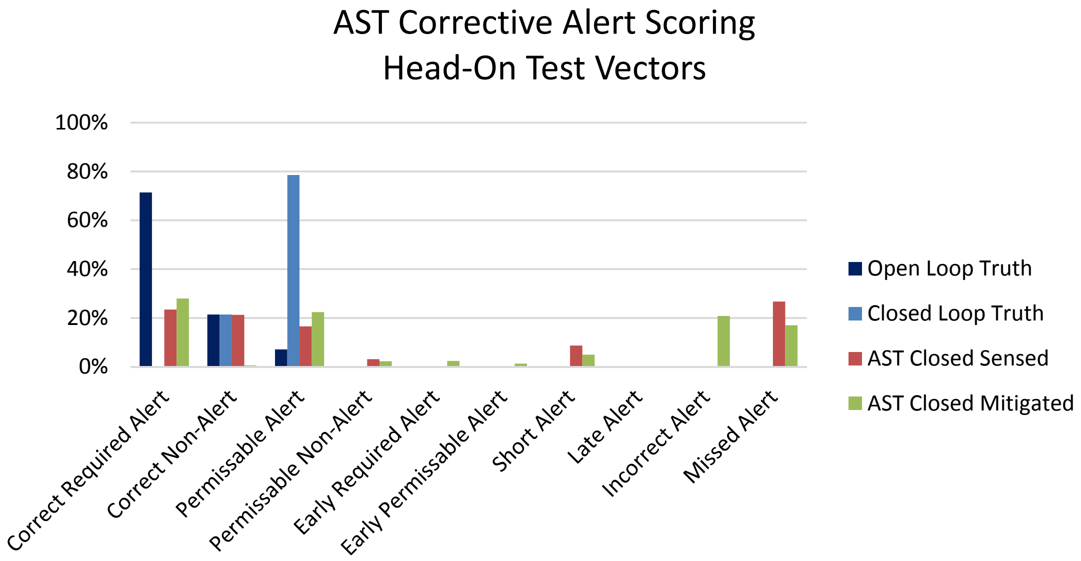

Figure 63. AST Corrective Alert Scoring for Head-On MOPS Requirement-Derived Test Vectors

Figure 64 shows results for Converging test vectors using the AST sensor. Closed loop Truth guidance shows 92% of encounters were within the "Permissible Alert" scoring criteria while the remaining 8% of encounters received permissible non-alerts. Sensed guidance decreased permissible alerts 31% from Truth guidance, shifting about 15% to desirable correct required alerts, but also shifting the same number to short alerts and 9% to missed alerts. Mitigated guidance, using the SUM approach, further decreased permissible alerts (to 49%), it also decreased short and missed alerts.

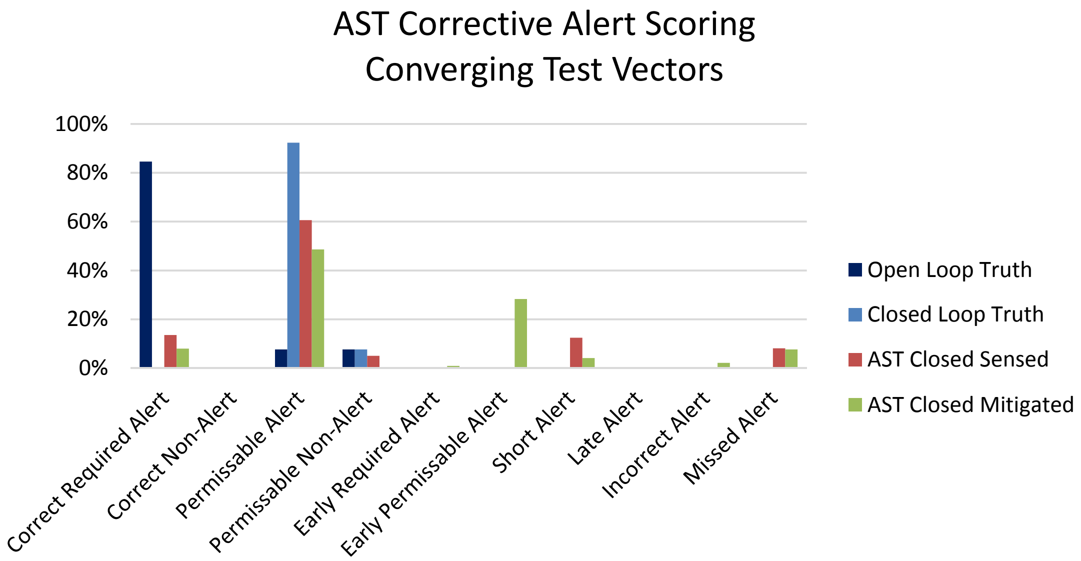

Figure 64. AST Corrective Alert Scoring for Converging MOPS Requirement-Derived Test Vectors

Figure 65 shows results for High Speed test vectors. Closed loop results of the Mitigated guidance using the SUM approach enabled 100% of the encounters to receive permissible alerts. Only 45% of encounters received permissible alerts using Truth guidance, while 63% of encounters were alerted in the same manner when Sensed guidance was used.

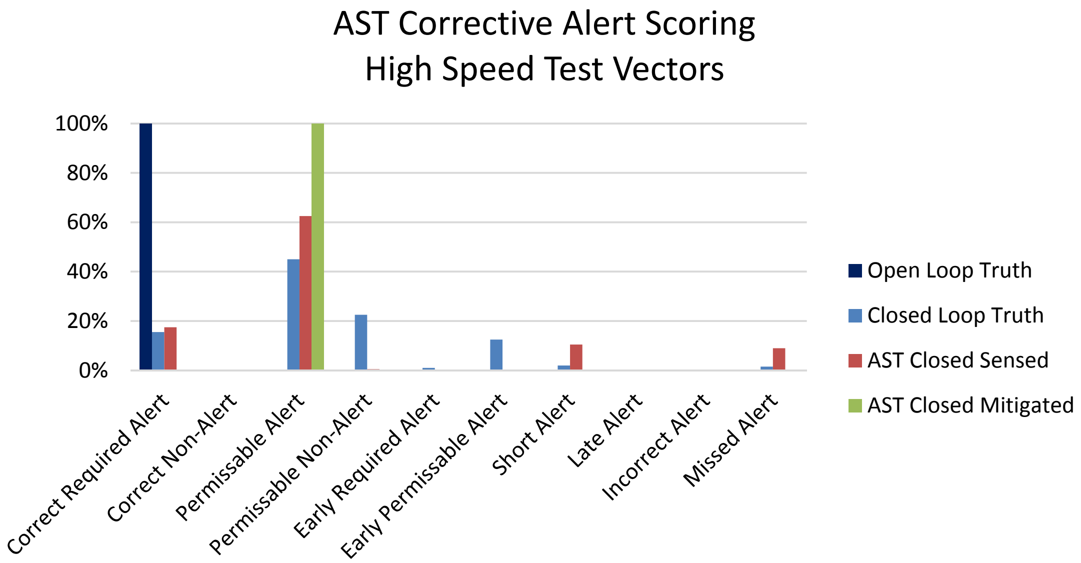

Figure 65. AST Corrective Alert Scoring for High Speed MOPS Requirement-Derived Test Vectors

Maneuvering test vectors results using the AST sensor are shown in Figure 66. Truth guidance in open and closed loop shows 57% of encounters received missed alerts while 63% of encounters received the same type of alert when Sensed Guidance was used. Mitigated guidance significantly decreased missed alerts to only 21%. The SUM approach also increased correct required alerts and early permissible alerts, with modest only increases in short, late, and incorrect alerts.

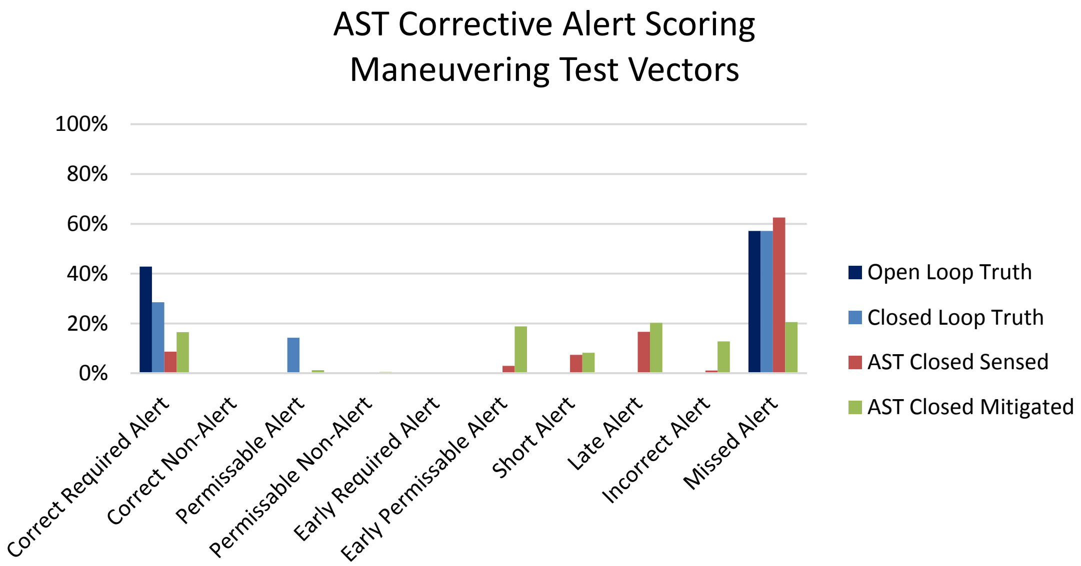

Figure 66. AST Corrective Alert Scoring for Maneuvering MOPS Requirement-Derived Test Vectors

Results for Overtake test vectors using AST are shown in Figure 67. All Truth guidance encounters scored in the desirable alert categories, with the majority (67%) in the "Permissible Alert" scoring criteria. Significantly fewer encounters (29%) using Sensed guidance received the same alert and fewer still (23%) when Mitigated guidance was used. Mitigated guidance shows the pilot model received early permissible alerts for 16% of encounters. Using Sensed guidance only 6% of encounters received early permissible alerts. Mitigated guidance shows 14% of encounters received missed alerts, which is 12% fewer encounters than when Sensed guidance was used.

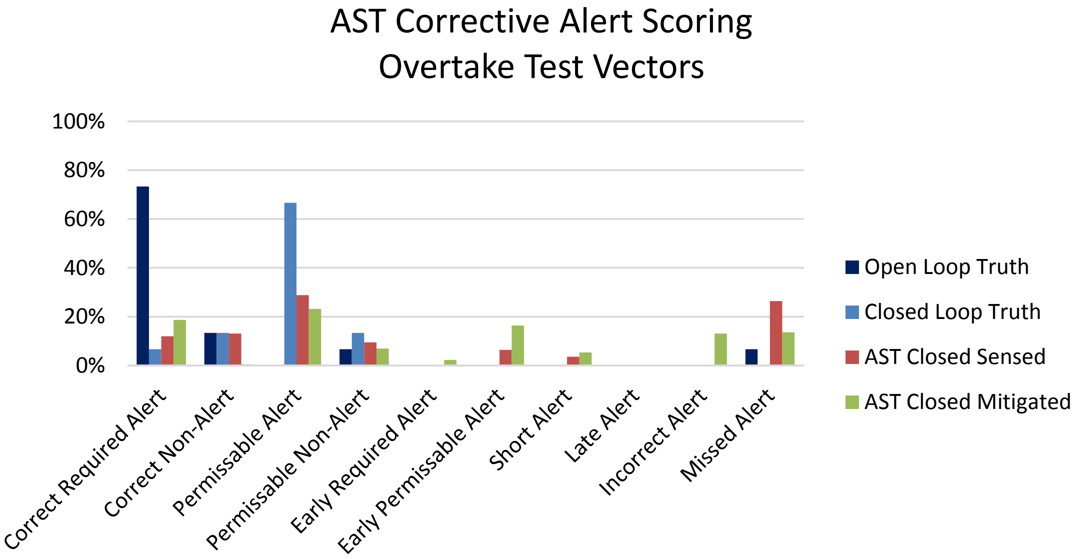

Figure 67. AST Corrective Alert Scoring for Overtake MOPS Requirement-Derived Test Vectors

6.2.1.3 Automatic Dependent Surveillance – Broadcast (ADS-B) Corrective Alerts

Figure 68 shows corrective alert results for Head-On test vectors using the ADS-B sensor. Results for the "Permissible Alert" scoring criteria show comparable findings within an 8% range when using closed loop Truth (80%), Sensed (72%), and Mitigated (78%) guidance. Comparable findings were also observed for the "Correct Non-Alert" scoring criteria (Open Loop Truth = 20%, Closed Loop Truth = 20%, and Sensed = 20%). Mitigated guidance results for correct non-alerts show 7% of encounters received that type of alert.

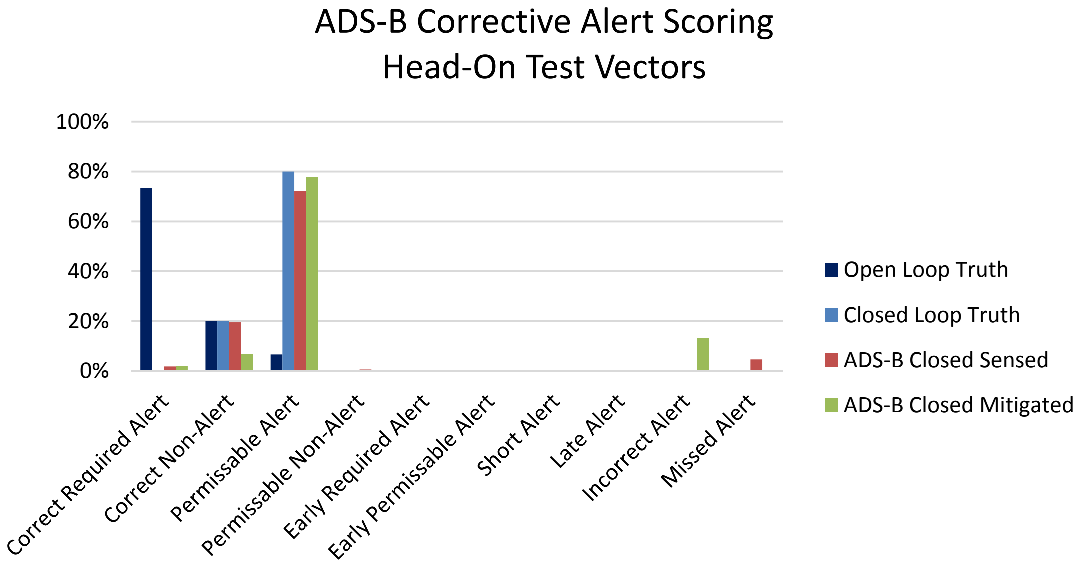

Figure 68. ADS-B Corrective Alert Scoring for Head-On MOPS Requirement-Derived Test Vectors

Figure 69 shows results for Converging test vectors using the ADS-B sensor. Closed loop Truth guidance findings show 95% of encounters were within the "Permissible Alert" scoring criteria while 93% of encounters received the same alert when Sensed guidance was used and 91% when Mitigated guidance was used. Mitigated guidance findings show that 7% of encounters received early permissible alerts. Notably, none of the encounters using any guidance type scored in the undesirable categories.

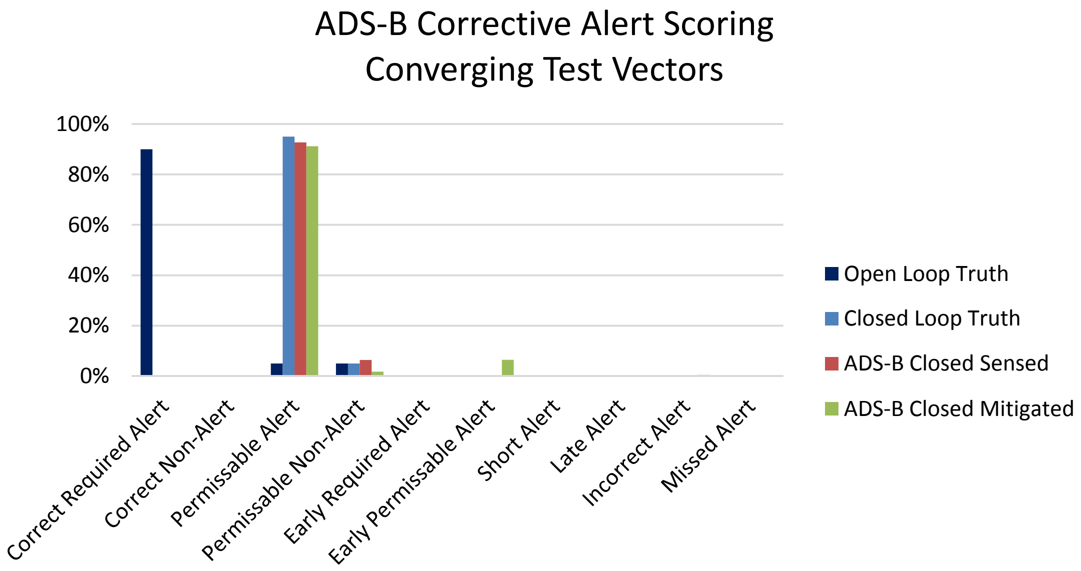

Figure 69. ADS-B Corrective Alert Scoring for Converging MOPS Requirement-Derived Test Vectors

Figure 70 shows corrective alert scoring results for High Speed test vectors as a function of ADS-B-based guidance. Open loop Truth results show 100% of encounters received correct required alerts, which indicates that an alert was issued for an encounter when an intruder aircraft was within the Hazard Zone. However, 100% of closed loop encounters received permissible alerts regardless of guidance used (Truth, Sensed, or Mitigated) indicating an alert was issued to the pilot model for an encounter when an intruder aircraft entered into the May-Alert Zone but before entering the Hazard Zone. Closed loop results may suggest that the pilot model received an alert ahead of the "Correct Required Alert" time seen in open loop runs in order to provide additional time for the ownship aircraft to maneuver.

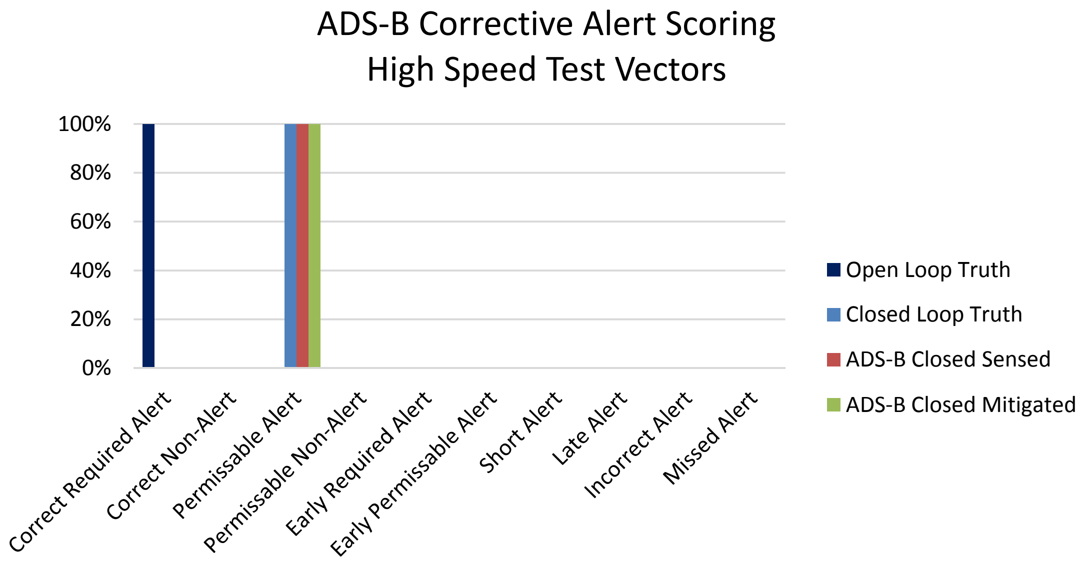

Figure 70. ADS-B Corrective Alert Scoring for High Speed MOPS Requirement-Derived Test Vectors

Figure 71 shows findings for Maneuvering test vectors using ADS-B-based guidance in closed loop testing. The majority of closed loop encounters (60%) using Truth guidance were observed within the "Missed Alert" scoring criteria, which compares directly to results seen when open loop testing was conducted. Sensed guidance results show slightly fewer (53% of encounters) received missed alerts. The SUM approach reduced the high percentage of missed alerts seen with Truth and Sensed guidance runs to 35%.

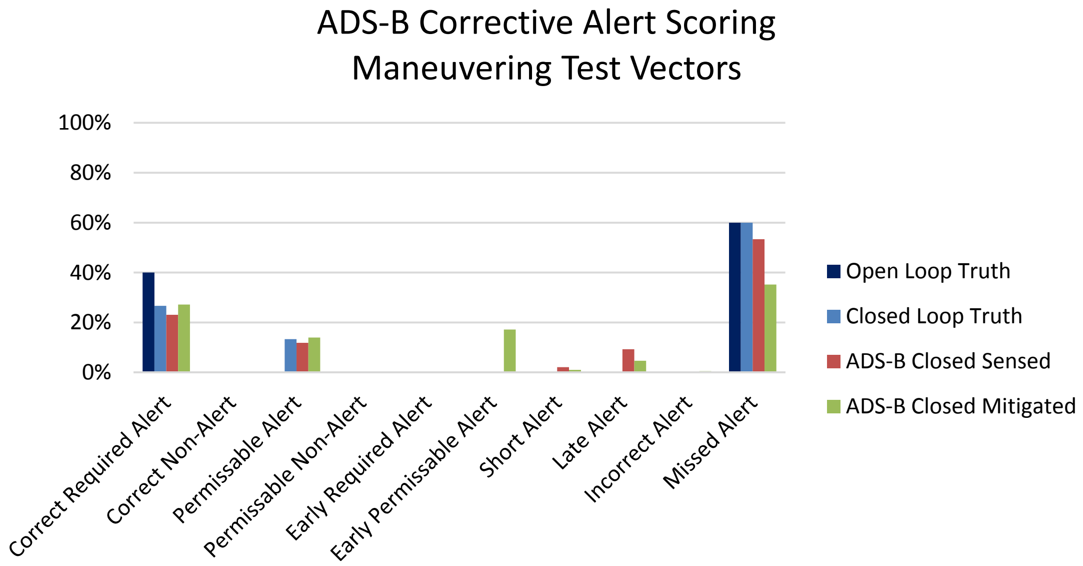

Figure 71. ADS-B Corrective Alert Scoring for Maneuvering MOPS Requirement-Derived Test Vectors

Corrective alert scoring results for Overtake test vectors using ADS-B are shown in Figure 72. Truth guidance runs show that the majority (69%) of closed loop encounters were within the "Permissible Alert" scoring criteria, with very comparable results for Sensed (63%) and Mitigated (64%) guidance. Open loop Truth shows the majority of encounters (67%) received correct required alerts while the remaining 33% received correct non-alerts.

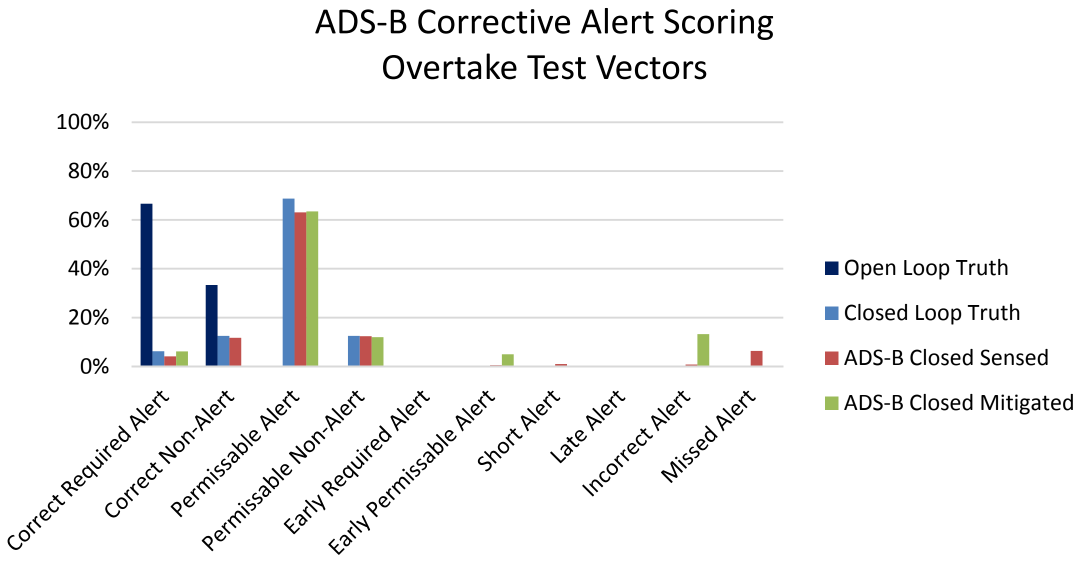

Figure 72. ADS-B Corrective Alert Scoring for Overtake MOPS Requirement-Derived Test Vectors

6.2.2 Warning Alert Scoring

Figures 73 through 86 show warning alert scoring histograms for radar, AST, and ADS-B guidance sources used in a closed loop simulation for MOPS Requirement-Derived test vectors.

6.2.2.1 Radar Warning Alerts

Figure 73 shows warning alert results for Head-On test vectors using the radar sensor for closed loop testing. Truth guidance shows 33% of encounters were within the "Permissible Alert" scoring criteria while the remaining 67% of encounters experienced correct non-alerts. Sensed guidance reduced permissible alerts by 12% and correct non-alerts by 20%. For the "Incorrect Alert" scoring criteria, results show 19% of encounters were within that criteria when Sensed guidance was used; however, Mitigated guidance using the SUM approach greatly increased encounters receiving incorrect alerts to 67%.

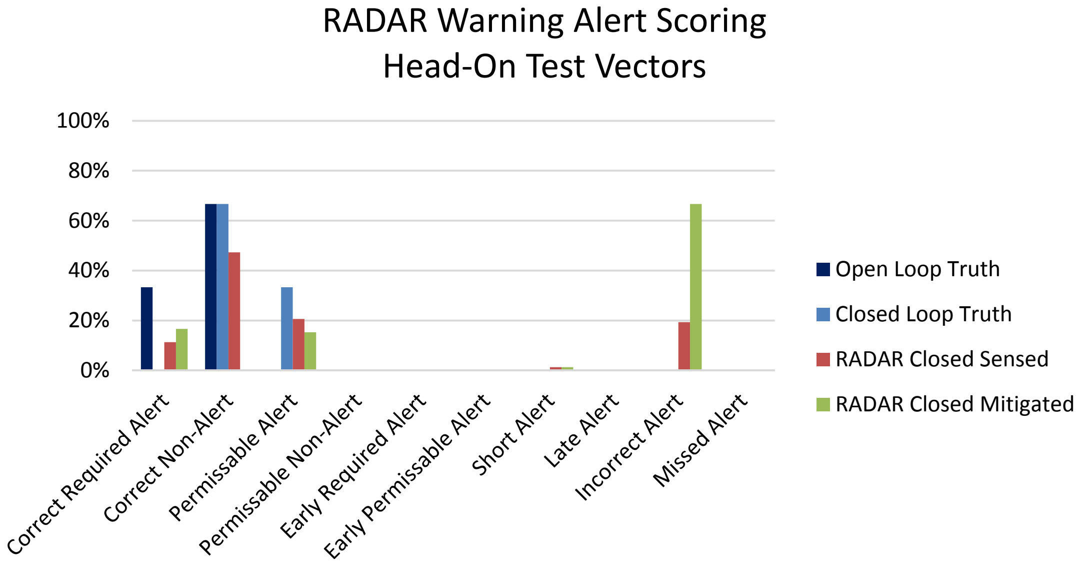

Figure 73. Radar Warning Alert Scoring for Head-On MOPS Requirement-Derived Test Vectors

Figure 74 shows warning alert results for Converging test vectors using the radar sensor. Closed loop Truth guidance shows 90% of encounters were within the "Permissible Alert" scoring criteria while the remaining 10% of encounters experienced permissible non-alerts. Sensed guidance shows a decrease of 25% in comparison to Truth guidance for permissible alerts, with the rest spread among several other criteria. Mitigated guidance using the SUM approach showed very little difference.

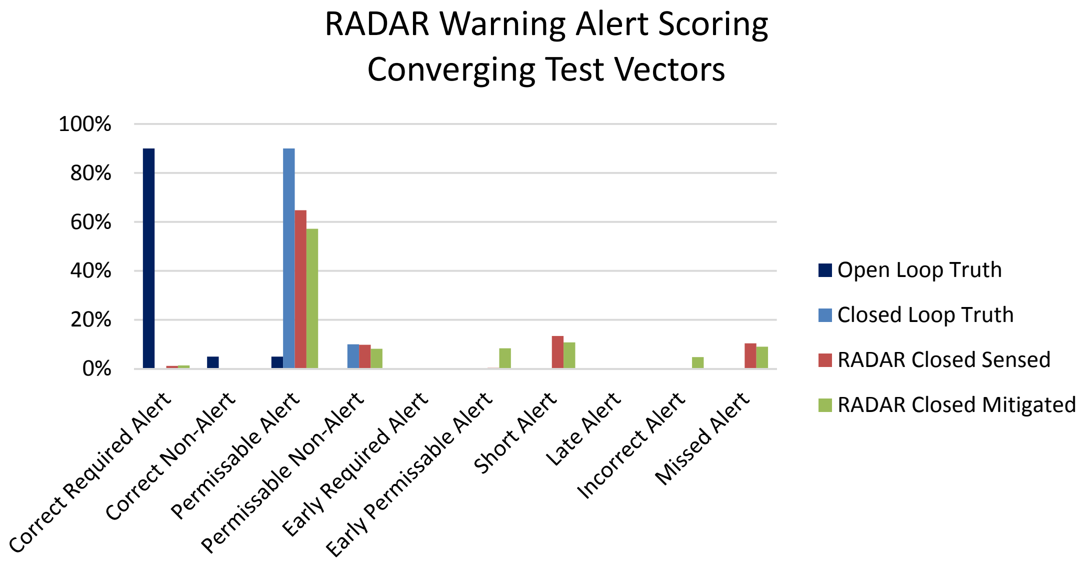

Figure 74. Radar Warning Alert Scoring for Converging MOPS Requirement-Derived Test Vectors

Figure 75 shows results for Maneuvering test vectors using the radar sensor. Truth guidance shows 100% of encounters were within the "Correct Required Alert" scoring criteria for both open and closed loop runs while only 1% of Sensed and 8% of Mitigated closed loop runs received those alerts, respectively. Sensed guidance shows 99% of test vectors encountered late alerts. Mitigated guidance runs were able to compensate for Sensed late alerts in only 7% of encounters.

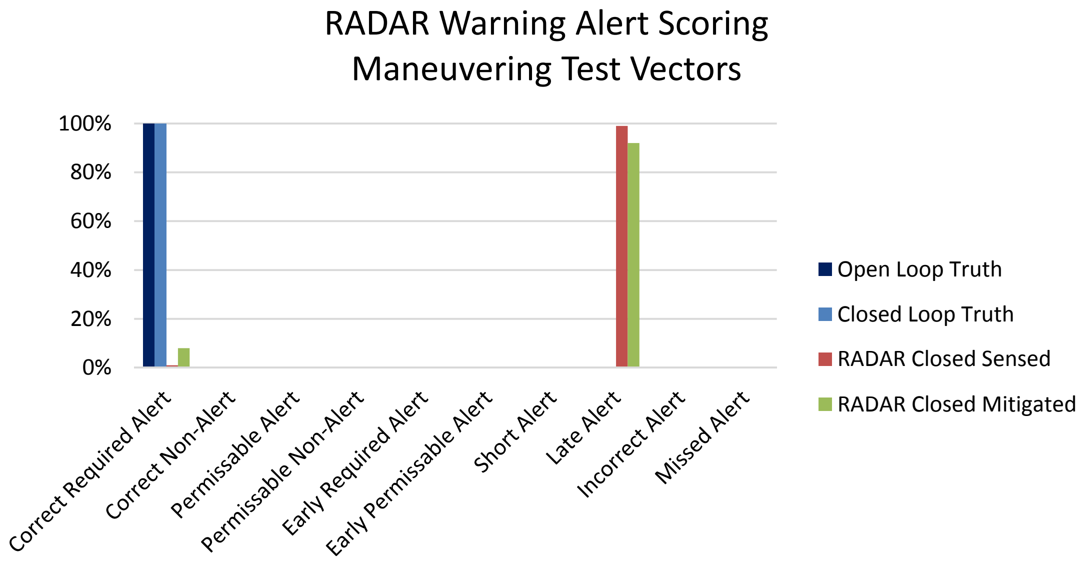

Figure 75. Radar Warning Alert Scoring for Maneuvering MOPS Requirement-Derived Test Vectors

Results for Overtake test vectors using the radar sensor are shown in Figure 76. Truth guidance in closed loop runs show an even percentage of encounters (33%) were within the “Correct Non-Alert,” “Permissible Alert,” and the “Permissible Non-Alert” scoring criteria. Sensed guidance runs show 33% of encounters received correct non-alerts, 37% received permissible alerts, and 21% received permissible non-alerts. The SUM approach shifted a significant number (40%) of encounters in these three desirable criteria to the “Early Permissible Alert” scoring criteria, but unfortunately shifted 45% of encounters to “Incorrect Alert.”

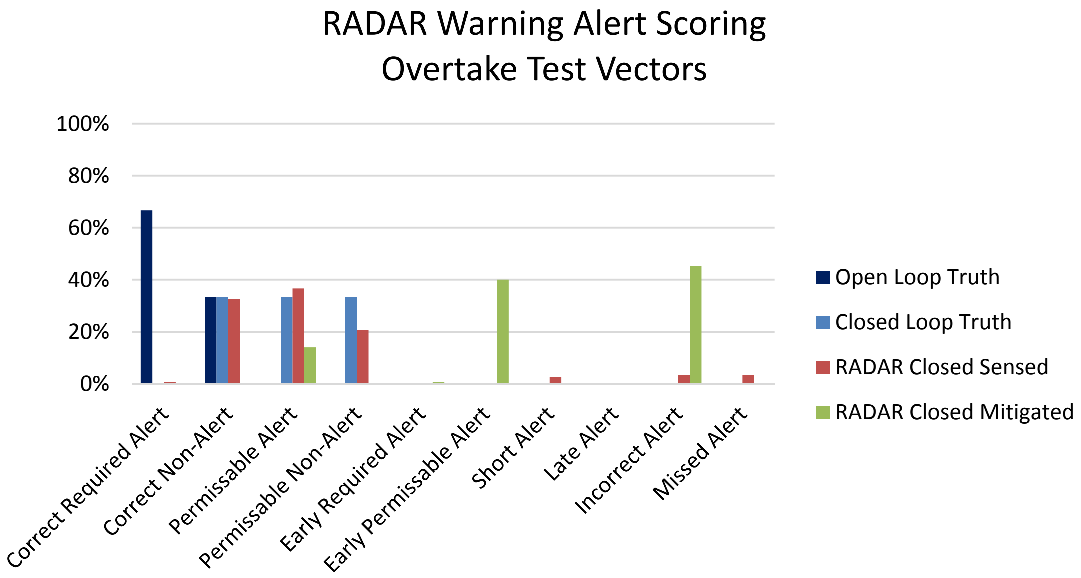

Figure 76. Radar Warning Alert Scoring for Overtake MOPS Requirement-Derived Test Vectors

6.2.2.2 Active Surveillance Transponder (AST) Warning Alerts

Figure 77 shows warning alert results for Head-On test vectors for the AST sensor for closed loop testing. Truth guidance shows 43% of encounters were within the "Permissible Alert" scoring criteria, 29% within the "Permissible Non-Alert" criteria, and 29% within the "Correct Non-Alert" scoring criteria. As expected, sensed guidance decreases these three desirable alerts and increases short, late, incorrect, and missed alerts. However, it also increases correct required alerts; in 29% of these encounters the sensed position and velocity of the intruder aircraft led to a correct alert. The SUM approach increased desirable alerts and decreased undesirable alerts, with the notable exception of a significant increase in incorrect alerts. Incorrect alerts are essentially early alerts, in this case caused by the conservative nature of SUM's approach to mitigating the sensor uncertainty.

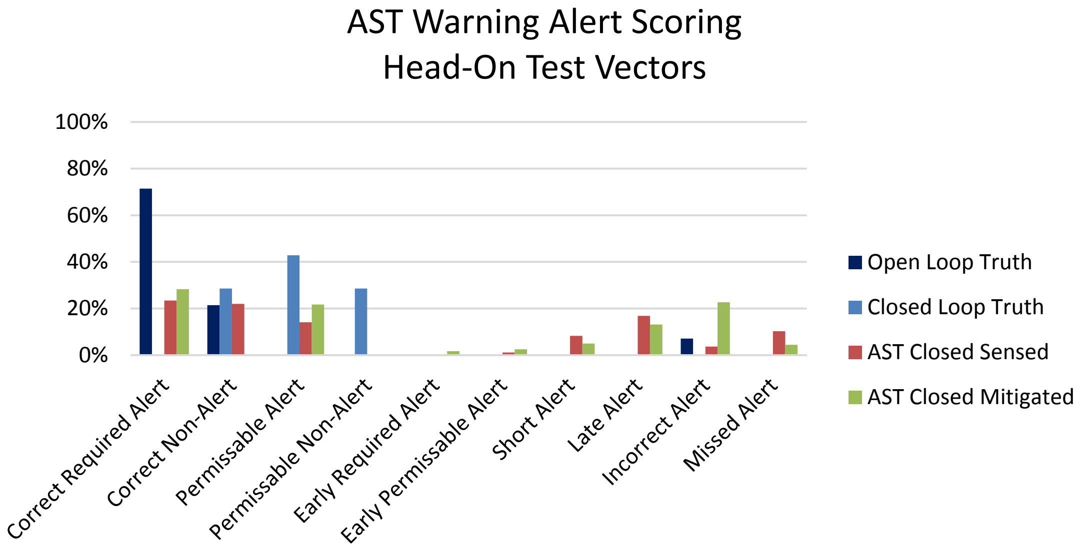

Figure 77. AST Warning Alert Scoring for Head-On MOPS Requirement-Derived Test Vectors

Results for warning alert scoring for AST for Converging test vectors are shown in Figure 78. Closed loop Truth guidance shows 92% of encounters were within the "Permissible Alert" scoring criteria while the remaining 8% were within the "Permissible Non-Alert" criteria. Sensed guidance shows 31% fewer in comparison to Truth guidance for permissible alerts, and the SUM approach reduced it even further to 49% of encounters. Although this percentage is less than that of Sensed (61%), Mitigated runs were also observed within the "Early Permissible Alert" scoring criteria for 28% of encounters. For the "Short Alert" scoring criteria, results show the Mitigated guidance compensated for the Sensed guidance by decreasing the percentage of encounters within that criteria to only 4%.

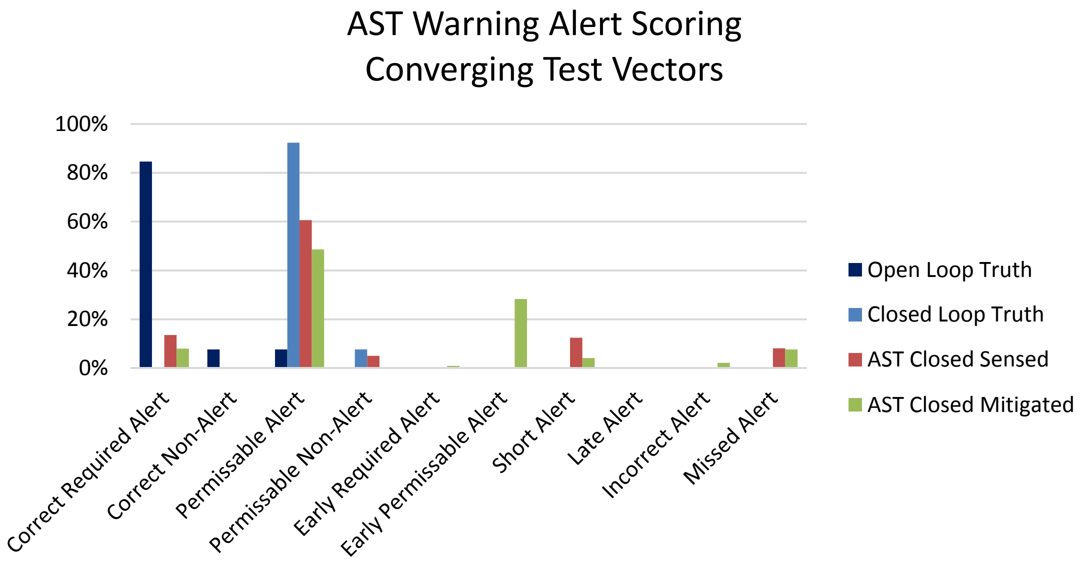

Figure 78. AST Warning Alert Scoring for Converging MOPS Requirement-Derived Test Vectors

Results for High Speed test vectors for warning alert scoring for AST are shown in Figure 79. The "Permissible Alert" scoring criteria shows 54% of encounters using Truth guidance were within that criteria while 23% of encounters were within the "Early Permissible Alert" criteria. Sensed guidance shows 63% of test vectors encountered permissible alerts. The SUM approach placed 75% of encounters within the "Permissible Alert" scoring criteria with the remaining 25% of encounters within the "Permissible Non-Alert" scoring criteria. For this High Speed encounter set, the SUM approach performed exceptionally well, providing maneuver guidance such that no warning was needed at all in 25% of the encounters, and all others resulted in permissible alerts.

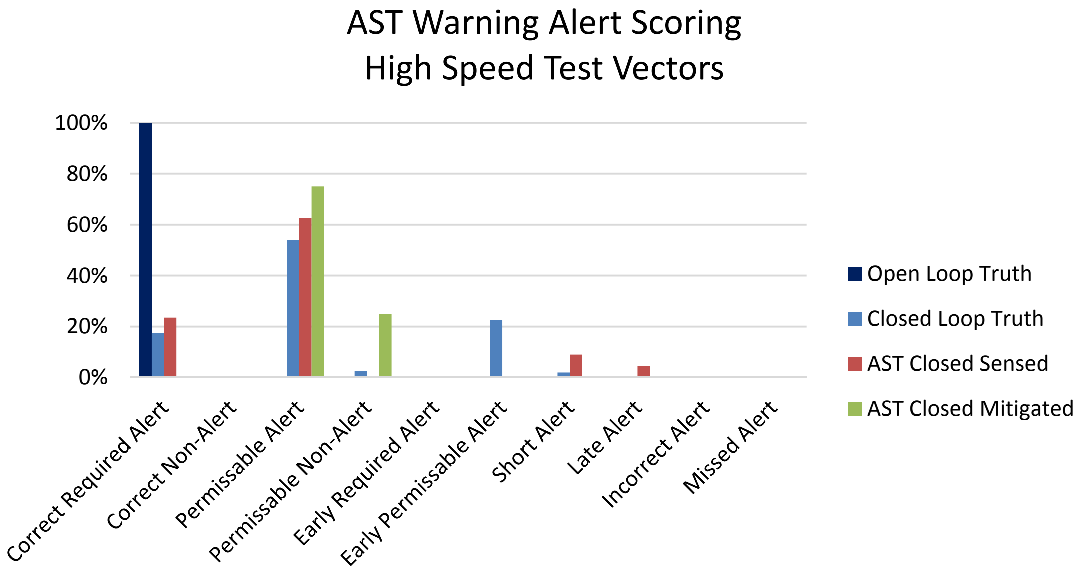

Figure 79. AST Warning Alert Scoring for High Speed MOPS Requirement-Derived Test Vectors

Results for Maneuvering test vectors for AST-based guidance are shown in Figure 80. The majority of closed loop encounters (71%) using Truth guidance were observed within the "Correct Required Alert" scoring criteria, which is 22% less than open loop Truth runs. Within that same scoring criteria, only 24% of encounters were observed using Sensed guidance and 27% when Mitigated guidance was used. 51% of Sensed guidance runs were within the "Late Alert" scoring criteria for maneuvering encounters; the SUM approach compensated for the Sensed guidance by decreasing the percentage of encounters within that scoring criteria to only 23%, which is 9% higher than the runs using Truth guidance. This set of maneuvering encounters is difficult for both Sensed and Mitigated guidance to handle, as evidenced by the significant distribution of encounters in the undesirable categories.

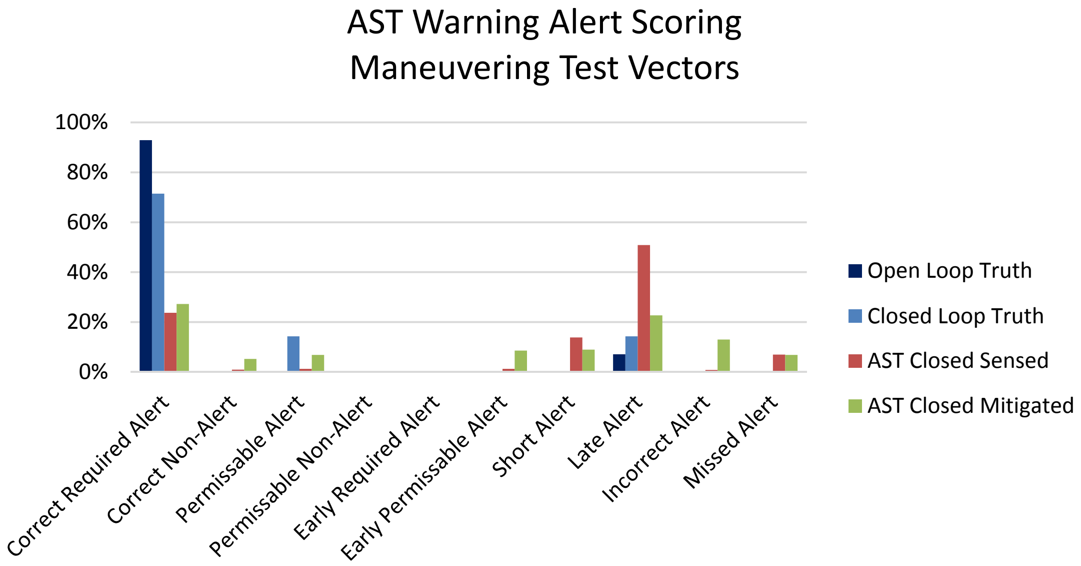

Figure 80. AST Warning Alert Scoring for Maneuvering MOPS Requirement-Derived Test Vectors

Results for Overtake test vectors for AST are shown in Figure 81. Closed loop Truth guidance runs show results for 47% of encounters being within the "Permissible Alert" scoring criteria while 27% of encounters were within the "Early Permissible Alert" criteria and the remaining encounters observed both correct required alerts and correct non-alerts. Sensed guidance shows 34% of test vectors received permissible alerts, and most of the rest received various undesirable alerts. The SUM approach correct required alerts and decreased most undesirable alerts, but also decreased permissible alerts and increased incorrect alerts.

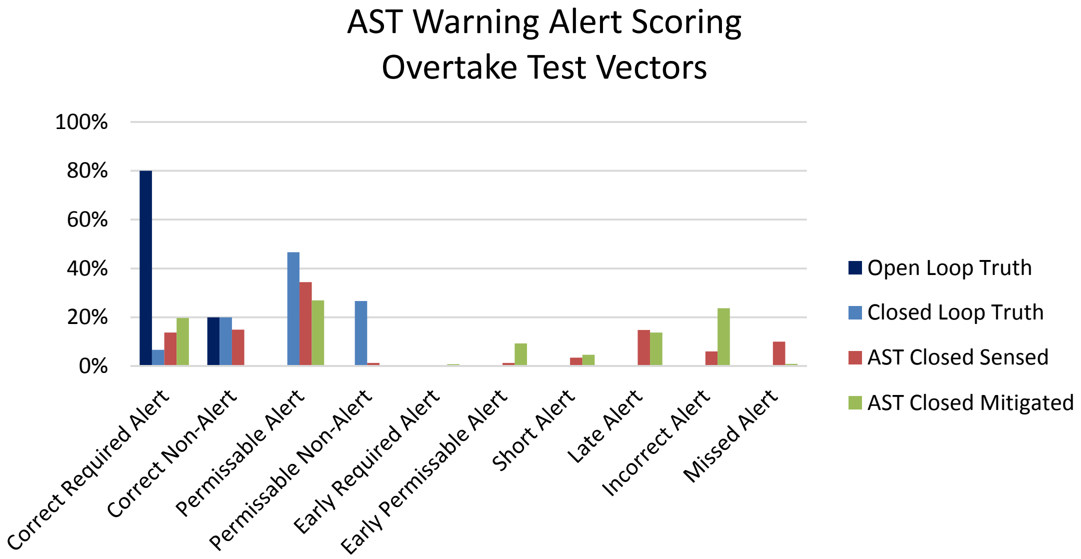

Figure 81. AST Warning Alert Scoring for Overtake MOPS Requirement-Derived Test Vectors

6.2.2.3 Automatic Dependent Surveillance – Broadcast (ADS-B) Warning Alerts

Figure 82 shows warning alert results for Head-On test vectors for the ADS-B sensor for closed loop testing. Results for the "Permissible Alert" scoring criteria show comparable findings when using closed loop Truth (40%), Sensed (41%), and Mitigated (38%) guidance. Comparable findings across the three guidance types were also observed for the "Permissible Non-Alert" scoring criteria (Truth = 33%, Sensed = 25%, and Mitigated = 33%).

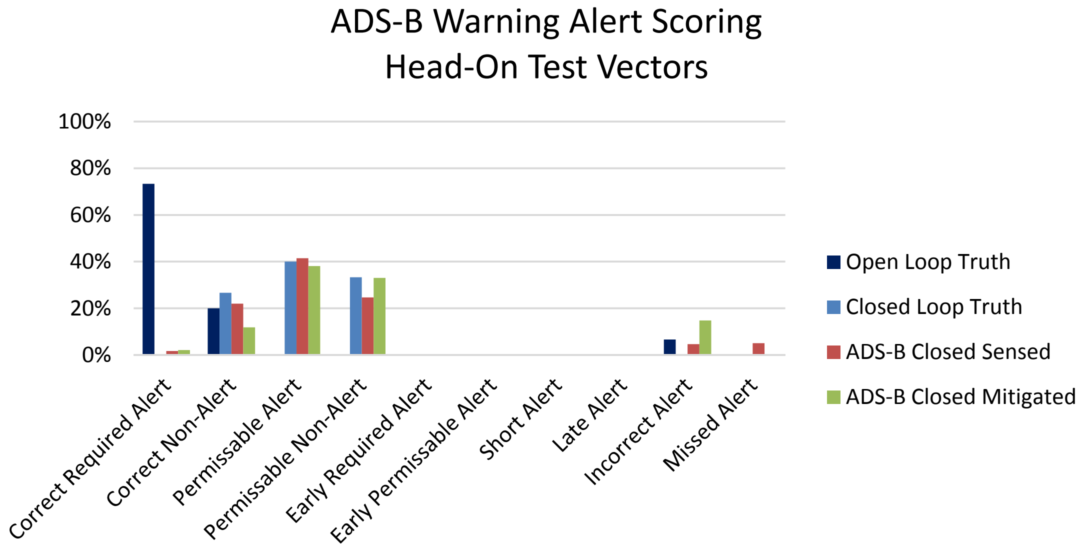

Figure 82. ADS-B Warning Alert Scoring for Head-On MOPS Requirement-Derived Test Vectors

Results for Converging test vectors for the ADS-B sensor are shown in Figure 83. Truth guidance findings in closed loop show 95% of encounters were within the "Permissible Alert" scoring criteria while 93% of encounters received the same alert when Sensed guidance was used and 91% when Mitigated guidance was used. Although Mitigated guidance shows a lesser percentage for permissible alerts when compared to Truth and Sensed guidance, findings show that 7% of encounters received early permissible alerts when the Mitigated guidance was used. This shows that the SUM approach slightly shifted encounters from within the "Permissible Alert" and "Permissible Non-Alert" scoring criteria when Sensed guidance was used by alerting the pilot model of an impending intruder aircraft at an earlier permissible time within the scenario. Warning alert scoring results for this type of encounter geometry are similar to those of the corrective alert scoring results that were presented in Figure 69.

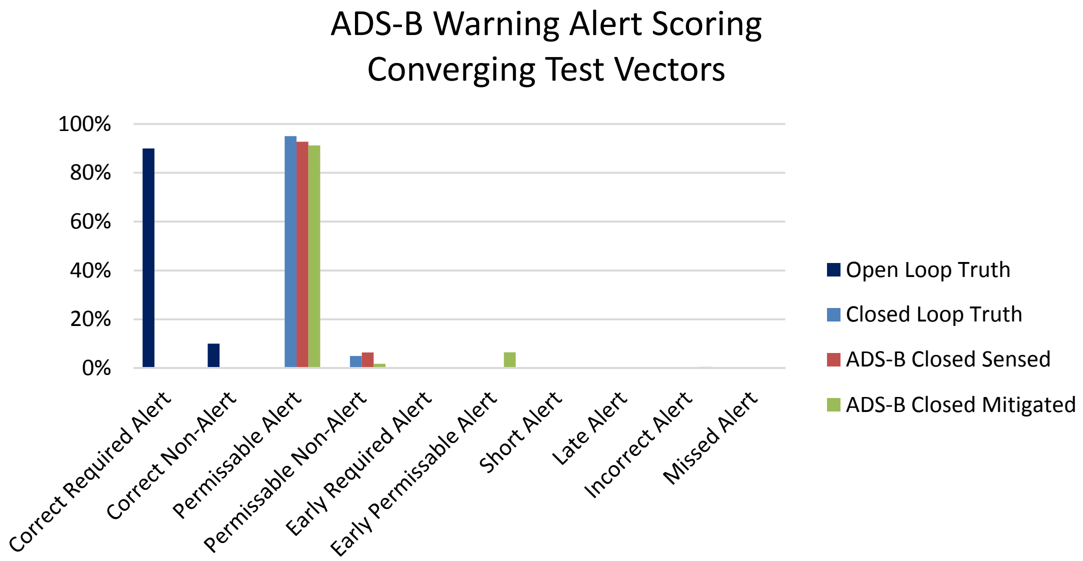

Figure 83. ADS-B Warning Alert Scoring for Converging MOPS Requirement-Derived Test Vectors

Figure 84 shows results for High Speed test vectors for the ADS-B sensor. Closed loop findings show that ADS-B sensor guidance performed better in High Speed encounters than in other encounter geometries when the ADS-B sensor was tested. Permissible alerts were received for 78% of encounters when both Truth guidance was used. When Sensed guidance was used, 79% of encounters received similar alerts and 75% when Mitigated guidance was used. Mitigated guidance showed a slightly higher percentage of encounters (~3%) received permissible non-alerts in comparison to when Truth (22%) and Sensed (21%) guidance was used.

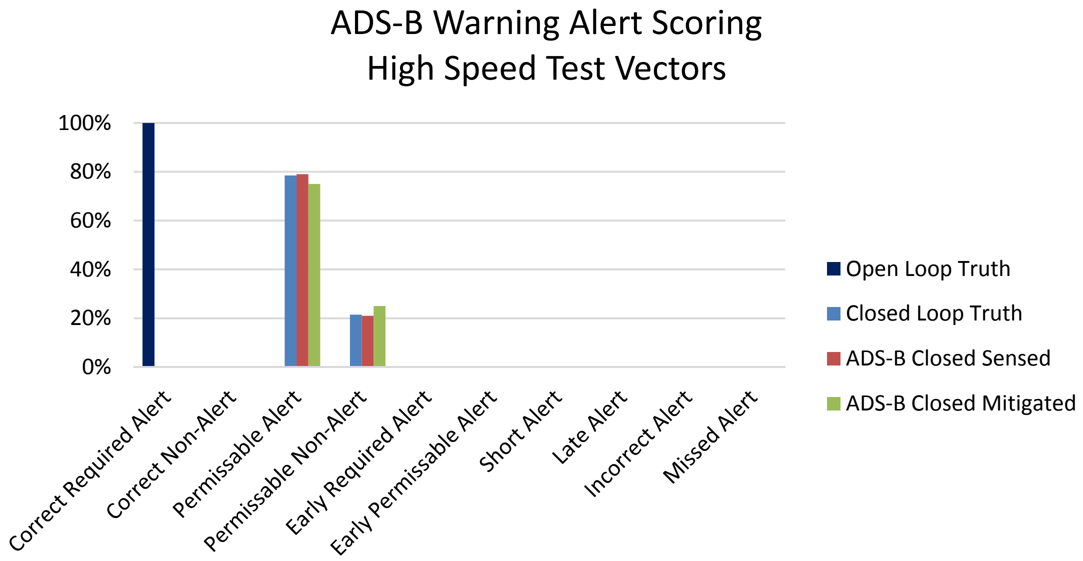

Figure 84. ADS-B Warning Alert Scoring for High Speed MOPS Requirement-Derived Test Vectors

Results for Maneuvering test vectors for ADS-B-based guidance are shown in Figure 85. The majority of closed loop encounters (73%) using Truth guidance were observed within the "Correct Required Alert" scoring criteria while 37% were observed using Sensed guidance and 47% when Mitigated guidance was used. Sensed guidance runs were predominantly (47%) within the "Late Alert" scoring criteria for maneuvering encounters; the SUM approach was able to decrease the percentage of encounters within that scoring criteria to only 20%.

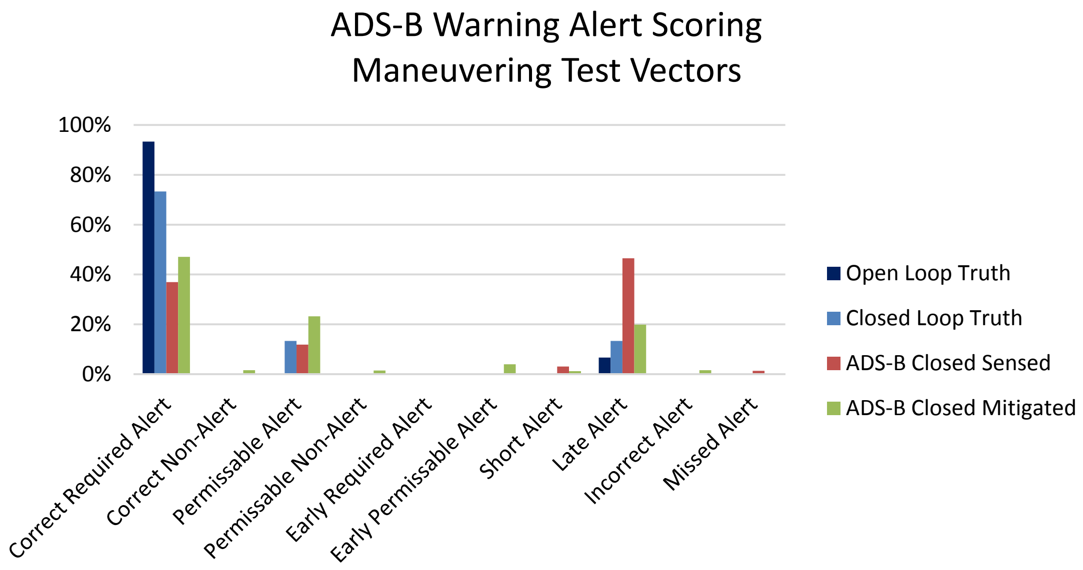

Figure 85. ADS-B Warning Alert Scoring for Maneuvering MOPS Requirement-Derived Test Vectors

Results for Overtake test vectors for ADS-B are shown in Figure 86. Truth guidance runs show 44% of closed loop encounters being within the "Permissible Alert" scoring criteria while 31% of encounters were within the "Permissible Non-Alert" criteria and the remaining encounters received both correct required alerts and correct non-alerts. Sensed guidance shows 45% of test vectors received permissible alerts. The SUM model approach showed results for 44% of encounters within the "Permissible Alert" scoring criteria.

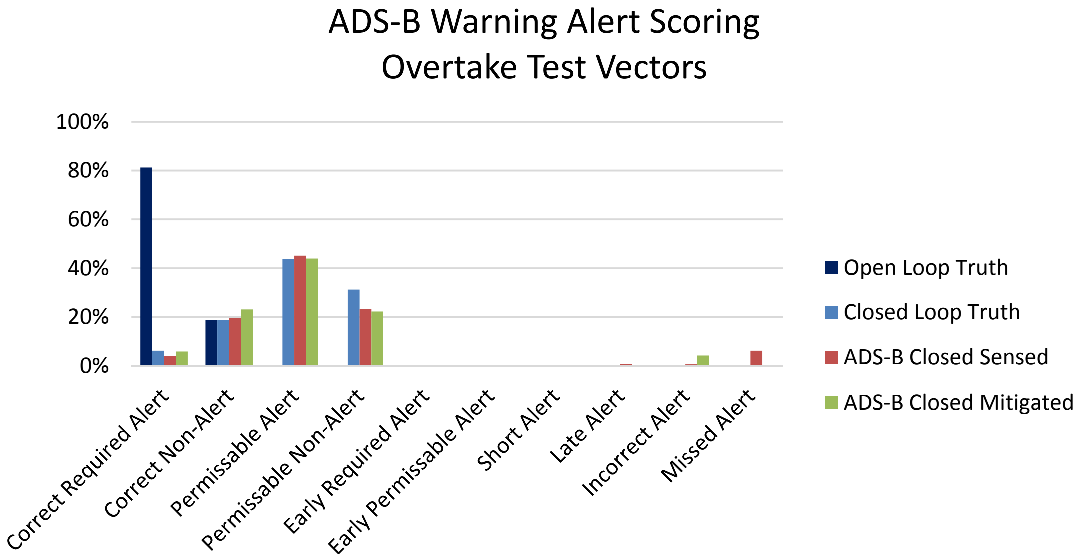

Figure 86. ADS-B Warning Alert Scoring for Overtake MOPS Requirement-Derived Test Vectors

6.3 Alert Jitter

6.3.1 Radar Alert Jitter

Figure 87 shows an alert jitter histogram for the radar sensor used for Head-On test vectors in a closed loop simulation. Open loop results with Truth guidance, which were evaluated against closed loop encounters, show 33% of encounters with an alert jitter of "0" indicating no alerts were given, which is undesirable. 33% of open loop Truth runs resulted in an alert jitter of "1" and the remaining third had an alert transition of "2," which is the desirable number of increasing alerts. Closed loop Truth guidance matched results of open loop guidance for alert jitter of "0" and "1" but shows 0% of encounters experienced an alert jitter of "2." Sensed guidance results were distributed across the spectrum; however, Mitigated results show that the SUM approach significantly tightened the distribution, to the extent that 65% of encounters received the ideal alert jitter of "2."

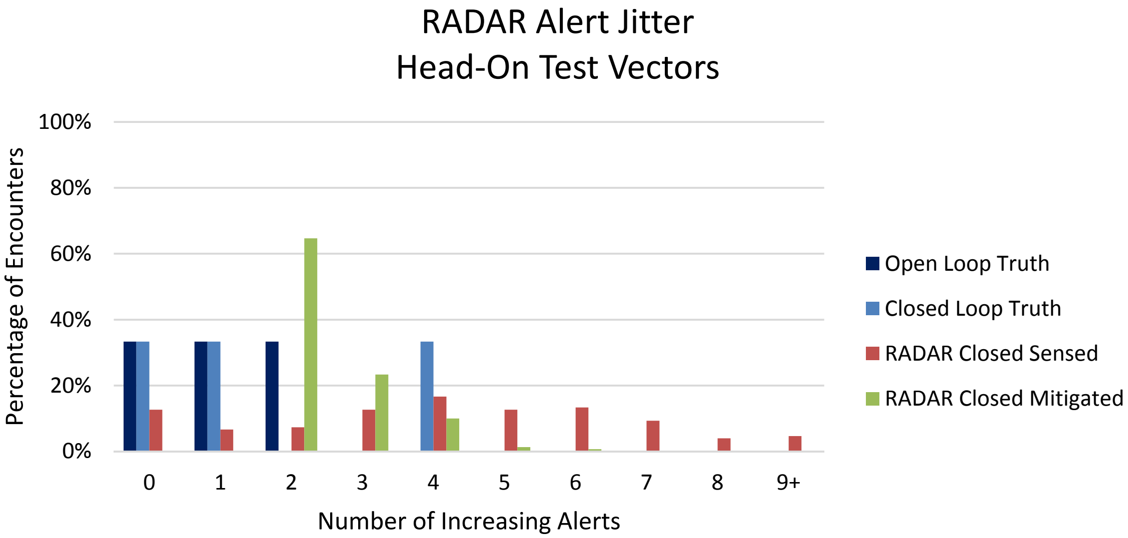

Figure 87. Radar Alert Jitter for Head-On MOPS Requirement-Derived Test Vectors

Figure 88 shows an alert jitter histogram for Converging test vectors in a closed loop simulation. Open loop results with Truth guidance show the majority of encounters (70%) presented the ideal number of increasing alerts, an alert jitter value of "2." Closed loop results show only 20% of encounters had an alert jitter value of "2" using Truth guidance, and 16% of encounters when Sensed guidance was used. Mitigated results show that the SUM approach significantly improved the distribution of Sensed results, and increased encounters with an alert jitter value of "2" to 37%.

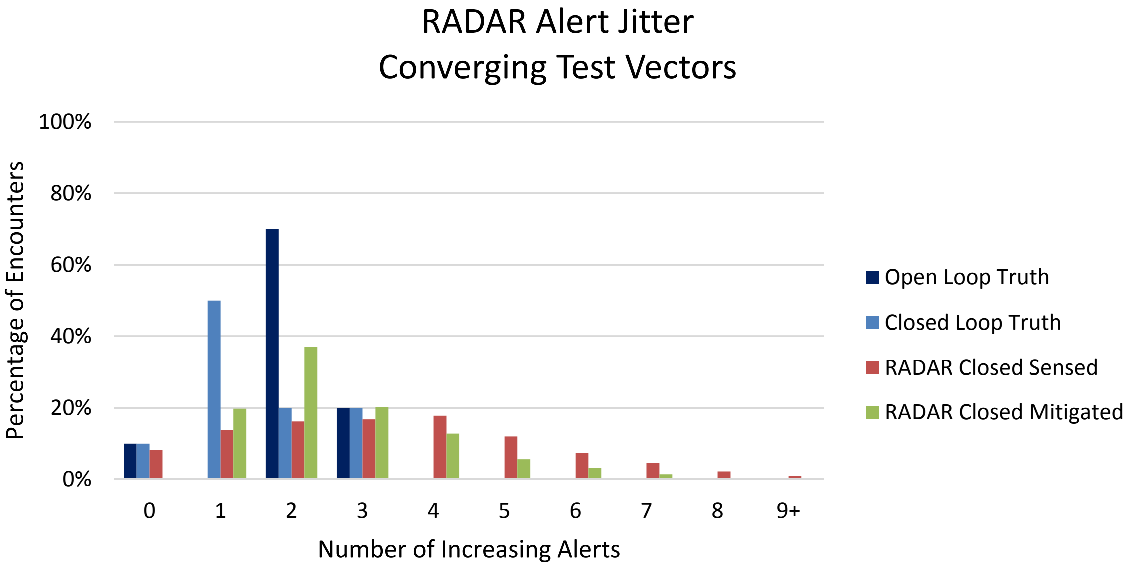

Figure 88. Radar Alert Jitter for Converging MOPS Requirement-Derived Test Vectors

An alert jitter histogram for Maneuvering test vectors is shown in Figure 89 for radar-based guidance. Open loop and closed loop results with Truth guidance show 100% of encounters presented the ideal number of increasing alerts, which is a value of “2” alerts per encounter. Closed loop Sensed guidance shows only 24% of encounters had an alert value of “2,” and only 3% of encounters when Mitigated guidance was used. Mitigated results show that, although the SUM approach did eliminate one part of the tail of the Sensed distribution, it also shifted a significant portion of Sensed encounters with an alert jitter value of “2” to a jitter value of “1.”

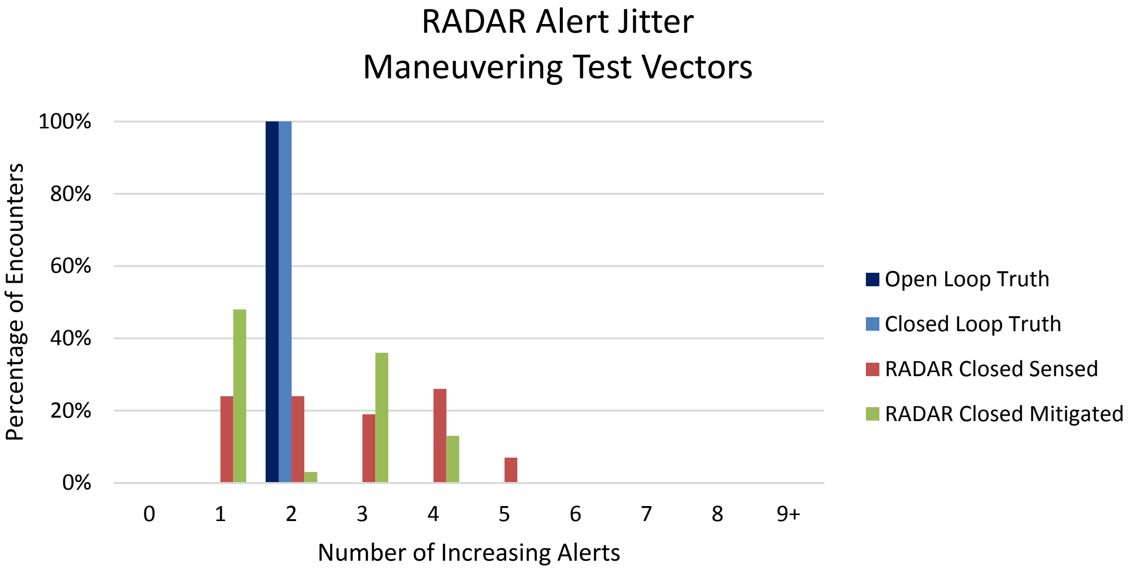

Figure 89. Radar Alert Jitter for Maneuvering MOPS Requirement-Derived Test Vectors

Alert jitter results for Overtake test vectors are shown in Figure 90 for radar-based guidance. Open loop results with Truth guidance show the majority of encounters (67%) received two alert transitions while the remaining 33% received only one alert transition. Closed loop Truth guidance shows 33% of encounters received an alert jitter of "2" while 67% received one alert transition. As expected, Sensed guidance results show a fairly wide distribution of alert jitter values. However, Mitigated results show that the SUM model approach somewhat increased the number of encounters with an alert jitter value of "2," but had very little effect on the distribution.

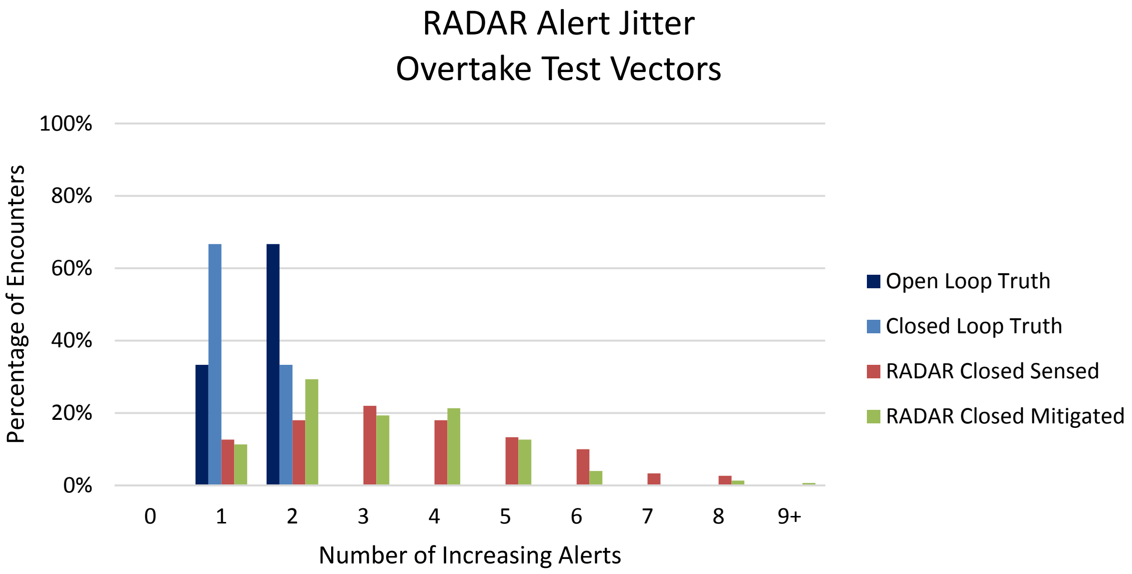

Figure 90. Radar Alert Jitter for Overtake MOPS Requirement-Derived Test Vectors

6.3.2 Active Surveillance Transponder (AST) Alert Jitter

Figure 91 shows an alert jitter histogram for the AST sensor used for Head-On test vectors in a closed loop simulation. Open loop results with Truth guidance show 50% of encounters received the desired two alert transitions. Closed loop Truth runs, however, only show 14% of encounters received two alert transitions while the majority of encounters received either one (36%) or three (36%) alert transitions. Sensed and Mitigated results show sporadic findings across all transition alert levels (0–9+); however, the SUM approach shifted the distribution slightly to the right. Across all alert jitter results, the DAA system performed least favorably using AST-based guidance.

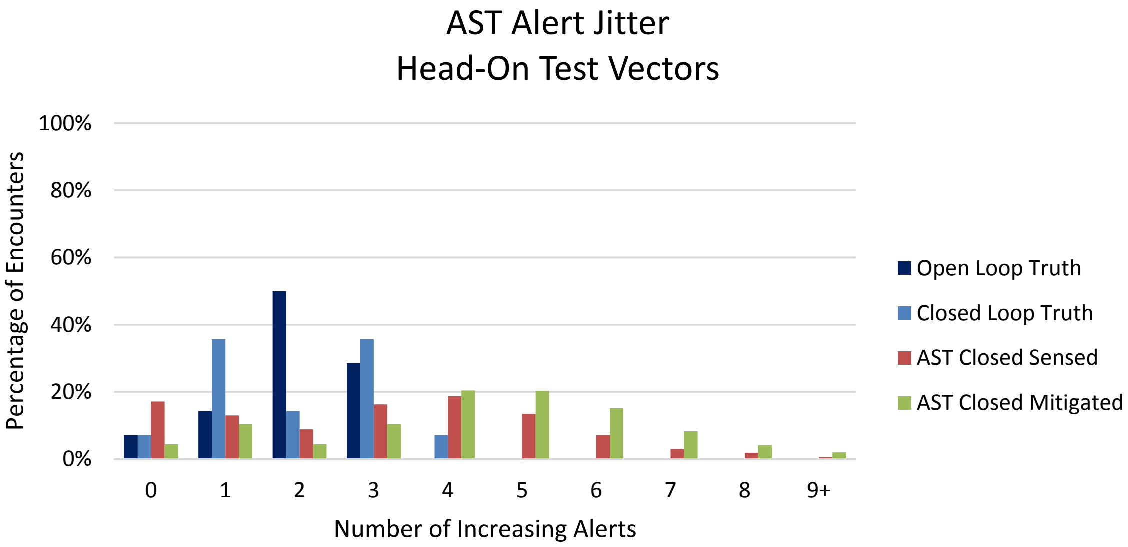

Figure 91. AST Alert Jitter for Head-On MOPS Requirement-Derived Test Vectors

Figure 92 shows an alert jitter histogram for Converging test vectors in a closed loop simulation. Open loop results with Truth guidance show the majority of encounters (77%) received the ideal number of alert transitions, "2." Closed loop Truth guidance shows only 23% of encounters had an alert jitter value of "2" while the majority of encounters (54%) received one alert transition. Sensed and Mitigated results show sporadic findings across all transition alert levels (0–9+).

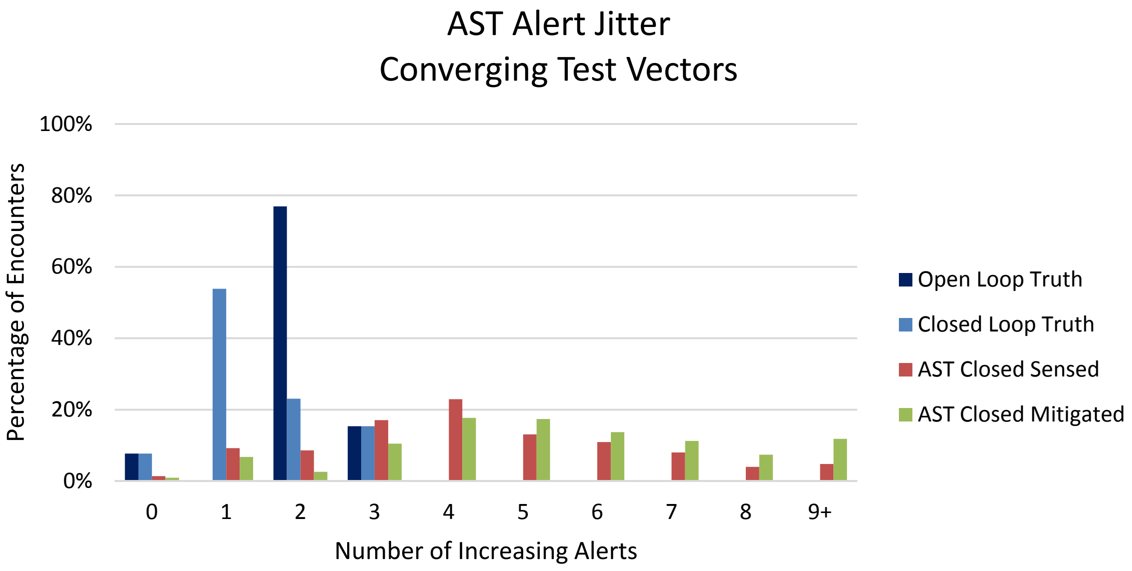

Figure 92. AST Alert Jitter for Converging MOPS Requirement-Derived Test Vectors

Alert jitter results for High Speed test vectors are shown in Figure 93 for AST-based guidance. Open loop results with Truth guidance show 100% of encounters received two alert transitions while 75% of closed loop Truth runs received two alert transitions. Findings for Sensed and Mitigated guidance runs show only 19% of encounters received the ideal number of alert jitter while the remaining encounters using Sensed and Mitigated guidance showed sporadic behavior across the remaining transition alert levels.

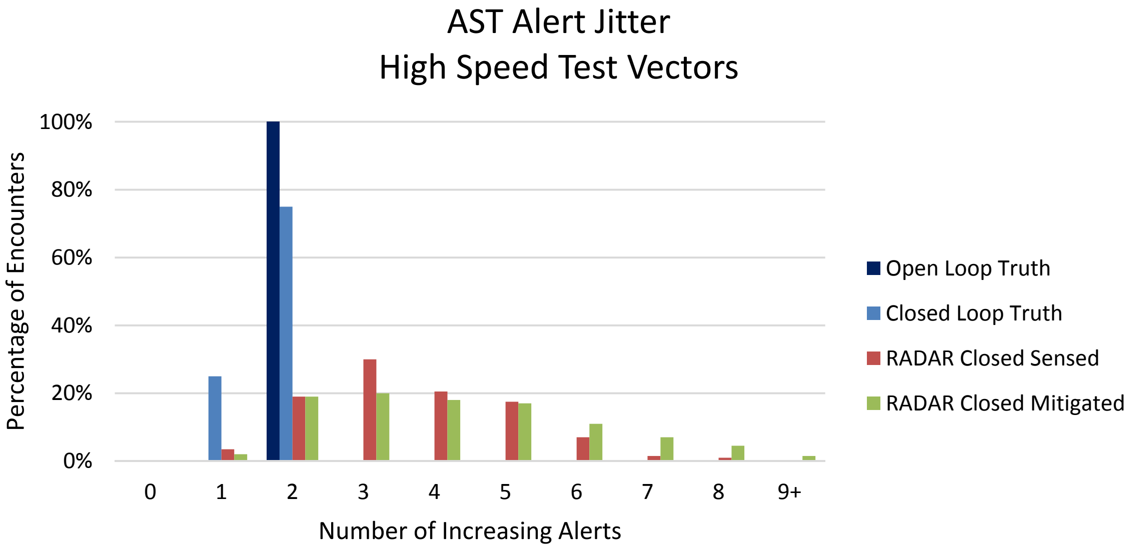

Figure 93. AST Alert Jitter for High Speed MOPS Requirement-Derived Test Vectors

An alert jitter histogram for Maneuvering test vectors is shown in Figure 94. Open loop and closed loop results with Truth guidance show 57% of encounters presented the ideal number of increasing alerts, which is a value of "2" alerts per encounter, while the remaining 43% received one alert transition. Sensed and Mitigated guidance showed sporadic behavior across the presented transition alert levels (0–9+).

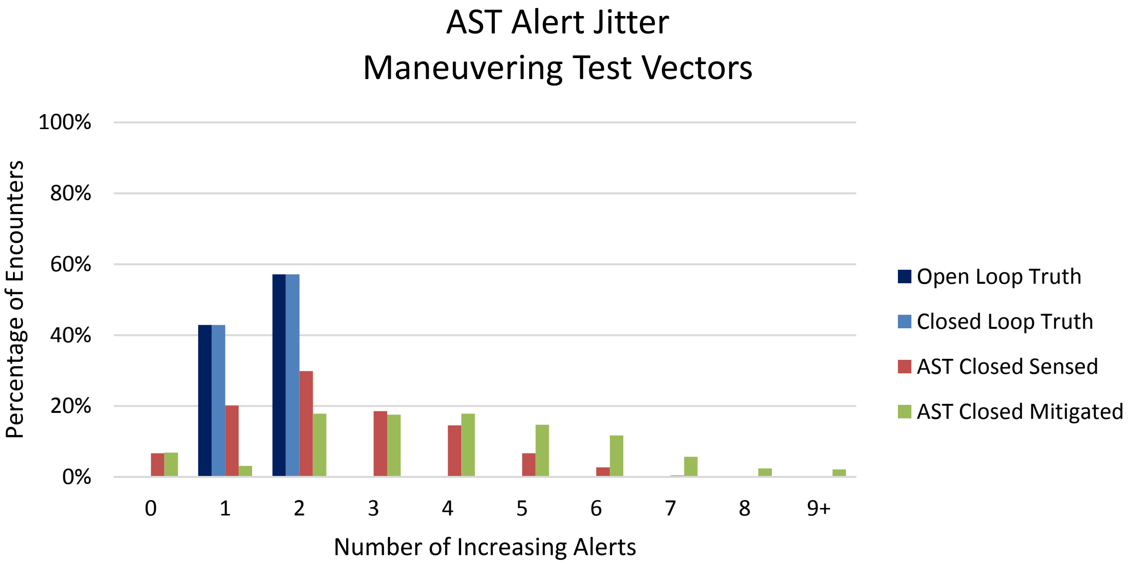

Figure 94. AST Alert Jitter for Maneuvering MOPS Requirement-Derived Test Vectors

Alert jitter results for Overtake test vectors are shown in Figure 95 for AST-based guidance. Open loop results with Truth guidance show 40% of encounters received two alert transitions, 20% received one alert transition, and 33% received three alert transitions. Closed loop Truth guidance shows 33% of encounters received an alert jitter of "2" and another 33% of encounters received one alert transition. Mitigated results show sporadic findings across presented transition alert levels (0–9+). In alert jitter, AST-based guidance caused the DAA system to perform least favorably among other sensor-based guidance.

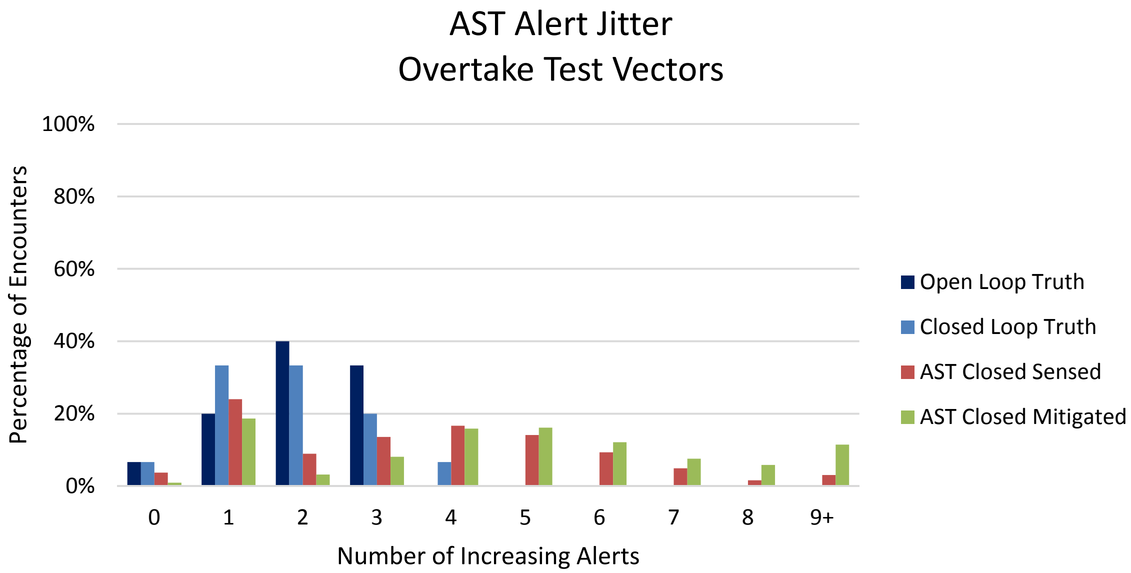

Figure 95. AST Alert Jitter for Overtake MOPS Requirement-Derived Test Vectors

6.3.3 Automatic Dependent Surveillance – Broadcast (ADS-B) Alert Jitter

Figure 96 shows an alert jitter histogram for Head-On test vectors for the ADS-B sensor used in a closed loop simulation. Open loop results with Truth guidance show 53% of encounters received two alert transitions while the remaining encounters received either zero alerts (7%), one alert transition (13%), or three alert transitions (27%). Closed loop Truth guidance shows 13% of encounters experienced an alert jitter of “2” which dropped to 27% of encounters when Sensed guidance was used. Mitigated results, however, show that the SUM approach somewhat tightened the Sensed distribution, enabling 39% of encounters to receive the ideal number, “2,” of alert transitions.

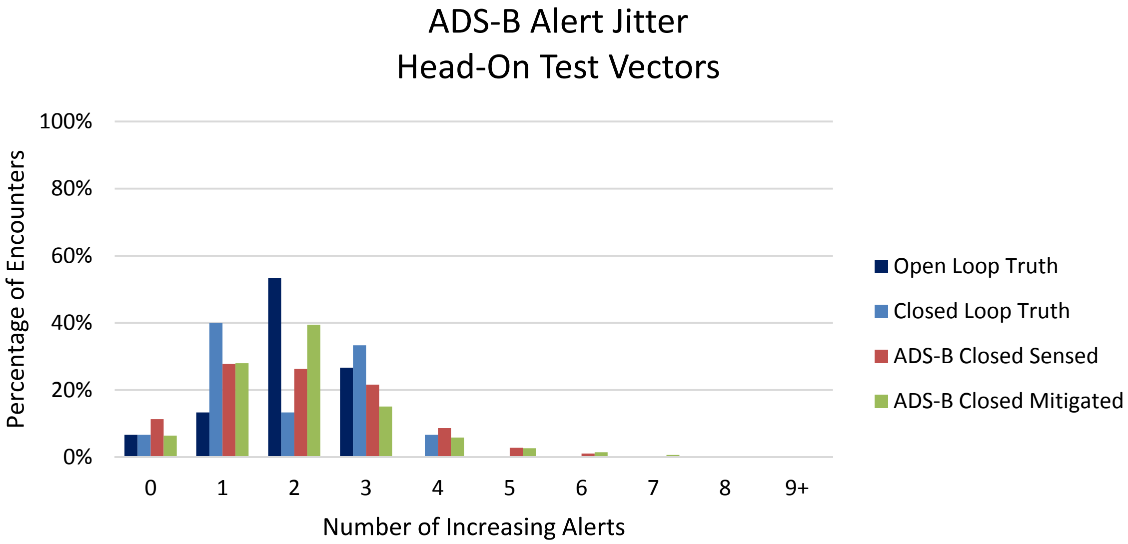

Figure 96. ADS-B Alert Jitter for Head-On MOPS Requirement-Derived Test Vectors

Figure 97 shows an alert jitter histogram for Converging test vectors in a closed loop simulation. Results for open loop runs using Truth guidance show the majority of encounters (80%) received two alert increases. Closed loop Truth guidance shows only 25% of encounters received two, while the majority of encounters (60%) received one alert transition. For runs using Sensed guidance, results show a distribution somewhat similar to the Truth distribution for the first four jitter values, but with a much longer tail. Mitigated guidance tightens the distribution only slightly and does not eliminate the significant tail.

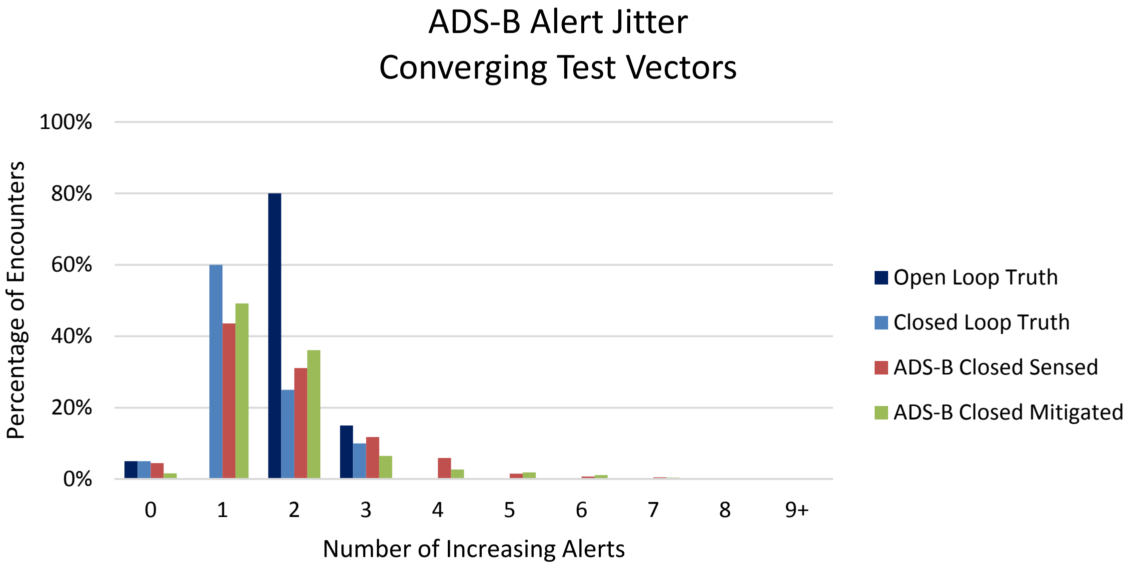

Figure 97. ADS-B Alert Jitter for Converging MOPS Requirement-Derived Test Vectors

Alert jitter results for High Speed test vectors are shown in Figure 98 for ADS-B-based guidance. Open loop Truth guidance results 100% of encounters received two alert transitions while 75% of closed loop Truth runs received an alert jitter of “2.” 61% of encounters received two alert transitions when Sensed guidance was used, with very few greater than two. The SUM approach tightened the distribution slightly.

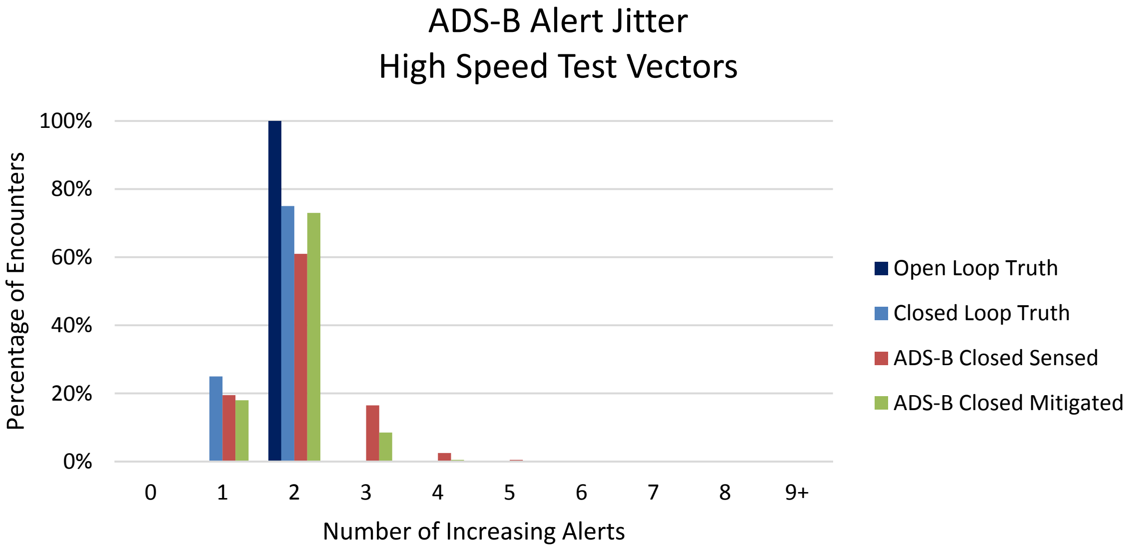

Figure 98. ADS-B Alert Jitter for High Speed MOPS Requirement-Derived Test Vectors

Alert jitter results for Maneuvering test vectors are shown in Figure 99 for ADS-B-based guidance. Results for open loop and closed loop runs using Truth guidance show 53% of encounters received two alert transitions whiles 47% of encounters received one alert jitter. Closed loop Sensed guidance shows 47% of encounters had an alert jitter value of "2" and 35% had an alert jitter value of "1." The SUM approach actually worsened the situation, reducing the number of encounters with one, two, and three alert increases and causing four or more alert increases in over a third of the Maneuvering Test Vector encounters.

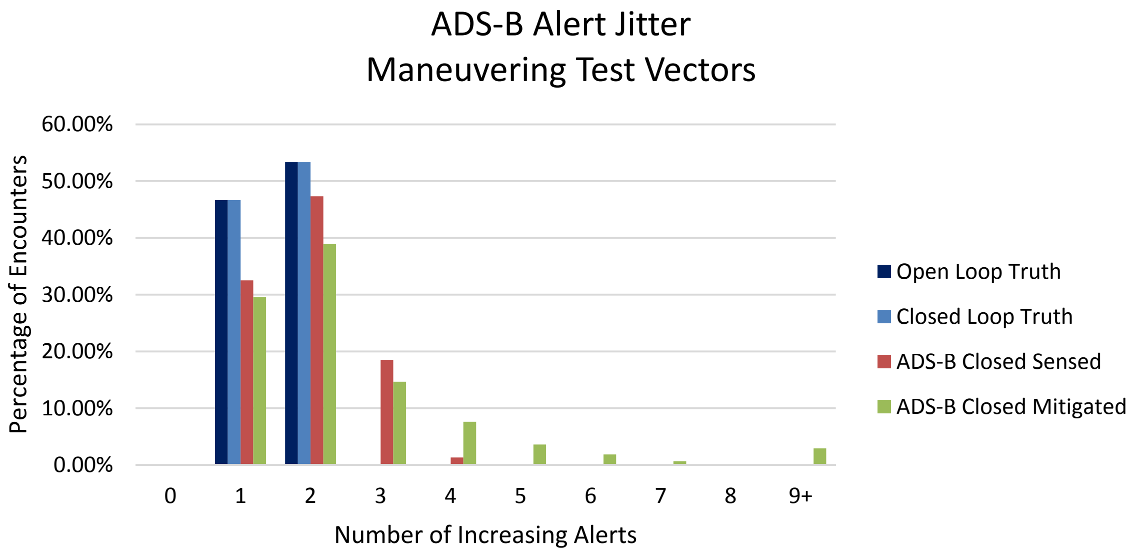

Figure 99. ADS-B Alert Jitter for Maneuvering MOPS Requirement-Derived Test Vectors

Alert jitter results for Overtake test vectors are shown in Figure 100 for ADS-B-based guidance. Open loop results with Truth guidance show a small distribution of encounters around an alert jitter value of "2" (44% received two alert transitions, 31% received three alert transitions, 19% received one alert transition and 6% received no alerts). Closed loop Truth results show a widening distribution, with fewer encounters (31%) receiving two alert transitions and more (38%) receiving one alert transition. Sensed results are similar to Truth, except with a significant tail. Mitigated results show comparable findings to closed loop Truth and Sensed.

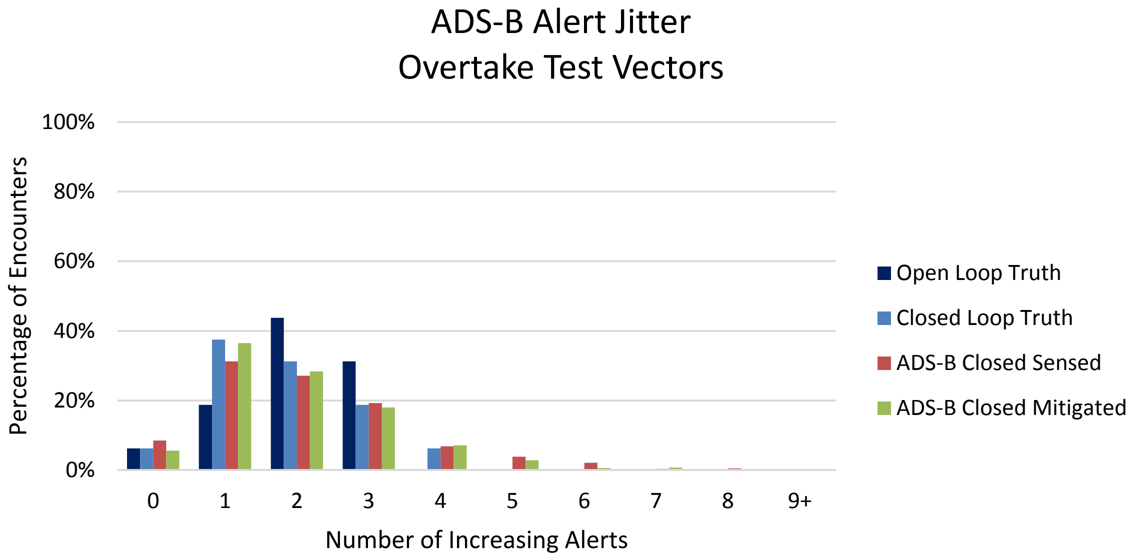

Figure 100. ADS-B Alert Jitter for Overtake MOPS Requirement-Derived Test Vectors

6.4 “Off-Nominal” Cases

In order to determine the causes behind the encounters in E2-V2 where high max SLoWC was measured, a few of the most severe cases were investigated individually. Cases with SLoWC above 70% which were also determined to have entered the NMAC volume at Closest Point of Approach (CPA) were selected for further analysis from the overall pool of closed-loop encounters. Replay animations and time history charts were used to analyze each case. Each high SLoWC case was compared to its respective truth surveillance run to determine whether inconsistent or incorrect guidance caused the pilot model to maneuver towards the intruder or if a LoWC was physically unavoidable given the encounter geometry. Three overall causes were uncovered in the case studies: maneuvering intruders which were impossible to avoid, the unrealistic behavior of the pilot model, and the guidance which resulted from the sensor uncertainty mitigation under certain conditions.

Maneuvering encounter 304 demonstrates a case where the blunder maneuver of the intruder creates a situation where a LoWC was unavoidable. The intruder aircraft begins the encounter laterally offset by 2500 feet traveling at 600 KTAS and the ownship traveling in the opposite direction at 250 KTAS. At a range of approximately 3 nmi, the intruder aircraft initiates an abrupt 90° turn towards the ownship. Figure 101 illustrates the geometry of encounter 304 with the closed loop ownship track histories for each run. Overall, the ownship response to the maneuvering intruder was uniform with all runs making an initial right turn away from the intruder. When provided with truth data (black line in Figure 101) the ownship makes an initial right turn to avoid the intruder while it was on an unchanging course followed by a more drastic ownship maneuver when the intruder began its turn towards the ownship. Many of the mitigated runs (red lines in Figure 101) also appear to follow this pattern of making an initial maneuver followed by a larger avoidance maneuver.

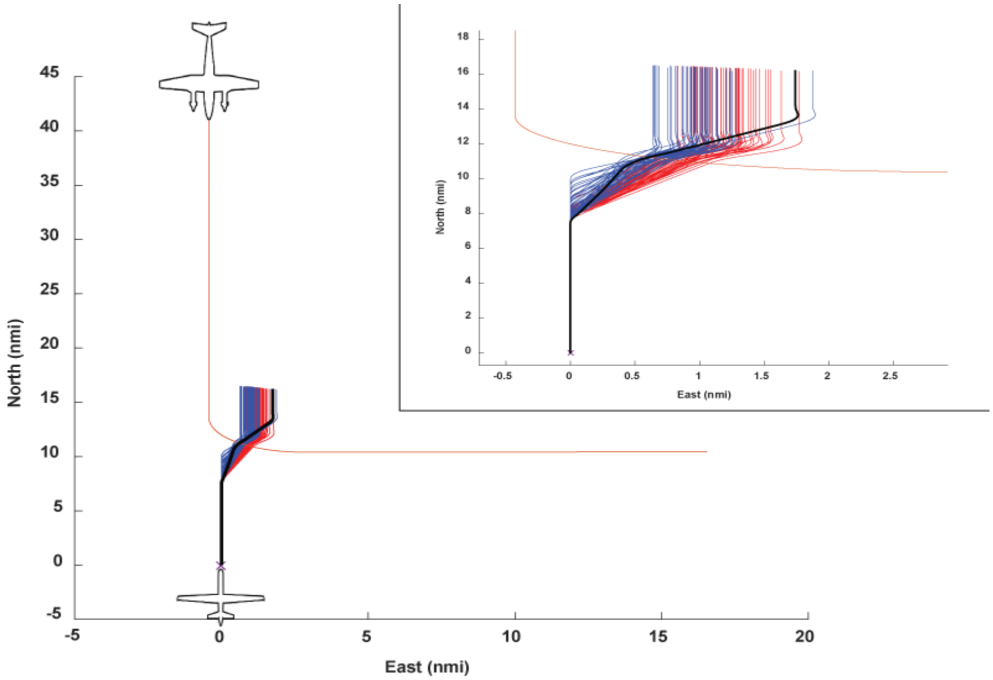

Figure 101. Track History for Encounter 304

The SLoWC histogram of all runs for encounter 304 (Figure 102) demonstrates that a LoWC was unavoidable for encounter 304. The severity of loss of well clear for all encounters ranged from 47% to 99% maximum SLoWC. The sensor uncertainty mitigation appeared to reduce the SLoWC compared to the truth and sensed runs, primarily due to the magnitude and timing of the initial ownship turn before the intruder's blunder which increased separation between the ownship and intruder.

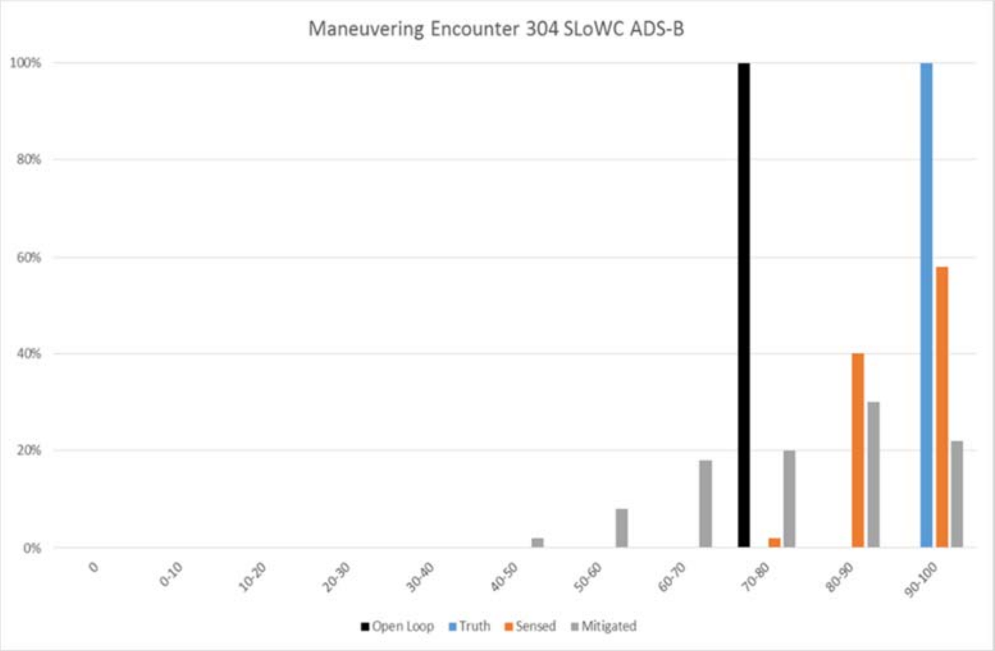

Figure 102. Histogram of all runs for Encounter 304

Figure 103 is a heading, alerting, and guidance time history of encounter 304 using truth surveillance data. The X-axis represents time in seconds since the start of the encounter and the Y-axis represents heading deviation of the ownship from the start heading. The current heading of the ownship is represented as a gray heading if no DAA alert is present, yellow if corrective alert is present and red if a warning alert is present. The black dots represent the heading commanded by the pilot model. The position of the DAIDALUS avoidance bands relative to the initial heading for each time step in the simulation is represented as orange bars and the recovery bands as green bars. Estimated time to LoWC at each time step (read in seconds on the Y-axis) is represented by purple triangles; purple triangles at the zero line represents a measured LoWC. The encounter begins benignly with a correct required corrective alert and a commanded heading approximately 10° from the start heading. The alerting changes back to the no alert level with the estimated time to LoWC reaching approximately 30 seconds. At 190 seconds after the beginning of the scenario the avoidance bands abruptly grow and a late warning alert was logged with a LoWC and NMAC subsequently logged. The pilot model eventually commanded a 30° heading change after the LoWC and returned to start heading after a LoWC was no longer projected by DAIDALUS. The maximum SLoWC measured in this run was 92% with an eventual CPA of 358 feet. The simultaneous warning alert and LoWC, with no immediately preceding alerting and guidance, using truth data, essentially means a LoWC was unavoidable. It is conceivable that a large avoidance maneuver very early in the encounter may have avoided a loss of well clear, but alerting and guidance occurring that early would require an unacceptably significant expansion of the well clear volume.

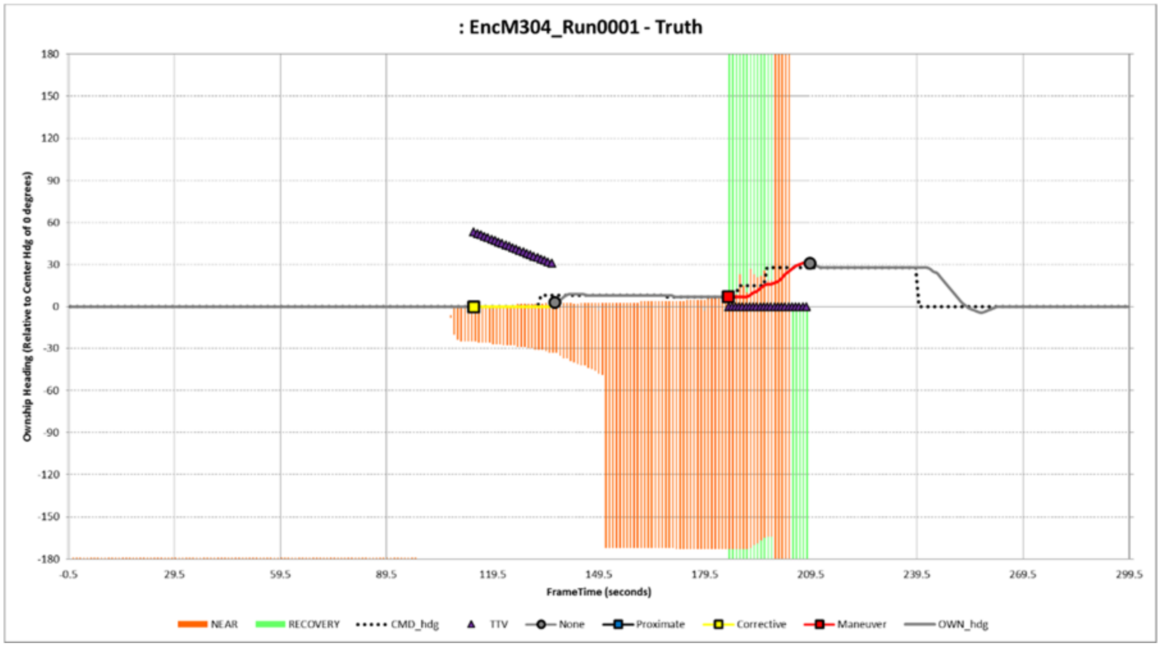

Figure 103. Alerting and Guidance Time History for Encounter 304 with Truth Surveillance Data

Figure 104 shows encounter 304 using sensed ADS-B surveillance data and displays a pattern similar to the truth surveillance data run. A correct required corrective alert was displayed and the pilot model commands a heading change of approximately 10° before a correct required warning alert was triggered. The estimated time to LoWC reaches approximately 23 seconds before the aircraft has maneuvered enough for the alerting to return to the no alert level. At 190 seconds after the start of the encounter a late DAA warning was triggered and a LoWC was subsequently logged. The pilot model immediately commanded a single heading change to approximately 20° before alerting and guidance no longer indicated a projected LoWC. The maximum SLoWC measured was 99.5% with an eventual CPA of 42 feet. Similar to the truth run for this encounter the simultaneous warning alert and LoWC indicate the abrupt blunder maneuver by the intruder aircraft made a LoWC unavoidable, however the smaller second commanded maneuver by the ownship in the sensed run apparently increased the severity of well clear loss.

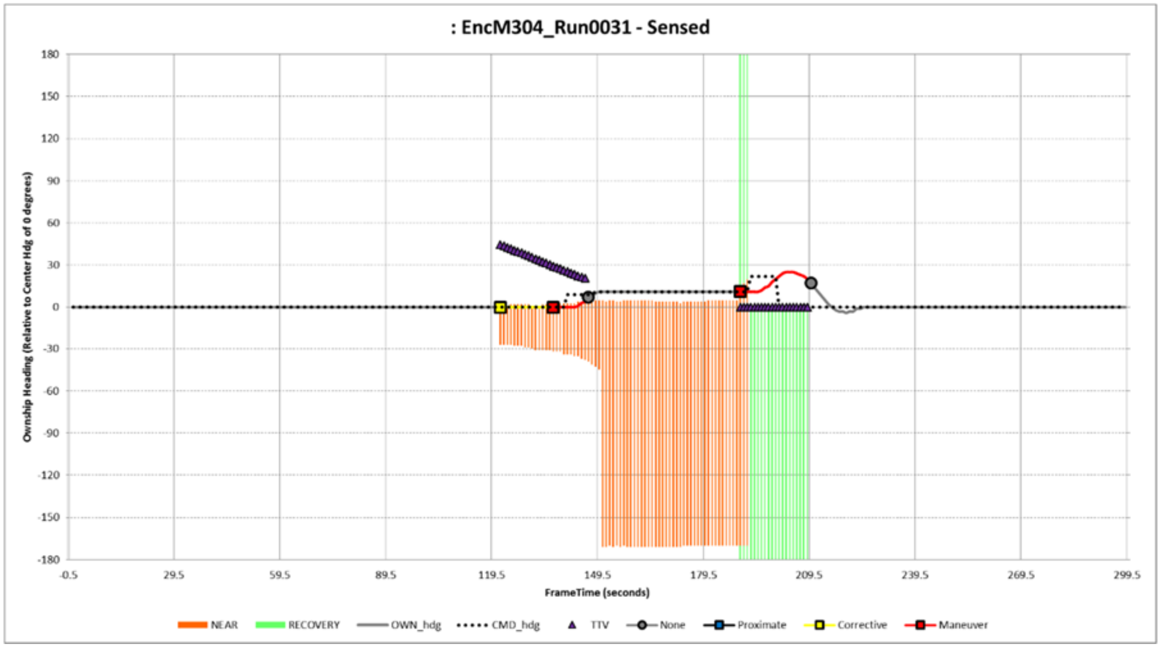

Figure 104. Alerting and Guidance Time History for Encounter 304 Sensed ADS-B Surveillance Senor

Figure 105 shows the alerting and guidance time history for encounter 304 using a mitigated ADS-B track. Once again a correct required corrective alert was displayed and a 25° heading deviation was commanded by the pilot model. A correct required warning alert was displayed before the alerting returned to the no alert level. A late warning alert and immediate LoWC were triggered by the maneuvering intruder, similar to the sensed run. The pilot model commanded an additional maneuver of about 40° before the alerting and guidance no longer indicated a projected LoWC and commanded a return to the start heading. The maximum SLoWC for this run was 48% with an eventual CPA of 1996 feet. In this case the sensor uncertainty mitigation caused the pilot model to make a larger initial deviation than was commanded in the truth or sensed runs, minimizing the max SLoWC and maximizing the CPA.

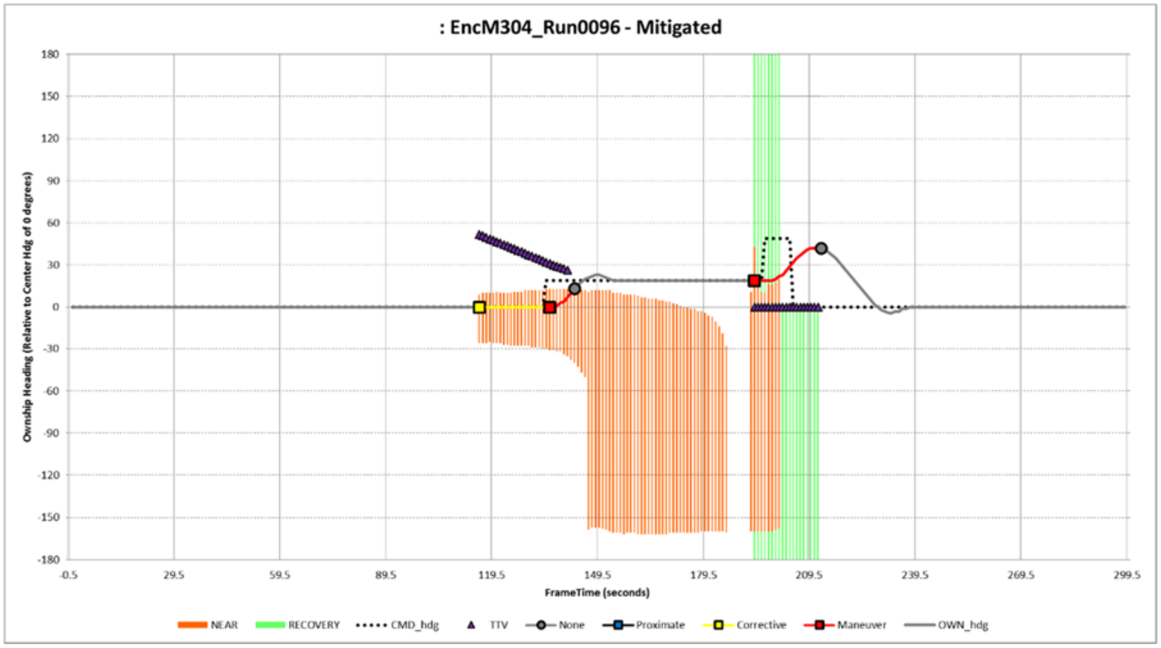

Figure 105. Alerting and Guidance Time History for Encounter 304 with Mitigated ADS-B Surveillance Sensor

The two other causes for high SLoWC encounters included unrealistic pilot model behavior and unusual guidance caused by the sensor uncertainty and mitigation. In cases where the sensed flight state is noisy or the guidance is frequently changing the favored direction of ownship maneuver, the pilot model can change the commanded heading from one direction to another. This can result in the ownship performing an initial correct deviation away from the intruder but then turn back towards the intruder or vice versa because of erroneous state information input to DAIDALUS. While it is possible a human UAS operator would follow guidance indicating a favored turn towards an oncoming intruder, it is more likely that a human operator would continue or increase an initial deviation. In cases where SUM is utilized and sensed flight state uncertainty is high, it is possible that the phantom intruders' future predicted flight states diverge to the point where the DAIDALUS algorithm can find well clear airspace between the phantom intruder as multiple aircraft. The net result of this in the DAA guidance was multiple, segmented bands which can lead the pilot model to maneuver between bands only for them to merge into a single band when the intruder approaches close enough.

Head-on encounter 216 using the AST sensor provides examples of both unrealistic pilot model behavior and sensor uncertainty mitigation which caused higher SLoWC values in some cases. The encounter begins with the intruder at a 3600 feet lateral offset at 600 KTAS while the ownship is at 200 KTAS flying in the opposite direction. The intruder was in a 1500 ft/min descent while the ownship was climbing at 1000 ft/min. Figure 106 shows that the track histories of the truth (black line), sensed (blue lines) and mitigated runs (red lines) are widely scattered between making left and right deviations, indicating the AST sensor produced multiple, scattered, intruder tracks under identical (Truth) circumstances.

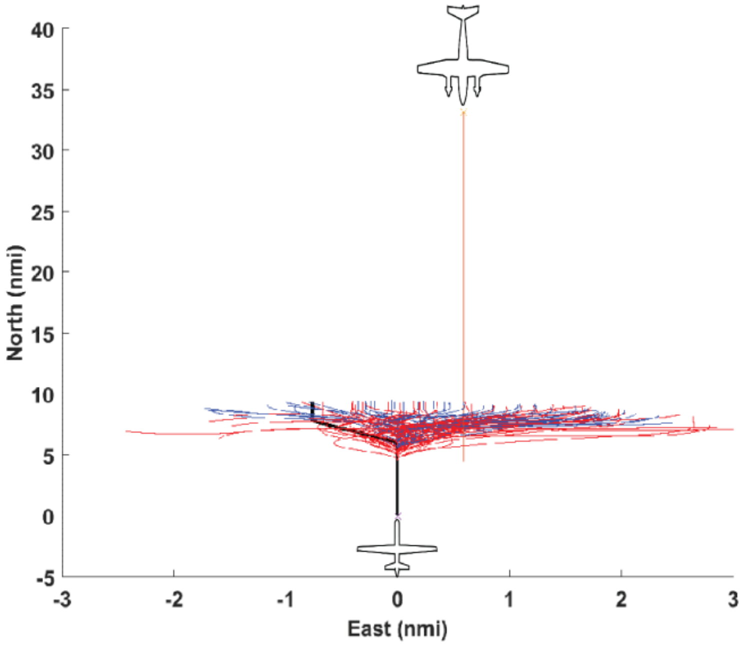

Figure 106. Track History for Encounter 216 with AST Surveillance Sensor

The SLoWC histogram of all runs for encounter 216 (Figure 107) shows that a large proportion of the sensed and mitigated runs avoided a LoWC altogether, indicating that LoWC occurrences were avoidable. Although the distribution of maximum SLoWC appears to be skewed towards low values or no LoWC, there were a significant number of runs above 70%.

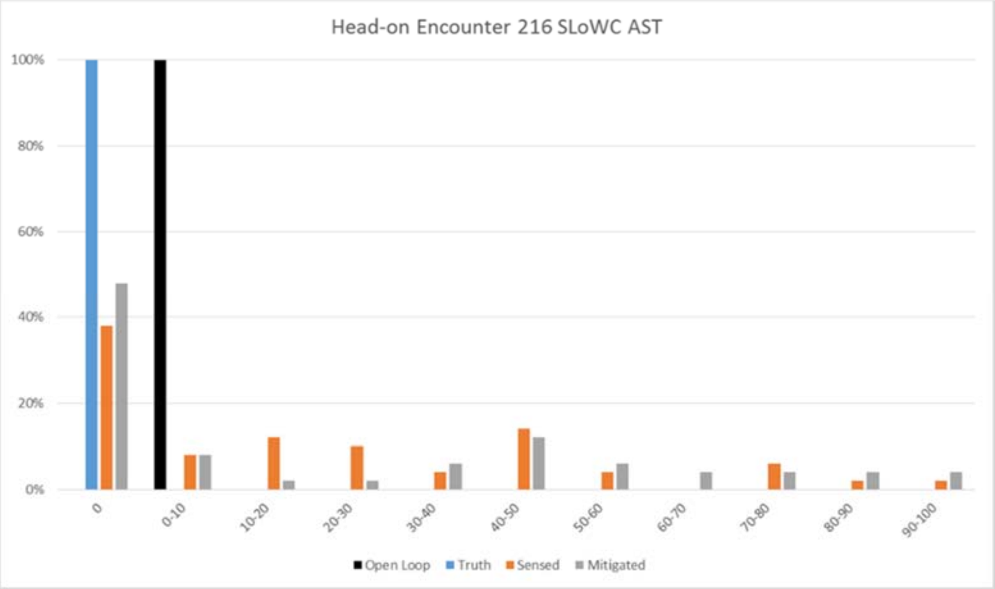

Figure 107. Maximum SLoWC Histogram for Encounter 216 with AST Surveillance Sensor

Figure 108 shows the alerting and guidance time history for encounter 216 using truth data. A permissible corrective alert was triggered followed by a single deviation commanded by the pilot model and alerting subsequently stopped indicating a loss of well clear; it was no longer predicted. A LoWC was not logged in this run and the CPA was well outside the lateral distance alerting threshold at 8209 feet.

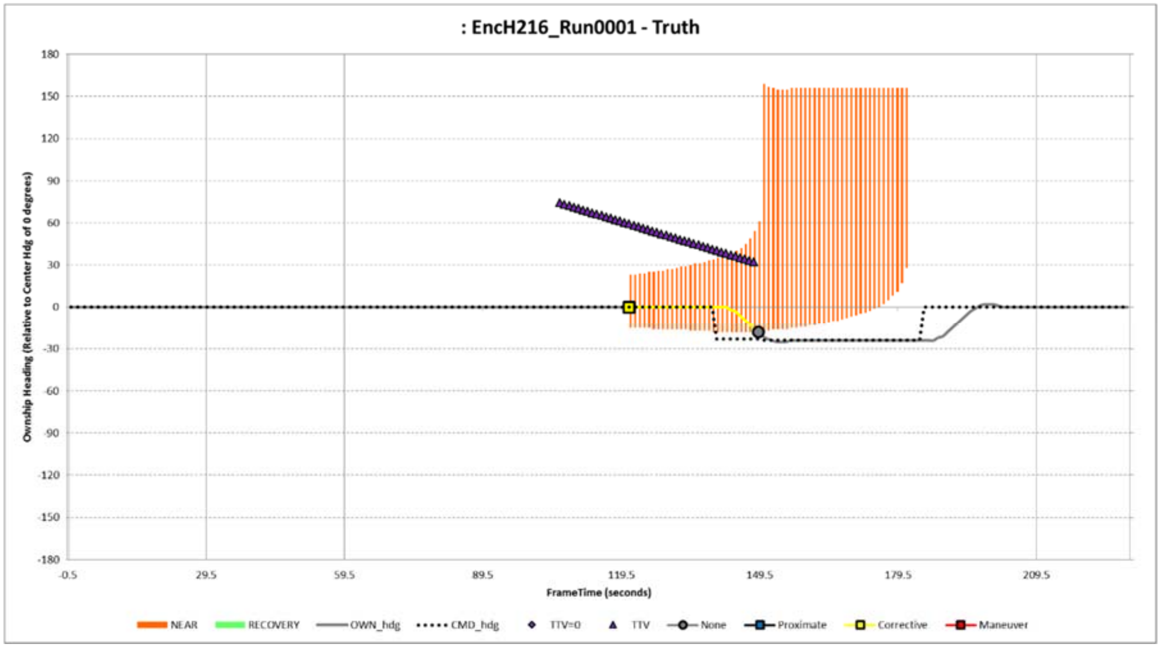

Figure 108. Alerting and Guidance Time History for Encounter 216 with Truth Surveillance Data

Figure 109 shows the alerting and guidance time history for encounter 216 using the AST surveillance sensor. The encounter begins with guidance bands off to one side of the ownship aircraft's nose which shift to cause a correct required corrective alert. The corrective alert was extinguished and almost immediately triggered again before being extinguished again. A correct required warning alert was triggered and the pilot model immediately commands a 15° deviation followed approximately 10 seconds later by a commanded 65° deviation following the changing band guidance. Following this, the recovery guidance bands briefly indicate a turn in the opposite direction was desired and the pilot model commanded an 89° turn in the opposite direction as a response. Three seconds after the change in direction was commanded, a LoWC was logged. The ownship began to change directions to follow the commanded heading, however the guidance bands once again reversed and the pilot model commanded a heading in the original direction. The ownship was eventually projected to be well clear of the intruder at 209 seconds after the start of the encounter. The maximum measured SLoWC was 78% and the eventual CPA was 847 feet. Although it is possible the ownship could have still lost well clear if the course reversal had not taken place, the reversal almost certainly increased the severity of well clear loss.

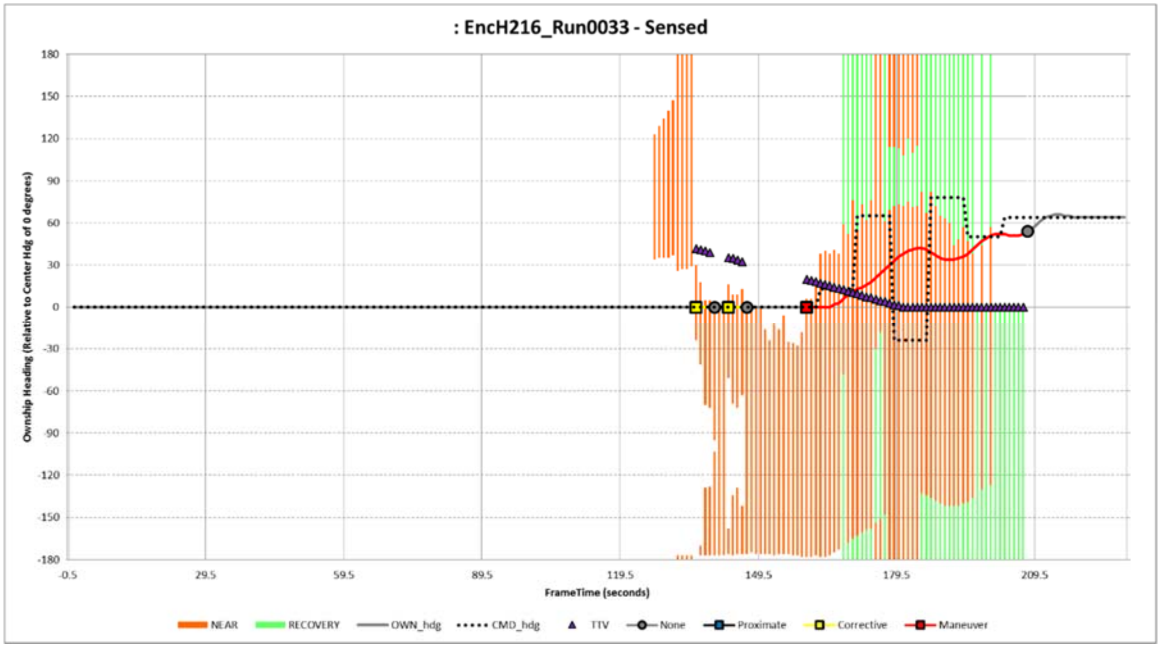

Figure 109. Alerting and Guidance Time History for Encounter 216 with Sensed AST Surveillance Sensor

Figure 110 shows the alerting and guidance time history for encounter 216 using the sensor uncertainty mitigation with the AST surveillance sensor. The effect of the high sensor uncertainty coupled with the uncertainty mitigation and high intruder speed caused segmented bands to be displayed starting at 108 seconds after the start of the encounter. This was a direct result of the DAIDALUS algorithm sensing the multiple phantom intruders being generated by the SUM as their projected flight states diverge. This caused the alerting to increase levels 6 times throughout the encounter and the commanded heading to change 7 times, with 2 complete commanded heading direction reversals. The measured maximum SLoWC was 93% and the eventual CPA was 237 feet. Future improvements to the SUM should prevent this issue by forcing the algorithm to sense only one phantom intruder.

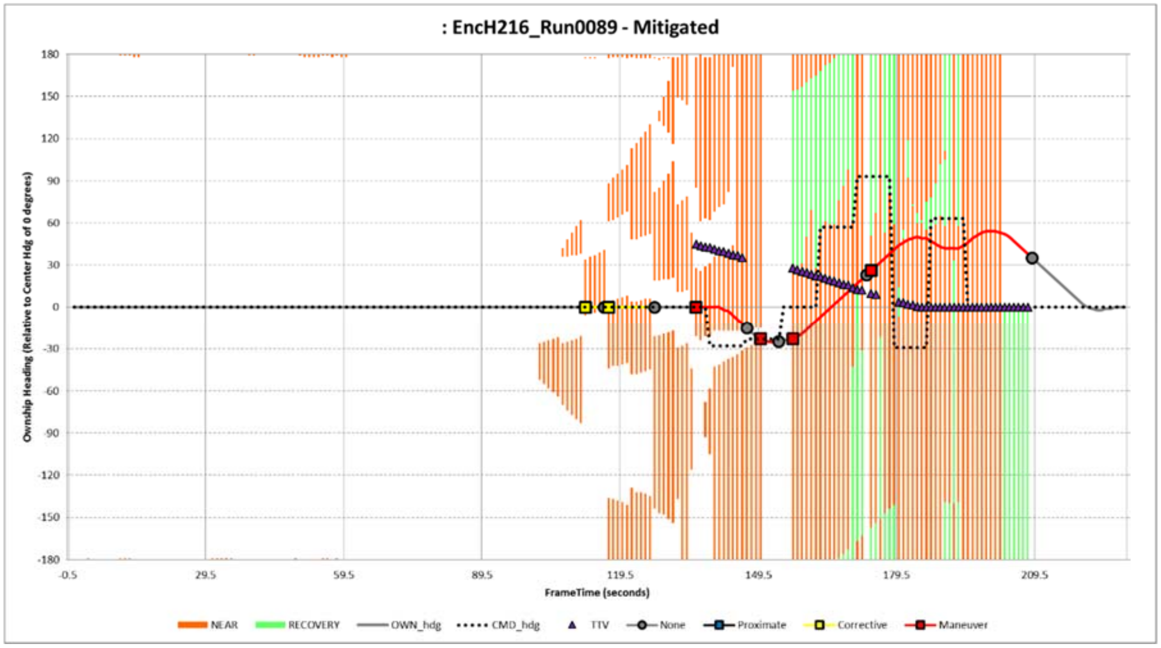

Figure 110. Alerting and Guidance Time History for Encounter 216 with Mitigated AST Surveillance Sensor

7. Conclusion

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 SC228 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, in order 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. In particular, the AST sensor produced very inaccurate and noisy intruder tracks that caused multiple issues with SLoWC and alerting, and experienced data dropouts in about 70% of the MOPS requirements-derived test vector runs. 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 update delays in the pilot model were longer than a human operator would likely have taken, and the current direction of maneuver was not considered, which led to some cases in which the pilot model tried to steer the UA out of an avoidance maneuver that a human operator would have simply maintained or increased. Also, in some encounters with high uncertainty about the intruder’s position and velocity, the sensor uncertainty mitigation (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.

Acknowledgements

“This work was conducted under the NASA Integrated Aviation Systems Program, UAS Integration in the NAS Project. The support of the Project manager, Ms. Laurie Grindle, is gratefully appreciated. The unfailing and tireless support of the many people involved in the planning and implementation of this simulation study is also gratefully appreciated. Gratitude is extended to Dr. James Comstock of the Crew Systems and Aviation Operations Branch at the NASA Langley Research Center in Hampton, Virginia for contributions to the experiment methodology and conduct. Gratitude is also extended for the tireless efforts of those participating through the NASA Langley Information Technology Enhanced Services (LITES) contract, including: Joel Ilboudo, Kristen Mark, and Elizabeth Weech as well as other support and management personnel.

Additionally, the authors would like to gratefully acknowledge Deepak Chauhan and Kevin Szagala of the FAA’s William J. Hughes Technical Center and Dr. Siva Sivananthan, Dr. Akhilesh Shrestha, and Dr. Petro Khomchuk of ARCON Corporation for their help in implementing the sensor and tracker models, Dr. Randal Guendel of MIT Lincoln Lab for his help in implementing the pilot model, Don Walker of the FAA for his leadership, and others in RTCA SC-228 who helped refine the study.

References

Calhoun, S. (2016). RTCA SC-228 DAA Surveillance M&S Discussion (PowerPoint Slides). CAL Analytics, LLC. January 2016. Not published.

Jack, D., Hoffler, K., Johnson, S. (2014). Exploration of the Trade Space Between Unmanned Aircraft Systems Descent Maneuver Performance and Sense-and-Avoid System Performance Requirements, 14th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference.

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.

Muñoz, C., Narkawicz, A., Hagen, G., Upchurch, J., Dutle, A., Consiglio, M., Chamberlain, J. (2015). DAIDALUS: Detect and Avoid Alerting Logic for Unmanned Systems, Proceedings of the 34th Digital Avionics Systems Conference (DASC 2015), Prague, Czech Republic, 2015.

Muñoz, C., Dutle, A., Narkawicz, A., Upchurch, J. (2016). Unmanned Aircraft Systems in the National Airspace System: A Formal Methods Perspective, ACM SIGLOG News, Vol. 3. Number 3, pp. 67-76.

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.

RTCA DO-317B (2014). Minimum Operational Performance Standards (MOPS) for Aircraft Surveillance Applications (ASA) System. RTCA, Inc., Washington, DC. June 2014.

Appendix A – Depiction of Encounter Geometries

Head-on Encounter Geometry

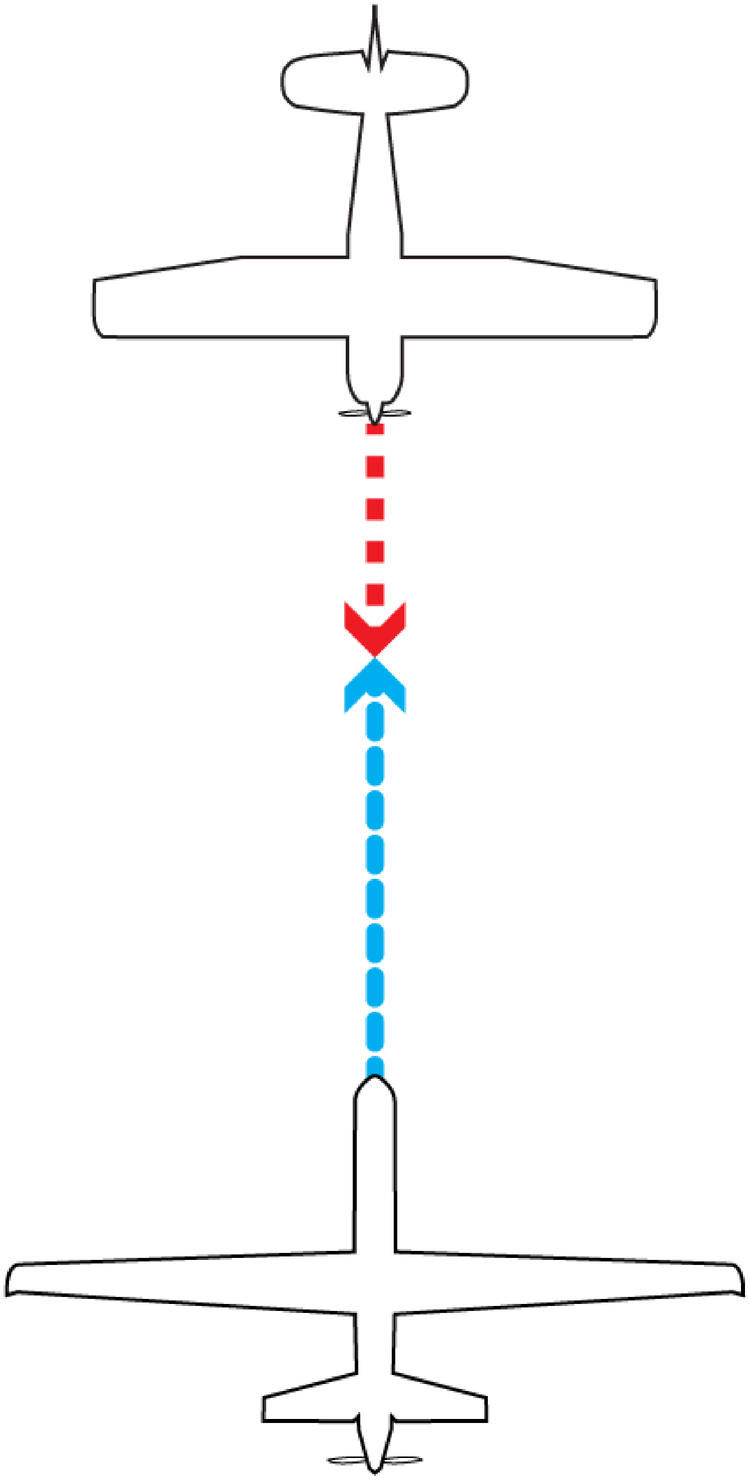

Figure A 1. Notional Diagram of Head-On Encounter Geometry

Crossing Encounter Geometry

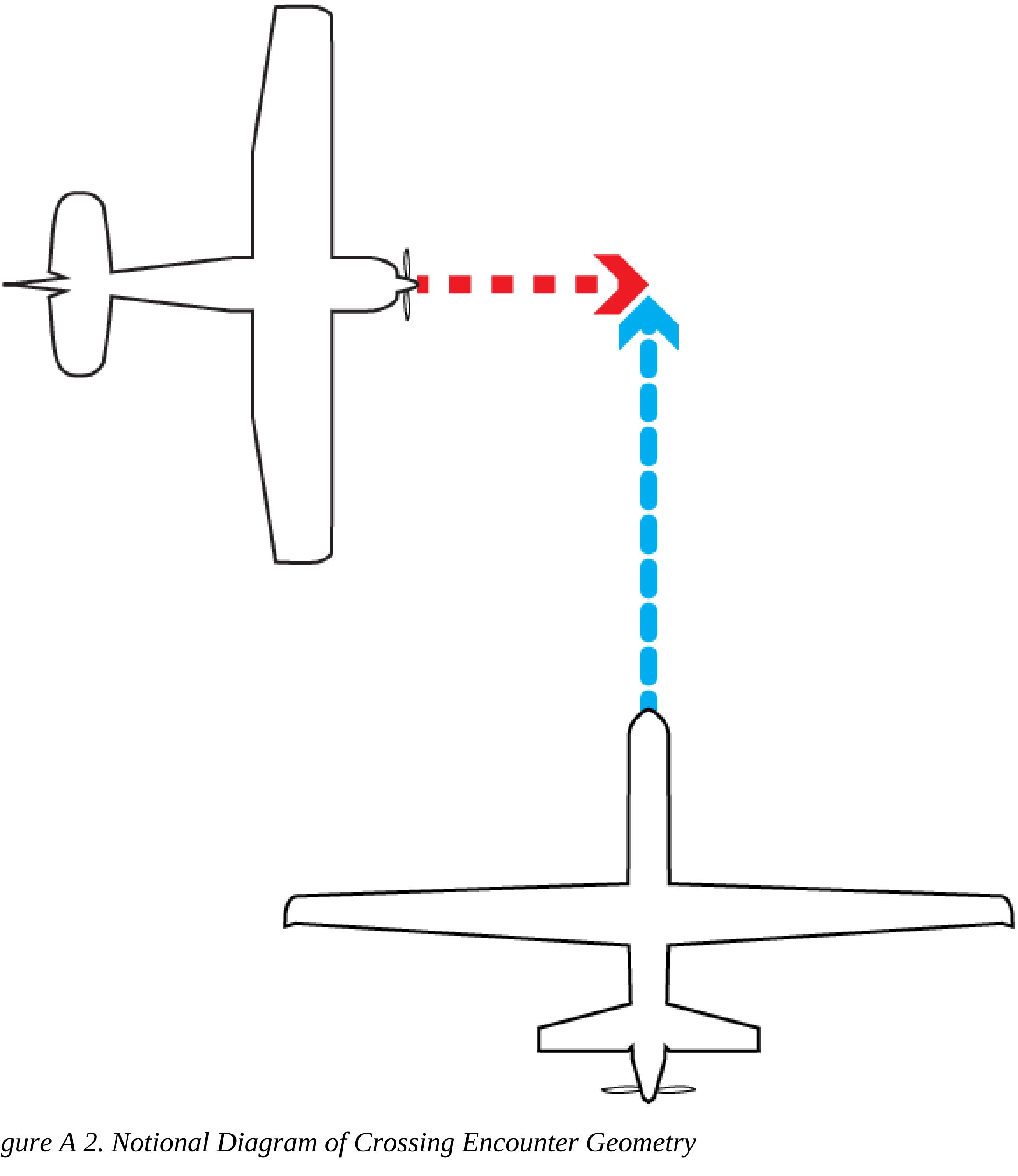

Figure A 2. Notional Diagram of Crossing Encounter Geometry

Overtake Encounter Geometry

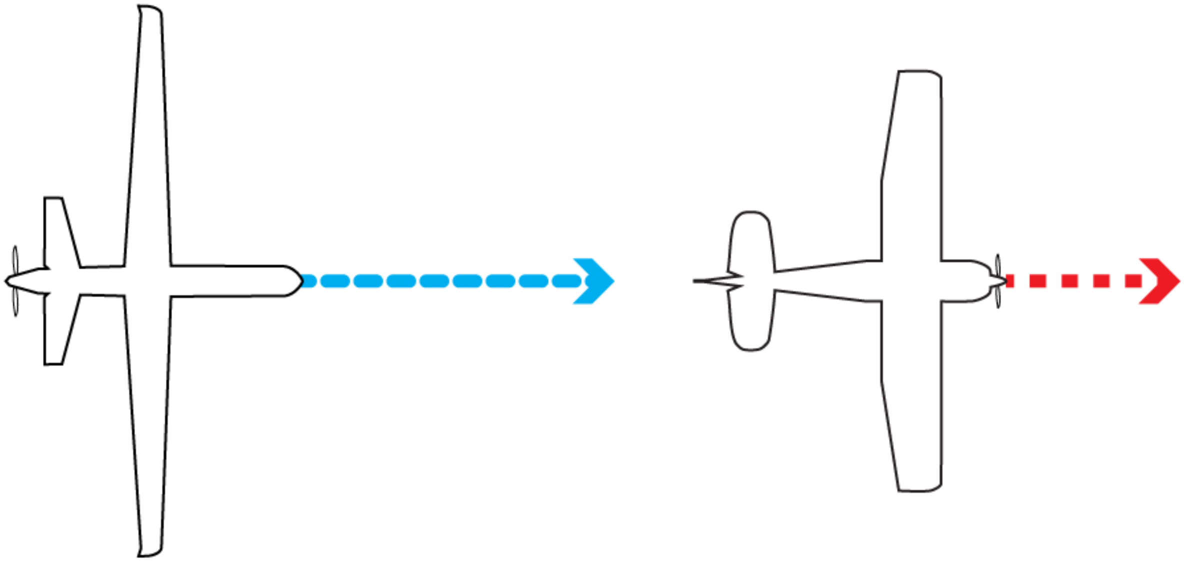

Figure A 3. Notional Diagram of Overtake Encounter Geometry

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)* 01-04-2017	**2. REPORT TYPE** Technical Memorandum	**3. DATES COVERED** *(From - To)*

4. TITLE AND SUBTITLE Unmanned Aircraft Systems Minimum Operations Performance Standards End-to-End Verification and Validation (E2-V2) Simulation	**5a. CONTRACT NUMBER** **5b. GRANT NUMBER** **5c. PROGRAM ELEMENT NUMBER**
6. AUTHOR(S) Ghatas, Rania W.; Jack, Devin P.; Tsakpinis, Dimitrios; Vincent, Michael J.; Sturdy, James L.; Munoz, Cesar A.; Hoffler, Keith D.; Dutle, Aaron M.; Myer, Robert R.; Dehaven, Anna M.; Lewis Elliot T.; Arthur, Keith E.	**5d. PROJECT NUMBER** **5e. TASK NUMBER** **5f. WORK UNIT NUMBER** 357672.04.01.07.04

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) NASA Langley Research Center Hampton, VA 23681-2199	**8. PERFORMING ORGANIZATION REPORT NUMBER** L-20780
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001	**10. SPONSOR/MONITOR'S ACRONYM(S)** NASA **11. SPONSOR/MONITOR'S REPORT NUMBER(S)** NASA-TM-2017-219598

12. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified
Subject Category 01
Availability: NASA STI Program (757) 864-9658

13. SUPPLEMENTARY NOTES

14. ABSTRACT

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 (CFR 14 91.113) of other aircraft. RTCA SC-228 has defined DAA Well Clear (DAAWC) to provide a quantified Well Clear volume to allow systems to be designed and measured against. Extended research efforts have been conducted to understand and quantify system requirements needed to support a UAS pilot’s ability 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.

15. SUBJECT TERMS

Detect; End-to-End Verification; Minimum operations performance standards; National airspace system; Umanned aircraft systems; Validation

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			STI Help Desk (email: help@sti.nasa.gov)
U	U	U	UU	124	**19b. TELEPHONE NUMBER** *(Include area code)* (757) 864-9658