[EN-A-042] The Effects of Alert Scoring and Alert Jitter on a Minimum Operations Performance Standards Unmanned Aircraft Systems Detect and Avoid System

(EIWAC 2017)

+Rania W. Ghatas* Dimitrios Tsakpinis** Robert R. Myer** and James L. Sturdy**

*: NASA Langley Research Center **: SAIC, Inc.
*: NASA Langley Research Center, Hampton, Virginia 23681, USA
**: SAIC, Inc., Hampton, Virginia 23666, USA

E-mail: *: rania.w.ghatas@nasa.gov; **: dimitrios.tsakpinis@nasa.gov; r.r.myer@nasa.gov; james.l.sturdy@nasa.gov

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 (DWC) 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 need to remain well clear of other aircraft. The efforts have included developing and testing sensor, algorithm, alerting, and display requirements. More recently, evaluation of sensor uncertainty and uncertainty mitigation strategies have been evaluated. This paper discusses alert scoring and alert jitter 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).

Keywords: Unmanned Aircraft Systems, National Airspace System, Detect and Avoid, Well Clear, Validation and Verification, Minimum Operational Performance Standards, Simulation Study, Alert Scoring, Alert Jitter

1. INTRODUCTION

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

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 attempts to steer the ownship aircraft well clear from intruder aircraft, having received collective input from the previous modules of the system. The resulting simulation provided the following key parameters, and many more, to evaluate the effectiveness of the MOPS DAA system: alert scoring and alert jitter.

2. METHOD

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

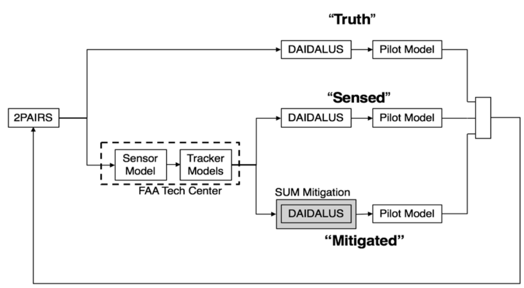

Figure 1. E2-V2 Simulation Architecture

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

The Sensor and Tracker models were developed and delivered by the Federal Aviation Administration (FAA) William J. Hughes Technical Center in support of RTCA SC-228. The sensors used in this study include: Automatic Dependent Surveillance – Broadcast (ADS-B) In, Active Surveillance Transponder (AST), and an air-to-air RADAR; each sensor was tested individually. The simulation architecture allows for the capability of flying in three modes, including: Truth, which uses perfect state information; Sensed, which uses degraded state information from the sensor; and Mitigated, which uses sensor degraded state information with a sensor uncertainty mitigation (SUM) approach.

The SUM approach, used in the Mitigated mode, creates phantom aircraft position and velocity based on estimated sensor uncertainty (Figure 2). Scaling factors were optimized to reduce frequency and severity of losses of well clear and to increase probability of accurate alerts and guidance. Jack, et al. (2017) [1] is a closely related paper presents the mitigation approach, results, and lessons learned from the SUM simulation study.

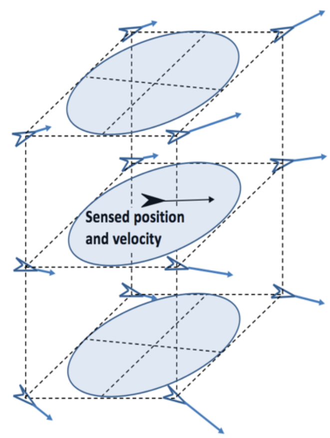

Figure 2. Sensor Uncertainty Mitigation

Multiple encounters from multiple sources were designed to show, through detailed examination of specific test vector and encounter cases, whether a MOPS-representative DAA system behaves acceptably. Each encounter was run several times through all three modes (Truth, Sensed, and Mitigated) for replication purposes to verify and validate the output data. The data was analyzed to determine the overall acceptability of a MOPS-representative system via the end-to-end simulation study. The paper will discuss, in further detail, the results of the study in addition to lessons learned and observations that were provided to SC-228 for use in developing the MOPS.

3. 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.

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" [2]. 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, and 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 [2].

Table 1 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.

Table 1. Final E2-V2 Test Vectors Set

	E2-V2 Test Vectors (based on Truth Tracks)			
Category Description	**Total**	**Radar**	**AST**	**ADS-B**
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	70	18	60	70

4. METRICS

4.1 Alert Scoring

Several metrics were used to analyze the large data set, one of which was the 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 3 shows a notional depiction of what constitutes a Hazard Zone (HAZ), in addition to a May-Alert Zone (MAZ), and Non-Hazard Zone (HAZNot) and Table 2 shows the parameters for calculating the size of the Hazard (HAZ) and Non-Hazard (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. The Hazard Zone is based on the DAA Well Clear volume (Table 2), and an alert is required if the intruder enters this region. The May-Alert Zone defines a volume around the ownship aircraft in which an alert may be signaled if an intruder aircraft is within that volume but is not required. Lastly, an intruder aircraft within the Non-Hazard Zone constitutes as remaining Well Clear; no alerts should be signaled for this zone (see RTCA, Inc., 2016 [2] for a full explanation of alerting requirements).

Figure 3. Notional Depiction of Hazard, May Alert, and Non-Hazard Zones

Using the HAZ and HAZNot definitions, the flow diagram in Figure 4 shows the methodology of scoring the alerting performance throughout an encounter. Upon completion of the simulation run, each alert was analyzed by comparing the time of HAZ entry and HAZNot departure are compared to the timing of each alert type, which is a function of sensor-degraded data.

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

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

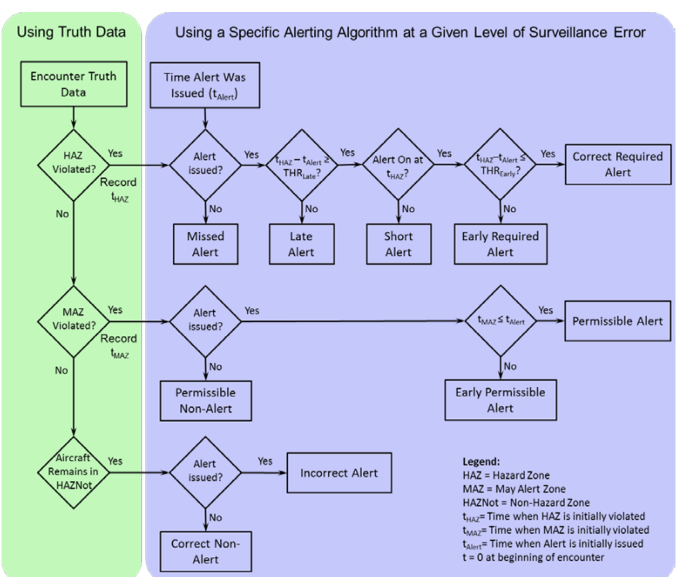

Figure 4. Alert Scoring Process

Encounter tracks with a HAZ violation are required to have an alert signaled. Together, the following performance metrics quantify an alerting system's performance for required alerts: Missed Alert, Late Alert, Short Alert, Early Required Alert, and 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, and 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 and Incorrect Alert.

4.2 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)" [2].

5. Alert Scoring Results

5.1 Corrective Alert Scoring

5.1.1 Radar Corrective Alerts

Corrective alert results for Head-On test vectors using the radar sensor for closed loop testing showed that 67% of Truth guidance 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).

Results for Converging test vectors showed that 90% of encounters were within the "Permissible Alert" scoring criteria while the remaining 10% of encounters experienced permissible non-alerts. Findings from Maneuvering test vectors showed that 50% of encounters were within the "Correct Required Alert" scoring criteria for open loop and closed loop runs when Truth guidance while the remaining 50% never received a corrective alert. Results for Overtake test vectors showed 33% of encounters were within the "Correct Non-Alert" scoring criteria with Truth guidance while the remaining 67% received permissible alerts.

5.1.2 Active Surveillance Transponder (AST) Corrective Alerts

Corrective alert results for Head-On test vectors using the AST sensor for closed loop testing showed that 21% of Truth guidance encounters were within the "Correct Non-Alert" scoring criteria while the remaining 79% were within the "Permissible Alert" scoring criteria. Sensed guidance shifted 25% of the encounters from Permissible Alerts to Correct Required Alerts, but also shifted encounters to Short (9%) and Missed Alerts (27%). Mitigated guidance using the SUM approach showed a decrease of 10% of the encounters that received missed alerts in comparison to Sensed guidance. Converging test vectors showed that 92% of encounters using closed loop Truth guidance were within the "Permissible Alert" scoring criteria while the remaining 8% of encounters received permissible non-alerts.

High Speed test vectors showed closed loop Mitigated guidance results 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. Maneuvering test vectors results showed 57% of encounters received missed alerts when Truth guidance in open and closed loop was used. 63% of encounters received the same type of alert when Sensed Guidance was used. Results for Overtake test vectors showed all Truth guidance encounters scored in the desirable alert categories, with the majority (67%) in the "Permissible Alert" scoring criteria.

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

Corrective alert results for Head-On test vectors using the ADS-B sensor showed that for the "Permissible Alert" scoring criteria, comparable findings were seen within an 8% range when closed loop Truth (80%), Sensed (72%), and Mitigated (78%) guidance were used. Comparable findings were also observed for the "Correct Non-Alert" scoring criteria. Mitigated guidance results for correct non-alerts showed 7% of encounters received that type of alert. For Converging test vectors, closed loop Truth guidance showed 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 showed that 7% of encounters received early permissible alerts. Notably, none of the encounters using any guidance type scored in the undesirable categories.

High Speed test showed that 100% of open loop Truth results 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. For Maneuvering test vectors, 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 showed 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%. In the case of Overtake test vectors, Truth guidance runs showed 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 showed the majority of encounters (67%) received correct required alerts while the remaining 33% received correct non-alerts.

5.2 Warning Alert Scoring

5.2.1 Radar Warning Alerts

Warning alert results for Head-On test vectors using the radar sensor for closed loop testing showed 33% of Truth guidance encounters were within the "Permissible Alert" scoring criteria while the remaining 67% of encounters experienced correct non-alerts. For Converging test vectors, closed loop Truth guidance showed 90% of encounters were within the "Permissible Alert" scoring criteria while the remaining 10% of encounters experienced permissible non-alerts. Sensed guidance showed a decrease of 25% in comparison to Truth guidance for permissible alerts, with the rest spread among several other criteria.

Truth guidance results for Maneuvering test vectors showed 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. Results for Overtake test vectors using Truth guidance in closed loop runs showed an even percentage of encounters (33%) were within the "Correct Non-Alert," "Permissible Alert," and the "Permissible Non-Alert" scoring criteria.

5.2.2 Active Surveillance Transponder (AST) Warning Alerts

Warning alert results for Head-On test vectors for the AST sensor for closed loop testing showed that 43% of Truth guidance 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 decreased these three desirable alerts and increased short, late, incorrect, and missed alerts. However, it also increased 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.

For Converging test vectors, results showed that 92% of encounters were within the "Permissible Alert" scoring criteria for closed loop Truth guidance while the remaining 8% were within the "Permissible Non-Alert" criteria. Results for High Speed test vectors showed 54% of encounters within the "Permissible Alert" scoring criteria using Truth guidance while 23% of encounters were within the "Early Permissible Alert" criteria. For Maneuvering test vectors, results showed that 71% of closed loop Truth guidance encounters 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. For Overtake test vectors, 47% of closed loop Truth guidance encounters were 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.

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

Warning alert results for Head-On test vectors using the ADS-B sensor in closed loop testing showed comparable findings for the "Permissible Alert" scoring criteria closed loop Truth (40%), Sensed (41%), and Mitigated (38%) guidance was used. Comparable findings across the three guidance types were also observed for the "Permissible Non-Alert" scoring criteria (Truth = 33%, Sensed = 25%, and Mitigated = 33%). For Converging test vectors, closed loop Truth guidance showed 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 showed a lesser percentage for permissible alerts when compared to Truth and Sensed guidance, findings also showed that 7% of encounters received early permissible alerts when the Mitigated guidance was used. 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 were similar to those of the corrective alert scoring results.

Results for High Speed test vectors in closed loop showed 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. For Maneuvering test vectors, 73% of closed loop Truth guidance encounters 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%. Truth guidance results for Overtake test vectors showed 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.

6. Alert Jitter Results

6.1 Radar Alert Jitter

Alert jitter for Head-On test vectors showed open loop results using Truth guidance showed 33% of encounters with an alert jitter of "0" indicating no alerts were given, which is undesirable. These were evaluated against closed loop encounters. 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 showed 0% of encounters experienced an alert jitter of "2." Sensed guidance results were distributed across the spectrum; however, Mitigated results showed that the SUM approach significantly tightened the distribution, to the extent that 65% of encounters received the ideal alert jitter of "2." For Converging test vectors, the open loop results with Truth guidance showed the majority of encounters (70%) presented the ideal number of increasing alerts, an alert jitter value of "2." Closed loop results showed 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 showed that the SUM approach significantly improved the distribution of Sensed results, and increased encounters with an alert jitter value of "2" to 37%.

Open loop and closed loop results with Truth guidance for Maneuvering test vectors showed 100% of encounters presented the ideal number of increasing alerts, which is a value of "2" alerts per encounter. Closed loop Sensed guidance showed only 24% of encounters had an alert value of "2," and only 3% of encounters when Mitigated guidance was used. Mitigated results showed 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. For Overtake test vectors with radar-based guidance, the open loop alert jitter results using Truth guidance showed the majority of encounters (67%) received two alert transitions while the remaining 33% received only one alert transition. Closed loop Truth guidance showed 33% of encounters received an alert jitter of "2" while 67% received one alert transition. As expected, Sensed guidance results showed a fairly wide distribution of alert jitter values. However, Mitigated results showed 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.

6.2 Active Surveillance Transponder (AST) Alert Jitter

Head-On test vectors using AST-based guidance in a closed loop simulation showed 50% of open loop encounters received the desired two alert transitions with Truth guidance. Closed loop Truth runs, however, only showed 14% of encounters received two alert transitions while the majority of encounters received either one (36%) or three (36%) alert transitions. Across all alert jitter results, the DAA system performed least favorably using AST-based guidance. For Converging test vectors, the open loop results with Truth guidance showed the majority of encounters (77%) received the ideal number of alert transitions, "2." Closed loop Truth guidance showed only 23% of encounters had an alert jitter value of "2" while the majority of encounters (54%) received one alert transition.

High Speed test vectors with AST-based guidance showed that 100% of open loop encounters using Truth guidance received two alert transitions while 75% of closed loop Truth runs received two alert transitions. Findings for Sensed and Mitigated guidance runs showed 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. For Maneuvering test vectors, 57% of both open loop and closed loop encounters using Truth guidance showed the ideal number of increasing alerts were presented, which is a value of "2" alerts per encounter, while the remaining 43% received one alert transition. Alert jitter results for Overtake test vectors showed that 40% of open loop results with Truth guidance received two alert transitions, 20% received one alert transition, and 33% received three alert transitions. Closed loop Truth guidance showed 33% of encounters received an alert jitter of "2" and another 33% of encounters received one alert transition. In alert jitter, AST-based guidance caused the DAA system to perform least favorably among other sensor-based guidance.

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

Alert Jitter results for Head-On test vectors using the ADS-B sensor showed that 53% of Truth guidance 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 showed 13% of encounters experienced an alert jitter of "2" which dropped to 27% of encounters when Sensed guidance was used. Mitigated results, however, showed that the SUM approach somewhat tightened the Sensed distribution, enabling 39% of encounters to receive the ideal number, "2," of alert transitions. Alert Jitter for Converging test vectors using Truth guidance showed the majority of encounters (80%) received two alert increases while closed loop Truth guidance showed only 25% of encounters received two alert transitions. The majority of encounters (60%) received one alert transition.

High Speed test vectors showed that 100% of open loop Truth guidance 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. For Maneuvering test vectors, 53% of Truth guidance open loop and closed loop runs received two alert transitions whiles 47% of encounters received one alert jitter. Closed loop Sensed guidance showed 47% of encounters had an alert jitter value of "2" and 35% had an alert jitter value of "1." For Overtake test vectors, Truth guidance results showed 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 showed a widening distribution with 31% of encounters receiving two alert transitions and 38% receiving one alert transition.

7. DISCUSSION

The demand for unmanned aircraft in mainstream aviation operations continues to grow. Understanding key detect and avoid system performance capabilities and limitations are essential to developing rules and regulations that allow routine UAS operations but maintain the safety of the National Airspace System. To understand these capabilities and limitations, as part of on-going RTCA SC-228 efforts, NASA Langley Research Center evaluated the Phase I DAA MOPS requirements with end-to-end functionality over a specific set of encounters, in a variety of geometries, and with specific surveillance sensor performance, 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. 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 severity of loss of well clear 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. Taken all together, none of the results of this study revealed surprising or serious problems with a Phase I DAA MOPS-compliant system. For more information, see Ghatas, et. al. (2017) [3].

8. ACKNOWLEDGMENTS

This work was conducted under the NASA Integrated Aviation Systems Program, UAS Integration into 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. Thanks are extended to Aaron Dutle, George Hagen, Cesar Muñoz, Anthony Narkawicz, and Jason Upchurch of the Safety Critical Avionics Systems Branch at the NASA Langley Research Center for contributions to the development of the DAIDALUS self-separation algorithms. Thanks are extended to Michael J. Vincent of the Crew Systems and Aviation Operations Branch at NASA Langley Research Center for his contributions to the End-to-End Verification and Validation Simulation (E2-V2). Thanks are extended to Keith D. Hoffler and Devin P. Jack of Adaptive Aerospace Group, Inc. for their contributions to E2-V2 and support of RTCA SC-228. Gratitude is also extended for the tireless efforts of those participating through the NASA Langley Information Technology Enhanced Services (LITES) contract, including: Anna M. DeHaven, 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.

9. REFERENCES

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

[2] 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.

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

7. COPYRIGHT