The Effects of Severity of Losses of Well Clear on Minimum Operations Performance Standards End-to-End Verification and Validation Simulation Study for Integrating Unmanned Aircraft Systems into the National Airspace System using Detect and Avoid Systems

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

Dimitrios Tsakpinis[2] and James L. Sturdy[3]
SAIC, Inc., Hampton, Virginia 23681

Devin P. Jack[4]
Adaptive Aerospace Group, Hampton, Virginia 23513

Robert R. Myer[5]
SAIC, Inc., Hampton, Virginia 23681

and

Anna M. DeHaven[6]
Craig Technologies, Inc., Hampton, Virginia 23681

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

[1] Human/Machine Systems Research Engineer, Crew Systems and Aviation Operations Branch, NASA Langley Research Center, Mail Stop 152, Hampton, Virginia 23681, AIAA Member
[2] Modeling/Simulation Engineer Principal, SAIC, Inc., NASA Langley Research Center Mail Stop 152, Hampton, Virginia 23681, Non-Member
[3] Modeling/Simulation Engineer Chief, SAIC, Inc., NASA Langley Research Center Mail Stop 152, Hampton, Virginia 23681, Non-Member
[4] Research and Development Engineer, Adaptive Aerospace Group, Inc., 100 Exploration Way, Suite 330, Hampton, Virginia 23666, AIAA Member
[5] Senior Software Engineer, SAIC, Inc., NASA Langley Research Center Mail Stop 152, Hampton, Virginia 23681, Non-Member
[6] Senior Software Engineer, Craig Technologies, Inc., NASA Langley Research Center Mail Stop 152, Hampton, Virginia 23681, Non-Member

I. Introduction

AS Unmanned Aircraft Systems (UAS) make their way to mainstream aviation operations within the National Airspace System (NAS), research efforts are underway to develop a safe and effective environment for their integration into the NAS. Detect and Avoid (DAA) systems are required to account for the lack of "eyes in the sky" due to having no human on-board the aircraft. The current NAS relies on pilot's vigilance and judgement to remain well clear (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 Severity of Losses of Well Clear (SLoWC) results and lessons learned from an end-to-end verification and validation (E2-V2) simulation study of a DAA system representative of RTCA's Special Committee (SC)-228 proposed Phase I DAA Minimum Operational Performance Standards (MOPS), which is outlined in DO-365. 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" (DO-365, 2017). It is based on the severity of violation into all three of the DAA Well Clear (DWC) components, which include: Horizontal Proximity, Horizontal Miss Distance Projection, and Vertical Separation. The SLoWC range is from 0% (no loss of well clear) to 100% (mid-air collision). 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 that maneuvers the ownship aircraft to remain DWC from intruder aircraft, having received collective input from the previous modules of the system. LaRC had a functioning batch simulation and added a sensor/tracker model from the FAA Tech Center, in-house developed sensor uncertainty mitigation strategy, and an in-house developed pilot model similar to one from MIT Lincoln Laboratory (MIT/LL). The resulting simulation provides the following key parameters, and many more, to evaluate the effectiveness of the MOPS DAA system: SLoWC, closest point of approach (CPA), and alerting performance metrics. The technique, SLoWC results, and lessons learned from a detailed examination of DAA system performance over specific test vectors and encounter cases during the simulation experiment will be presented in the paper.

II. Method

An end-to-end fast-time simulation tool was developed that encompasses simplified unmanned aircraft (UA) maneuver dynamics and all of the components of a DAA system. The system provides for one UA and a single intruder to fly a pre-determined encounter trajectory while having the UA either continue the trajectory and measure DAA system alerting or follow DAA system maneuver guidance per a simple deterministic pilot model. Figure 1 shows the simulation architecture used in E2-V2, which portrays the data flow of the simulation used in the study including a model of aircraft dynamics, a representative DAA algorithm, a sensor/tracker model that encompasses uncertainty modeling, and a deterministic pilot model that was used to close the loop on aircraft encounters. Aircraft dynamics are 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.

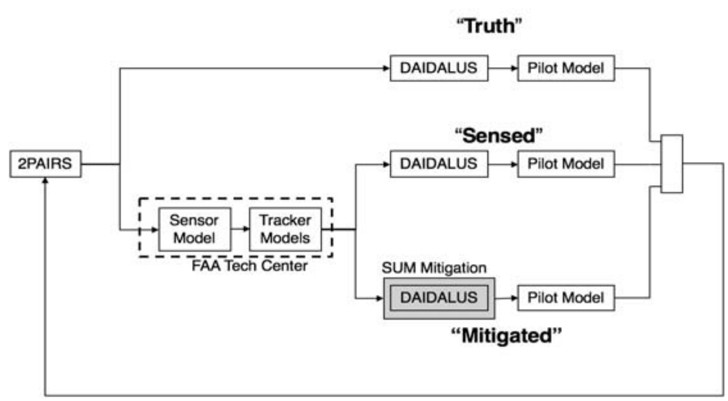

Figure 1. E2-V2 Simulation Architecture

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. Further details regarding each sensor used can be found in Appendix Q of RTCA DO-365 (2017). The simulation architecture allows for the capability of flying in three modes, including:

- Truth: Uses perfect state information,
- Sensed: Uses degraded state information from the sensor, and
- Mitigated: 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) is a closely related paper that presents the mitigation approach, results, and lessons learned from the SUM simulation study.

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

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

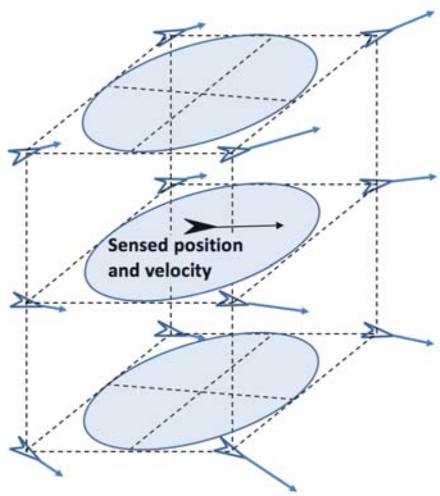

Figure 2. Sensor Uncertainty Mitigation Approach

III. Scenarios

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

Encounters originated from two main categories: National Airpsace System (NAS)-Derived Encounter Sets and MOPS Requirements-Derived Test Vectors. This paper, however, focuses on the SLoWC results of the 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" (DO-365, 2017).

The tracks were derived from multiple sources (DO-365, 2017), 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 (DO-365, 2017).

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. Some tests vectors were not utilitzed in the study due to sensor field-of-regard issues in which the encounter took place outside the the sensor's detection range while other test vectors were designed with the sole intention of causing a loss of well clear. As a result, the three left columns show differing numbers of test vectors simulated per sensor type.

Table 1. Final E2-V2 Test Vectors Set

	E2-V2 Test Vectors (based on Truth Tracks)		
Category Description	**Radar**	**AST**	**ADS-B**
MOPS: Head-On	3	14	15
MOPS: Converging	10	13	20
MOPS: High Speed	0	4	4
MOPS: Maneuvering	2	14	15
MOPS: Overtake	3	15	16
Total	18	60	70

IV. Metrics

A. Severity of Loss of Well Clear (SLoWC)

Several metrics were used to analyze the large data set, one of which is the Severity of Loss of Well Clear (SLoWC). SLoWC is a metric used "to assess the severity of Loss of DAA Well Clear on a per-encounter basis by capturing the most serious instance of Loss of Well Clear throughout an encounter" (DO-365, 2017). It is based on the severity of violation into all three of the DWC components, which include: Horizontal Proximity (τ_{mod}), Horizontal Miss Distance (HMD) Projection, and Vertical Separation (d_h). The resulting SLoWC ranges from 0% (DAA Well Clear maintained throughout the encounter) to 100% (mid-air collision).

V. Results

This paper will focus on the Severity of Loss of Well Clear (SLoWC) results. SLoWC ranges from 0% (no loss of well clear) to 100% (mid-air collision).

A. Radar SLoWC

Figures 3 through 6 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 3) 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.

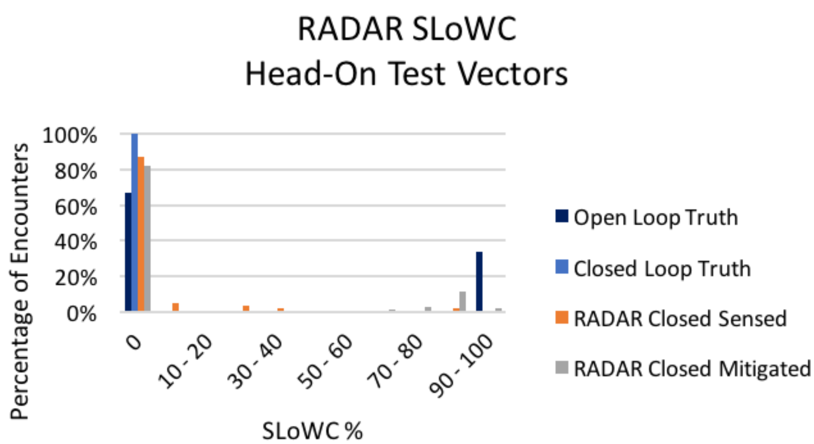

Figure 3. Radar SLoWC for Head-On MOPS Requirement-Derived Test Vectors

Similarly, results for Converging test vectors (Figure 4) 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 the majority of Converging encounters using Sensed or Mitigated guidance below 60% SLoWC.

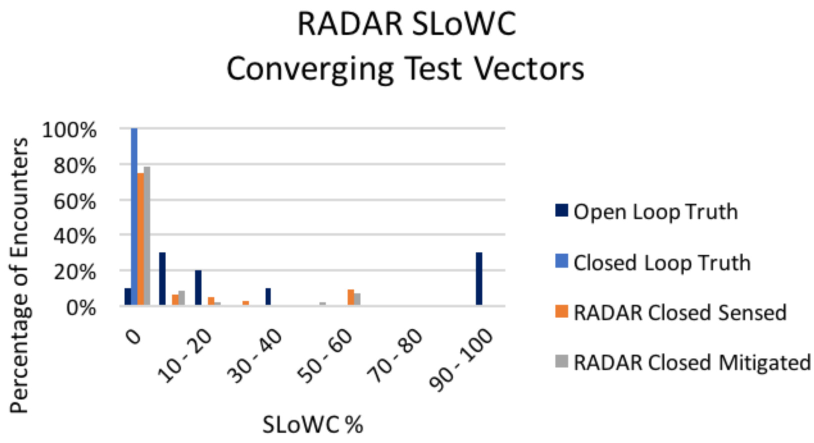

Figure 4. Radar SLoWC for Converging MOPS Requirement-Derived Test Vectors

Results for Maneuvering test vectors (Figure 5) show that 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.

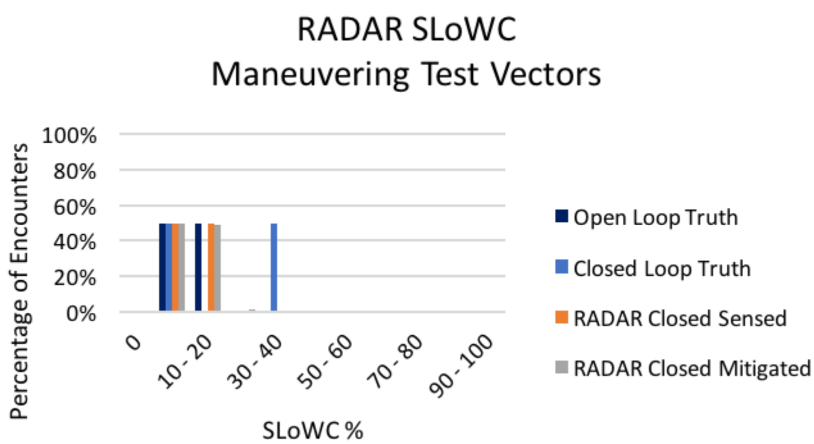

Figure 5. Radar SLoWC for Maneuvering MOPS Requirement-Derived Test Vectors

Figure 6 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.

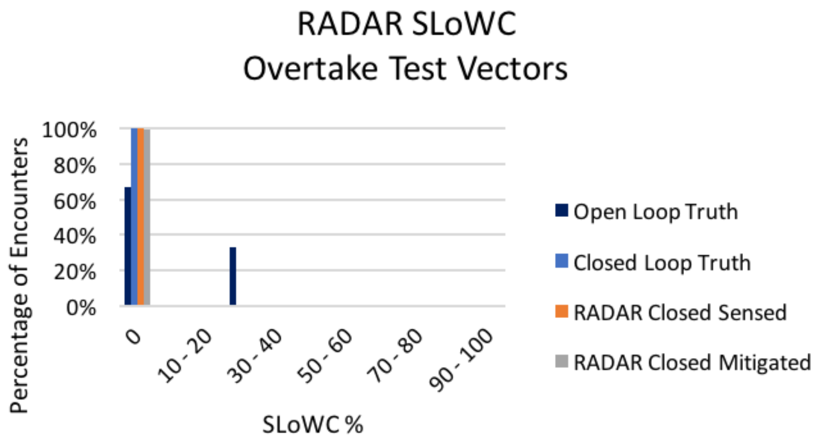

Figure 6. Radar SLoWC for Overtake MOPS Requirement-Derived Test Vectors

B. Active Surveillance Transponder (AST) SLoWC

Figures 7 through 11 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 7) 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.

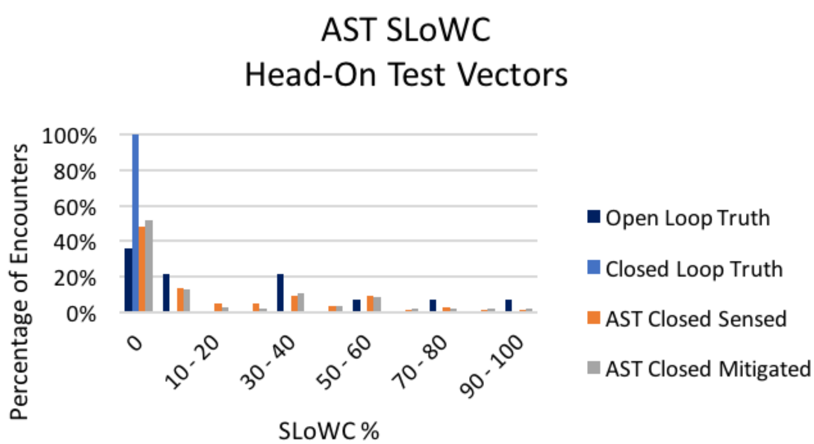

Figure 7. AST SLoWC for Head-On MOPS Requirement-Derived Test Vectors

Similarly, results for Converging test vectors (Figure 8) 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 the majority of closed loop SLoWC values above 50% and increasing the number of well clear encounters to 79%.

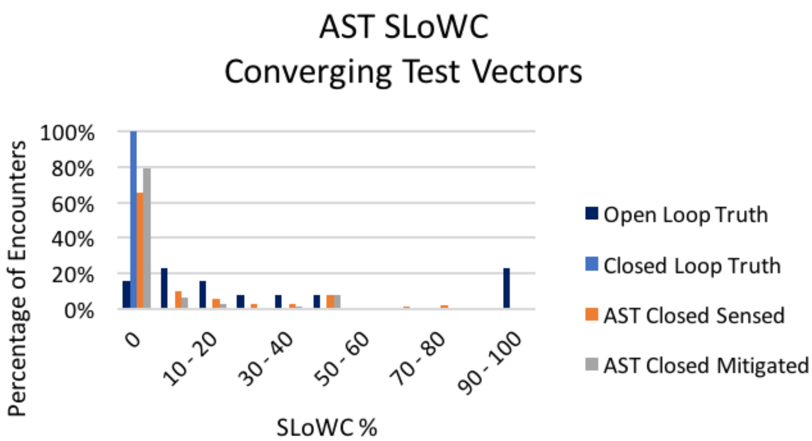

Figure 8. AST SLoWC for Converging MOPS Requirement-Derived Test Vectors

Figure 9 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%), an increase of 17% over Sensed guidance.

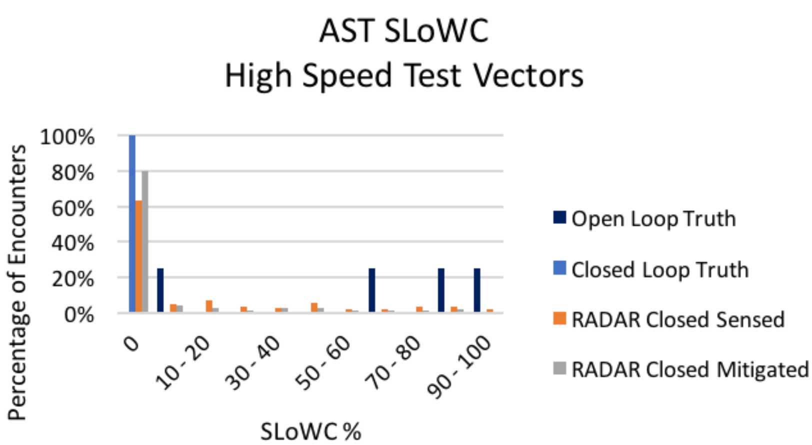

Figure 9. AST SLoWC for High-Speed MOPS Requirement-Derived Test Vectors

Figure 10 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.

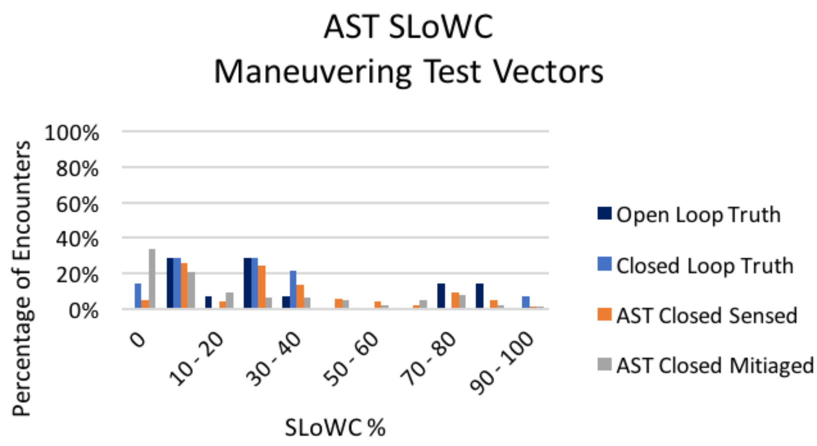

Figure 10. AST SLoWC for Maneuvering MOPS Requirement-Derived Test Vectors

Figure 11 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.

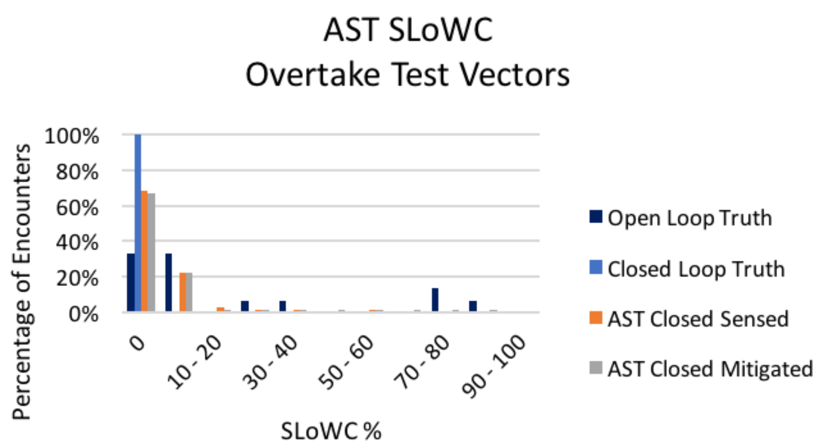

Figure 11. AST SLoWC for Overtake MOPS Requirement-Derived Test Vectors

C. Automatic Dependent Surveillance – Broadcast (ADS-B) SLoWC

Figures 12 through 16 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 12) 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. The majority of encounters using both Sensed and Mitigated guidance had a SLoWC of 0% (96% for closed loop Sensed and 97% for closed loop Mitigated).

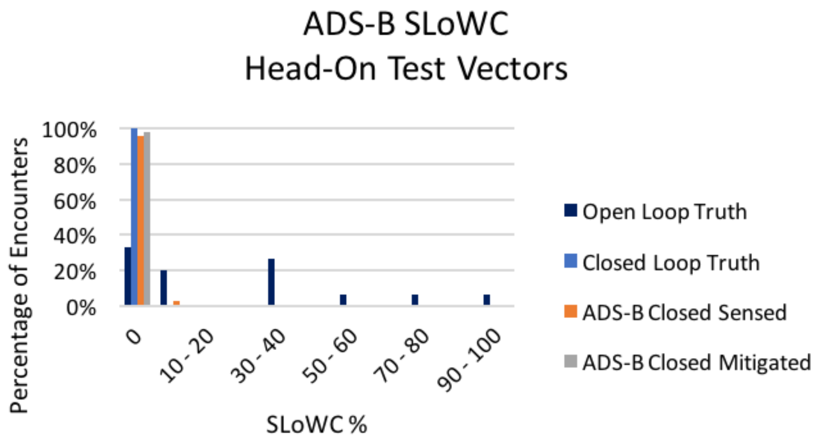

Figure 12. ADS-B SLoWC for Head-On MOPS Requirement-Derived Test Vectors

Results for Converging test vectors using ADS-B (Figure 13) 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.

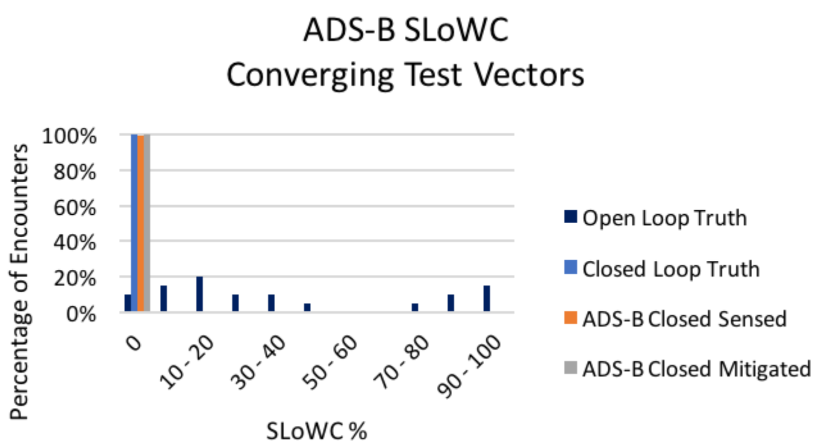

Figure 13. ADS-B SLoWC for Converging MOPS Requirement-Derived Test Vectors

Figure 14 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).

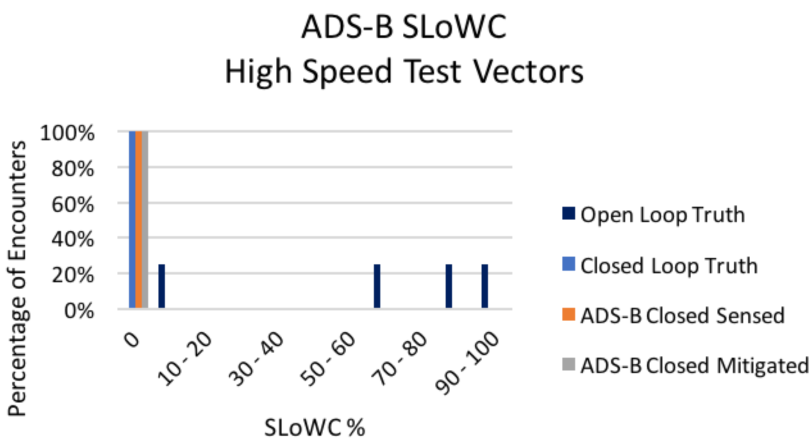

Figure 14. ADS-B SLoWC for High Speed MOPS Requirement-Derived Test Vectors

Figure 15 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.

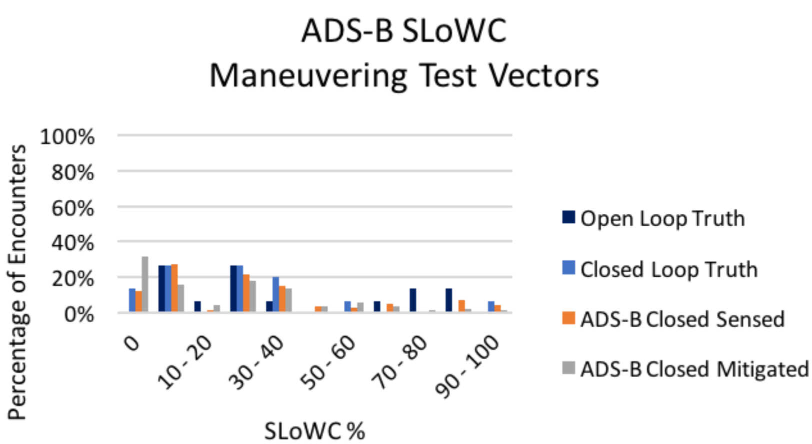

Figure 15. ADS-B SLoWC for Maneuvering MOPS Requirement-Derived Test Vectors

Figure 16 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.

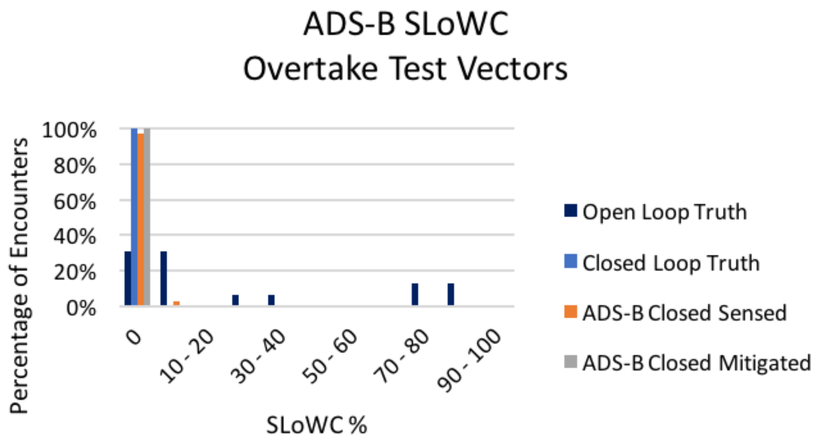

Figure 16. ADS-B SLoWC for Overtake MOPS Requirement-Derived Test Vectors

VI. 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.s

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. In particular, the AST sensor produced very inaccurate and noisy intruder tracks that caused multiple issues with SLoWC, 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. Details of the full simulation study can be found in Ghatas, et al. (2017).

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 is extended to Keith D. Hoffler 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.

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