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# Mitigating the Impact of Sensor Uncertainty on Unmanned Aircraft Operations

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# Abstract

Without a pilot onboard an aircraft, a Detect-and-Avoid (DAA) system, in conjunction with surveillance sensors, must be used to provide the remotely-located Pilot-in-Command sufficient situational awareness in order to keep the Unmanned Aircraft (UA) safely separated from other aircraft. To facilitate safe operations of UA within the U.S.' National Airspace System, the uncertainty associated with surveillance sensors must be accounted for. An approach to mitigating the impact of sensor uncertainty on achievable separation has been developed to support technical requirements for DAA systems.

# 1 Introduction

With an increasing interest from industry and civil entities in flying Unmanned Aircraft Systems (UAS) within the United States' National Airspace System (NAS), operational analyses are occurring to enable access while maintaining the NAS' high level of safety and operational efficiency. Without a human pilot on-board to see and avoid other aircraft, UAS pilots in remote ground control stations must rely on sensors and Detect-and-Avoid (DAA) systems to detect intruder aircraft and provide suggestive guidance to maintain a safe separation threshold. Further, human pilots must remain well clear from other aircraft using a subjective separation threshold based on the pilot's judgement and experience. DAA systems need a quantitative separation threshold for use in guidance and alerting calculations. Using a quantitative definition of a separation threshold, DAA systems can provide suggestive guidance and situational awareness via an alerting scheme to the UAS pilot to assist in safe flight operations.

RTCA Special Committee 228 (SC-228), a federal advisory committee consisting of government and industry stakeholders, has drafted minimum operational performance standards (MOPS) to provide technical requirements for DAA systems. Part of the MOPS development effort was defining a quantitative separation threshold, termed DAA Well Clear (DWC), which defines a spatial- and temporal-based separation threshold for use in DAA systems. Also, an alerting scheme was defined with respect to the DWC definition. Much of the MOPS, including the DWC and alerting scheme definitions, were created using perfect surveillance data. Analysis introducing sensor uncertainty typical of real-life flight operations to the defined MOPS requirements must be completed.

To provide timely alerts and maneuver guidance to the UAS operator, the DAA system must account for the imprecision of sensed intruder position and velocity. This paper presents an approach to account for sensor errors, how the approach was tuned, and an assessment of its effectiveness . The methodology is referred to as the Sensor Uncertainty Mitigation (SUM) approach. The SUM 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. The intruder and phantom intruders are all passed to the DAA algorithm resulting in a block of intruders that span a sigma-multiple of the possible intruder locations and velocities arrayed around the sensed position and velocity.

# 2 Background

To assist the Federal Aviation Administration (FAA) in integrating UAS in to routine operations of the NAS, civil and industry stakeholders have developed minimum technical requirements for DAA systems through SC-228. The DAA system is a key component of a UAS responsible for providing the pilot in command situational awareness through multiple sensors and a defined alerting scheme. In order to develop the Phase 1 MOPS for DAA systems, SC-228 defined operational assumptions for use of UAS not authorized for operation through 14 Code of Federal Regulations (CFR), Part 107 (i.e., small UAS). The MOPS restricts UAS flight operations to Instrument Flight Rules (IFR) traversing through Class D, E, and G airspace up to Class A airspace which begins above 18,000 ft MSL.  Within Class A airspace, it is assumed that air traffic services will provide active separation service; thus, is out of scope for this MOPS. Terminal airspace is not considered.

## 2.1 Quantitative Definition of Well Clear

Per 14 CFR 91.113 [1], "vigilance shall be maintained by each person operating an aircraft so as to see and avoid other aircraft. When a rule of this section gives another aircraft the right-of-way, the pilot shall give way to that aircraft and may not pass over, under, or ahead of it unless well clear". Thus, utilizing an onboard pilot's ability to see and avoid traffic, an aircraft must remain ‘well clear’ from other vehicles at all times. With a pilot onboard, the definition of well clear is qualitative, based on the ability, judgment, and preferences of the pilot in command. Without an onboard pilot, a quantitative definition of well clear is required to establish separation requirements for unmanned aircraft DAA systems. A quantitative definition of well clear provides a repeatable target for which a DAA system may support safe separation from other aircraft  by providing information to the pilot or to automation. The DAA Well Clear volume is intended to include interoperability principles with respect to Air Traffic Control (ATC) operations and current collision avoidance systems such as the Traffic alert and Collision Avoidance System (TCAS). To ensure interoperability with the current NAS, values used to define the well-clear volume must be large enough to avoid issuance of TCAS corrective resolution advisories but not so large as to interfere with ATC separation services [2]. This definition has been discussed and refined through a process involving NASA, DoD, FAA, and SC-228.

The proposed definition of a DAA Well Clear volume is represented using the following inequality:

*Equation 1: DAA Well Clear Definition*

$$[0 \leq \tau_{mod} \leq \tau^*_{mod} \,.and.\, HMD \leq HMD^*].and.[0 \leq \tau_v \leq \tau^*_v \,.or.\, -h^* \leq dh \leq h^*]$$

where HMD is the kinematic projection of horizontal miss distance in feet, $\tau_v$ is the vertical tau or time to co-altitude in seconds, and dh is the vertical separation in feet between the two aircraft involved in the encounter. The value of $\tau_{mod}$ is inherited from TCAS [3] and given in seconds by

*Equation 2: DAA Well Clear Definition*

$$\tau_{mod} = \frac{DMOD^2 - r^2}{\dot{r}r}$$

where TCAS defines DMOD as a horizontal distance threshold with varying values depending on the ownship’s altitude and r = range and $\dot{r}$ = range rate between the two aircraft. For the purposes of the DAA Well Clear definition, the HMD* is used in place of DMOD. In Equations 1 and 2, the lack of a superscript denotes the instantaneous value at any given time during the encounter. The superscript * denotes the value given as a minimum in the quantitative definition of well clear. Table 1 shows the numeric values used to define the DAA Well Clear threshold.

*Table 1. Proposed DAA Well-Clear definition.*

| Parameter | Symbol | Units | Value |
|---|---|---|---|
| Vertical Displacement | h* | feet | 450 |
| Modified Tau | $\tau^*_{mod}$ | seconds | 35 |
| Horizontal Miss Distance | HMD* | feet | 4000 |
| Time to Co-Altitude | $\tau^*_v$ | seconds | 0 |

The horizontal separation requirements are segregated from the vertical separation requirements. In other words, if an aircraft is adequately separated in the vertical plane to avoid a loss of DAA Well Clear, the horizontal separation has no effect, and vice versa. Figure 1 shows a simplified notional depiction of the DAA Well Clear definition, though its actual shape is more complex. The figure also separates vertical and horizontal separation requirements.

In both the horizontal and vertical dimensions, the definition incorporates a time and a distance constraint on the separation requirement. In the horizontal dimension, both time and distance constraints must be violated in order to have a loss of DAA Well Clear; whereas, in the vertical dimension, violation of either the time or distance constraints will result in a loss of DAA Well Clear.

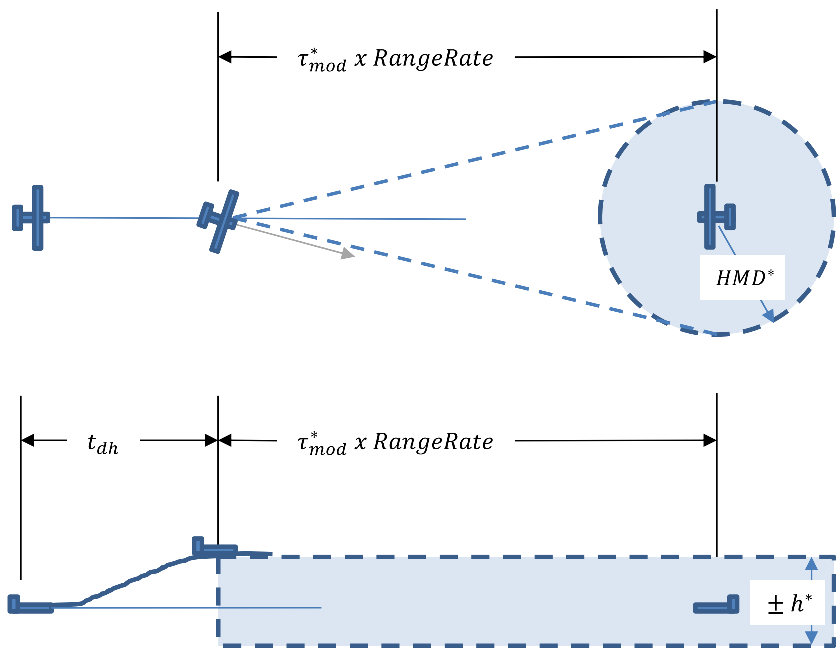


*Figure 1. Simplified Depiction of DAA Well Clear.*

In the horizontal dimension, as shown in Figure 1, the aircraft must remain outside of a time-based boundary ($\tau^*_{mod}$) unless the projected minimum distance between the two aircraft is greater than the specified HMD*. The HMD is a kinematic projection using the velocity vectors of the ownship and intruder aircraft. Thus, the maneuvering aircraft must turn to a heading that achieves a projected value of HMD greater than HMD* to achieve well clear as opposed to being physically offset by a distance of HMD*. The angle that provides the required HMD projection varies greatly with the initial range between the encountering aircraft.

In the vertical plane, as shown in Figure 1, the aircraft must remain outside of a time-based boundary ($\tau^*_v$) and a spatial boundary defined by ±h*. In contrast to the horizontal separation requirements, the vertical separation is not a projection but an absolute vertical distance between the aircraft. Since the vertical boundary is fixed, the time required to reach the specified vertical separation h*, or $t_{dh}$, must be analyzed. [4]

## 2.2 Metrics

### 2.2.1 Severity of Loss of Well Clear (SLoWC)

The Severity of Loss of Well Clear (*SLoWC*) metric is 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. Based on the Well Clear definition, this severity metric is assessed based on the severity of the local penetration into all three of the Well Clear components: Horizontal Proximity, Horizontal Miss Distance Projection and Vertical Separation. Further information regarding the SLOWC metric can be found in the DAA MOPS Appendix L.5.1.5 [5].

The combined severity at any instance during an encounter from all three components can be expressed as:

*Equation 3: Calculation of SLoWC for Each Time Step*

$$SLoWC_i = \left(1 - RangePen_i \oplus HMDPen_i \oplus VertPen_i\right) * 100\%$$

$RangePen_i$, $HMDPen_i$, and $VertPen_i$ are defined in the subsequent paragraphs. The Fernandez-Guasti Squircle operator, $\oplus$, is used to combine the normalized penetrations from all three dimensions.

***Equation 4: Fernandez-Guasti Squircle Operator Definition.***

$$x \oplus y \equiv \sqrt{x^2 + (1 - x^2)y^2}$$

The overall *SLoWC* penetration for the entire encounter is:

***Equation 5: Calculation of SLoWC for Encounter.***

$$SLoWC = MAX(SLoWC_i)$$

The resulting *SLoWC* ranges from 0% to 100% with 0% indicating Well Clear, and 100% representing full penetration into the Well Clear protection volume, i.e. both aircraft at the same place at the same time.

#### *2.2.1.1 SLoWC Horizontal Proximity*

The normalized horizontal proximity penetration is analogous to assessing the penetration into the $\tau_{mod}$ dimension.

The local normalized horizontal proximity penetration is defined as:

***Equation 6: Calculation of RangePen.***

$$RangePen_i = MIN\left(\frac{r_i}{S_i}, 1\right)$$

Where the required horizontal range, $S_i$, given the local horizontal range rate and Well Clear's DMOD and $\tau_{mod}^*$ yields:

***Equation 7:Calculation of Required Horizontal Range, S.***

$$S_i = MAX\left(DMOD,\ \frac{1}{2}\left(\sqrt{(\dot{r}_i\tau_{mod}^*)^2 + 4DMOD^2} - \dot{r}_i\tau_{mod}^*\right)\right)$$

where:
$i = [t_1, t_2, t_3, \cdots t_{end-1}, t_{end}]$
DMOD = 4000'
$\tau_{mod}^*$ = 35 s,
$r_i$ = horizontal range
$\dot{r}_i$ = horizontal range rate

The resultant normalized horizontal penetration produces a value ranging from one to zero with one indicating the edge of $\tau_{mod}^*$, and zero representing full penetration into the horizontal proximity dimension.

#### 2.2.1.2 SLoWC Horizontal Miss Distance Projection

The normalized HMD penetration is based on the ratio of the local HMD projection versus Well Clear's DMOD requirement:

*Equation 8: Calculation of HMDPen.*

$$HMDPen_i = MIN\left(\frac{HMD_i}{DMOD}, 1\right)$$

$$HMD_i = \sqrt{(dx + v_{rx}t_{CPA})^2 + \left(dy + v_{ry}t_{CPA}\right)^2}\Bigg|_i$$

*where*:

$t_{CPA} = -\dfrac{d_x v_{rx} + d_y v_{ry}}{v_{rx}^2 + v_{ry}^2}$

$\mathrm{HMD}|_{\mathrm{t_{CPA}} \leq 0} = r_{\mathrm{i}}$

$i = [t_1, t_2, t_3, \cdots t_{end-1}, t_{end}]$

$dx = \text{Aircraft separation in the x} - \text{direction using truth data}$

$dy = \text{Aircraft separation in the y} - \text{direction using truth data}$

$v_{rx} = \text{Relative velocity in the x} - \text{direction using truth data}$

$v_{ry} = \text{Relative velocity in the y} - \text{direction using truth data}$

The resultant normalized HMD Penetration yields a value ranging from one to zero with one indicating the edge of DMOD, and zero representing full penetration into the DMOD requirement.

#### 2.2.1.3 SLoWC Vertical Separation

The normalized penetration of the vertical component is assessed based on the ratio of local vertical separation, $dh_i$ versus Well Clear's h*:

*Equation 9: Calculation of HMDPen.*

$$VertPen_i = MIN\left(\frac{dh_i}{h^*}, 1\right)$$

*where*:

$i = [t_1, t_2, t_3, \cdots t_{end-1}, t_{end}]$

$h* = 450'$

$dh_i = abs(h1, i - h2, i)$

Similarly, the resultant normalized vertical penetration produces a value ranging from one to zero, with one indicating the edge of vertical threshold and zero representing full vertical penetration into the $h^*$requirement.

### 2.2.2 Alert Jitter

Alerting is based on sensed relative position and velocity of intruder aircraft, per Appendix Q of the Phase 1 DAA MOPS [5]. Since alerting is a function of sensor-degraded data, it is therefore subject to uncertainty associated with sensor noise. A nuisance characteristic associated with alerting is an unnecessary number of transitions between alert levels. The resulting alerting performance may cause a decrease in safety due to pilot distraction or the pilot's lack of trust in the alerting system. To measure the number of transitions, the metric Alert Jitter is defined. Alert Jitter is the number of increasing alert transitions which occurred throughout the encounter. An increasing alert transition is defined as 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). Only the increasing alert levels are measured to minimize duplicate measurements. For example, for a simple co-altitude encounter the alert sequence is expected to be from <No Alert> to <Corrective Alert> to <Warning Alert>, which is represented by an Alert Jitter value of 2.

# 3 Simulation Environment

A fast-time simulation tool was developed to model UA system components including an aircraft performance model (2PAIRS), models of three sensor types, a DAA Tracker model, a deterministic pilot model, and the reference DAA algorithm Detect and AvoID Alerting Logic for Unmanned Systems (DAIDALUS [6])from the forthcoming Phase 1 DAA MOPS. The tool also provides for intruder states to be read in from a file or for intruders to fly straight and level trajectories during each run. One ownship and multiple intruders are supported by the tool but the results presented here are from a single intruder. There are three paths for data flow within the simulation tool:

1. The first path, labelled "Truth" in Figure 2, provides true (i.e., perfect) state data as output by 2PAIRS to DAIDALUS, which outputs guidance to the pilot model. The pilot model then determines a heading change command with respect to the truth-based guidance bands.
2. The second path, labelled "Sensed" in Figure 2, provides true state data to the Sensor/Tracker suite which degrades the state data using sensor uncertainty assumptions. After degradation, the state data is provided to DAIDALUS which outputs guidance bands based on the degraded state data of the ownship and intruder. The pilot model then determines a heading change command with respect to the degraded state based guidance bands.
3. The third path, labelled "Mitigated" in Figure 2, provides true state data to the Sensor/Tracker suite which degrades the state data using sensor uncertainty assumptions. After degradation, the state data is then provided to the SUM Mitigation software, which acts as a wrapper around DAIDALUS. The SUM Mitigation wrapper determines the positions and

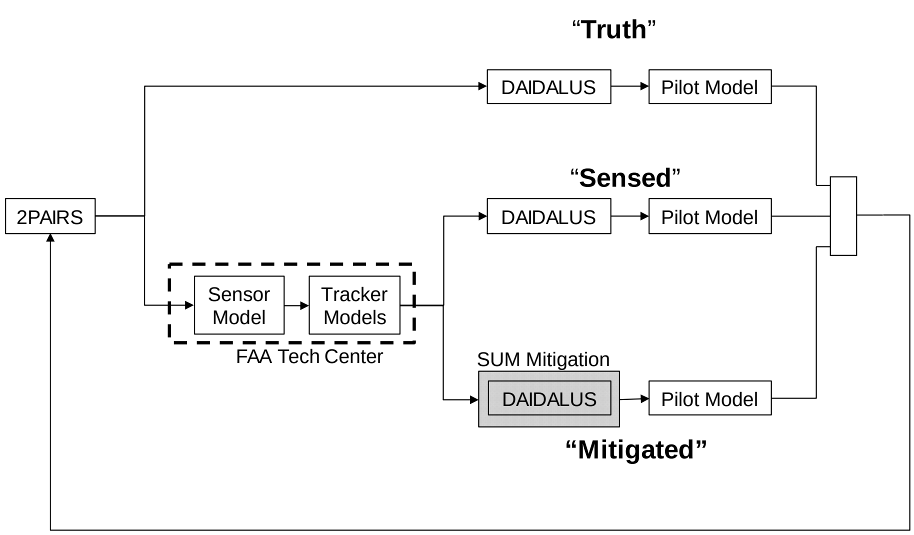


*Figure 2. Simulation Environment*

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 states, and the phantom aircraft states. The pilot model then determines a heading change command with respect to the resulting guidance bands.

More detailed descriptions of each component of the simulation tool shown in Figure 2 are provided in the following sections.

## 3.1 Aircraft Dynamics Assumption

A model of aircraft dynamics in a lateral maneuver was used. The simulation tool 2 degrees-of-freedom Prototyping Aircraft Interaction Research Simulation (2PAIRS) [7] was used to model the UA’s dynamics throughout the encounter. When prompted by the pilot model, the aircraft initiates a 3 deg/sec turn at 5 deg/sec roll rate. The assumed maneuver rates and accelerations of this study did not stress the performance model; thus, the commanded maneuvers were achieved and maintained.

2PAIRS accepts multiple input formats depending on the particular study. For ownship, 2PAIRS accepts first-order aircraft parameter values (e.g., maximum Thrust-to-Weight, wing loading, coefficient of lift) and is able to define the ownship’s trajectory assuming level, unaccelerated flight. Alternatively, 2PAIRS accepts ownship trajectory files as input. The input trajectory is followed until the DAA system and pilot model determine that a maneuver is required, at which point the 2PAIRS flight dynamics assumptions over-ride the input trajectory array and a maneuver is performed. When provided an array, 2PAIRS estimates the attitude and state information of the UAS.

For intruder aircraft, 2PAIRS accepts 3-dimensional trajectory arrays as input. The intruder’s positon and velocity follow the input arrays; aircraft dynamics are not calculated for the intruder aircraft.

## 3.2 Pilot Model

A simplified pilot response model was implemented to minimize the variability in the response caused by maneuver selection and timing. The pilot model commanded a lateral maneuver in the positive heading direction (i.e., turn right).

The timing of the maneuver was constant relative to an estimated Time to Violation (TTV) output by the DAIDALUS algorithm. The maneuver was commanded when TTV = 10 seconds, or 10 seconds prior to a DAA Well Clear volume penetration. Using a constant TTV provides a consistent time of response relative to the airborne hazard. Per MOPS specifications, an alert should be issued no less than 15 seconds prior to a LoWC (TTV = 15 seconds). Allowing 5 seconds for the pilot to input the commanded maneuver and for the maneuver to reach the airborne UA results in the choice to maneuver at TTV =10 seconds.

## 3.3 Sensor and Tracker Model

Simulation models representing three types of airborne surveillance sensors were used: Automatic Dependent Surveillance – Broadcast (ADS-B), Active Surveillance Transponder (AST), and Air-to-Air RADAR. The tracker model is a best source selection tracker. To reduce the impact of the tracker model’s best source criteria, only single sensor data is passed to the tracker. The simulation models representing the three types of sensors were developed by the FAA’s William J. Hughes Technical Center in support of SC-228 modeling and simulation efforts. Further information on the Tracker model and Sensor models can be found in Phase 1 DAA MOPS Appendix F and Appendix Q [5], respectively.

### 3.3.1 RADAR

The radar model embodies the error among readings of range, range rate, azimuth, and elevation. The directional nature of the radar sensor necessitates the modeling of both a detection range and a field of regard. The table below holds values per state describing the modeled amount of error per sigma and the bias associated with each distribution as well as the update rate, detection range, and field of regard state restrictions.

Runs incorporating only radar degraded data are representative of flight operations involving an equipped UAS and a non-cooperative intruder. Non-cooperative intruders are aircraft operating in the NAS with no transponder (i.e., aircraft not broadcasting their location to other NAS users via ADS-B or responding to transponder interrogations from Active Surveillance systems).

*Table 2. Radar 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 |
| **State** | **Value** | |
| Update Rate | 1 second | |
| Tracking Range | 5 nmi (< 100kts. Intruder)<br>6.5 nmi (100-300kts. Intruder)<br>8 nmi (> 130kts. Intruder) | Detection Range Scale Factor<br>Az: [0, 30], 1.0<br>Az: [30, 60], 0.84<br>Az: [60, 90], 0.46<br>Az: [90, 110], 0.45 |
| Field of Regard | +/- 15 Elevation (Stabilized with respect to velocity vector)<br>+/- 10 Azimuth | |
| Probability of Track | Pr(Track) = 1 | |

### 3.3.2 Active Surveillance

Active surveillance uses the standard TCAS transponder interrogation that provides range, bearing, and altitude to the intruder. The following table provides the assumed model performance for both Mode-S and Mode-C active surveillance.

AST-only runs are representative of flight operations involving a properly-equipped UAS and an intruder equipped with either a Mode C or Mode S transponder. Mode A transponders were not considered because such systems are rare.

*Table 3. Active Surveillance 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<br><br>[-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) |
| **State** | **Value** | | |
| Update Rate | 1 second | | |
| Detection Range | Mode C = < [9.5, 6, 3.3] nmi<br>Mode S = < 15.6 nmi | | |
| Probability of Reception/Detection | Mode C = 0.90<br>Mode S = 0.95 | | |
| Field of Regard | [-15, +20 degrees) Elevation | | |

### *3.3.3 ADS-B*

Automatic Dependent Surveillance–Broadcast (ADS-B) is a precise satellite-based surveillance system. ADS-B Out uses GPS technology to determine an aircraft's location, airspeed and other data, and broadcasts that information to a network of users, including other airborne aircraft. Although ADS-B has a variety of performance levels, the following assumptions were used to model ADS-B equipped intruder aircraft.

Runs incorporating ADS-B only sensor degraded state data are representative of flight operations involving intruder aircraft equipped with ADS-B Out.

*Table 4. ADS-B Model Parameters.*

| | State | Absolute Error (per AC) 1-sig | Bias | Time Correlation |
|---|---|---|---|---|
| NACp = 7 | Horizontal Position | 75.6m | 0 | 300 sec |
| | Baro Altitude | 0 | Per TSAA model | |
| NACv = 1 | Horizontal Velocity | 4m/s | 0 | 300 sec |
| | Vertical Velocity | 1.707m/s (95%) | | |
| **State** | **Value** | | | |
| Update Rate | dt = 1 second | | | |
| Latency Effects (Uncompensated) | <.4sec | | | |
| Detection Range | DR = <20NM | | | |
| Probability of Reception / Detection | PD: 0.95 | | | |

### *3.3.4 Ownship Navigation (NAV) Model*

The ownship navigation system is based on Inertial Navigation System / Global Positioning System (INS-GPS) performance, and provides the ownship's position, velocity, and attitude information. The following table provides the assumed performance of the ownship navigation system, which in large part is based on expected ADS-B performance.

For attitude estimation, the tracker is provided true attitude state information (roll, pitch, yaw) of the ownship. The attitude is then degraded using the attitude absolute error standard deviations shown in Table 5.

*Table 5. Navigation (NAV) Model Parameters.*

| State | | Absolute Error (per AC) 1-sig | Bias | Time Correlation |
|---|---|---|---|---|
| Horizontal Position | NACp = 7 | 75.6m | 0 | 300 sec |
| Baro Altitude | | 0 | ICAO 10 Annex Bias model | |
| Horizontal Velocity | NACv = 1 | 4m/s | 0 | 300 sec |
| Vertical Velocity | | 1.707m/s (95%) | | |
| Attitude [Roll, Pitch, Yaw/Heading] | | [0.2, 0.2, 0.4] degs | | |

#### 3.3.5 Tracker

The primary function of the Tracker is to receive surveillance data from various sensors, form a single track for each detected target, and present the track information together with ownship information to the DAA algorithm for use in alerting and guidance functions. The Tracker model utilized best source selection criteria to provide a single track to the DAA system. In order to avoid complications caused by source selection, a single surveillance source was used at a time.

### 3.4 DAIDALUS

DAIDALUS is a software implementation intended to satisfy the operational and functional requirements detailed in NASA's DAA concept of integration for UAS [2]. In particular, DAIDALUS provides algorithms that: 1) determine the current, pairwise well-clear status of the ownship and all aircraft inside its surveillance range, 2) compute maneuver guidance in the form of ranges of maneuvers that a pilot-in-command (PIC) may take that will cause the aircraft to maintain or increase separation from the well clear violation volume, or allow for recovery from loss of separation in a timely manner within the performance limits of the ownship aircraft, and 3) determine the corresponding alert type, based on a given alerting schema, corresponding to the level of threat to the well-clear volume. In the developed simulation tool, DAIDALUS utilized a thresholds-based alerting schema [6].

## 4 Sensor Uncertainty Mitigation (SUM)

Sensor uncertainty will cause Losses of DAA Well Clear (LoWC) frequently unless the uncertainty in position and velocity is accounted for. This section describes the Sensor Uncertainty Mitigation (SUM) approach used for the current study and how the scaling factors were tuned.

## 4.1 SUM Approach Description

In the north and east dimensions, the north, east, and north-east (covariance) standard deviation estimates are analyzed using eigenvalue/eigenvector decomposition to determine the major and minor error ellipse axes and magnitudes. The angle of the major/minor axes of the uncertainty ellipse is determined by the ratio of largest eigenvector. This is done because radar and AST sensors typically have much better accuracy in range than in azimuth, which makes the error ellipse highly elongated. Generally, the major and minor horizontal velocity error ellipse axes are closely aligned with those of the positional error, and for this mitigation algorithm they are assumed to be coincident.

*Table 6. Sensor Uncertainty Mitigation scaling factors*

| Scaling Factor | Numeric Value |
|---|---|
| Horizontal Position | 1.5 |
| Horizontal Velocity | 0.5 |
| Vertical Position | 1.0 |
| Vertical Velocity | 1.0 |

For generating intruder input to the DAA algorithm, each intruder's sensed state (3D position and velocity) is passed to the DAA algorithm along with a set of 'phantom' intruder states. These phantoms are generated by enumerating displacements of the sensed state (position and velocity) of the intruder in the positive and negative direction of each of the horizontal error ellipse axes and the vertical axis using a scaling factor multiplied by the matching standard deviation for that axis. This effectively puts an intruder at the vertices of a box bounding the error ellipses corresponding to the scale factors. The numeric values of the scaling factors, presented in Table 6, were chosen based on a study detailed in Section 4.2.

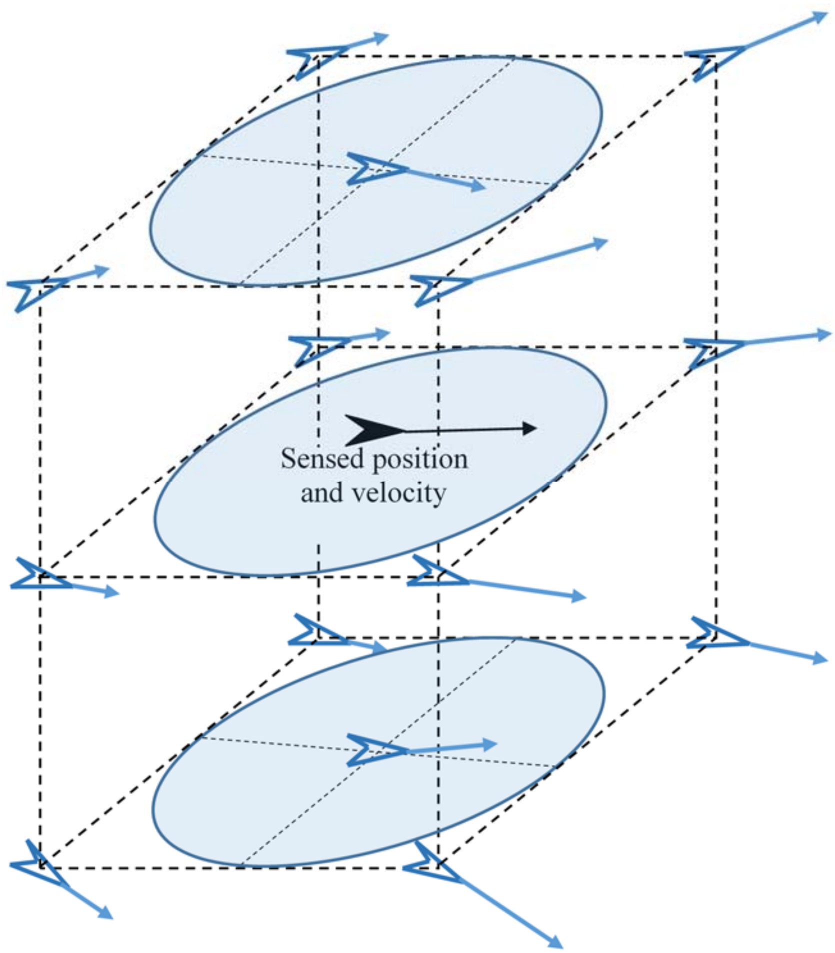


*Figure 3. Notional Depiction of Sensor Uncertainty Mitigation (SUM) Volume.*

In performing the enumeration, an additional set of phantom intruders is placed either at the sensed intruder altitude and altitude rate, or, if the sensed altitude of the intruder could be coincident with ownship's altitude within the look ahead time, at the ownship altitude and vertical rate (zero vertical displacement). This middle plane ensures that potential conflicts are not missed by propagating ownship between the upper and lower surfaces, which in the case of radar can be widely spaced due to the large vertical uncertainty.

As a final processing step, the altitude and speed bands of the DAA algorithm are post-processed to remove and non-conflict regions that lie entirely within the upper and lower surfaces (as propagated out to the look ahead time) or that represent ownship vertical speeds that would not escape the upper or lower surface within the look ahead time.

## 4.2 Tuning of SUM Scaling Factors

The position and velocity of the SUM 'phantom' intruders are dependent on the scalar multiplication of the uncertainty estimate provided by the DAA Tracker. Determining the value of the scalar multiple used in the SUM approach is a function of the UA system, DWC definition, alerting times, and other parameters. To optimize the performance for the MOPS representative DAA system, a multiplier tuning study was done. This section outlines the study as well as the methodology used to determine the optimal SUM Scaling Factor settings. The robustness of the tuning was not evaluated. Similar methodology can be used to tune the SUM approach for differing MOPS, DWC, and Alerting Criteria.

### *4.2.1 Experiment Design*

Simulation runs were completed for every combination of encounter and SUM scaling factors in the test matrix as detailed in the following sections. Due to the stochastic nature of the sensor-tracker models, replicates were used. For each combination of encounter, SUM scaling factors, and sensor type, the following number of replicates were used for each guidance type: 1 Truth replicate, 10 Sensed replicates, and 10 Mitigated replicates.

The complete tuning experiment design consists of 612 total encounters. With the specified number of replicates, the resulting experiment contained 32,436 total runs.

*Table 7. Experiment Design – Encounter Parameters*

| Factor | Value |
|---|---|
| UA Airspeed | 130 KTAS |
| Intruder Airspeed | 100, 200 KTAS |
| Relative Bearing | -45, 0, 45 deg |
| UA Turn Rate | 1.5, 3 deg/sec |

### *4.2.2 Encounter Set*

A full factorial of the encounter parameters in Table 7 was used to define the encounter set used to identify the SUM Scaling Factor setting which provided the best response. The resulting encounter set contains 36 unique encounters.

Figure 4 depicts the geometries of the encounters used in the tuning study. The ownship, shown in blue, is flying straight and level at a constant 130 KTAS, and maneuvers to the right when prompted by the pilot model. The intruder aircraft are positioned such that there will be a direct collision at t = 120 seconds if no avoidance maneuver is performed by the UA. The non-maneuvering intruders are flying at airspeeds chosen such that there are intruder aircraft flying both slower and faster than the UA. Note the change in relative velocity vectors between the ownship and the two intruder airspeeds at +- 45 deg.

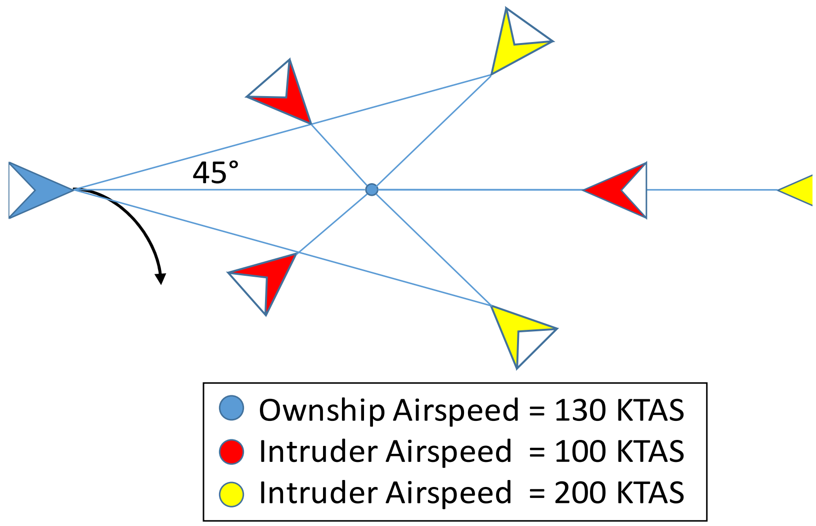


*Figure 4.Tuning Study - Encounter Geometry.*

No encounters were evaluted with the UA overtaking the intruder because they are not stressing cases.

#### *4.2.3 Scaling Factors*

A 2-level full factorial design was used to analyze the response with the four SUM scaling factors being the independent variables. Table 8 contains information on the factor levels. Including a single center point, the 2-level factorial design resulted in 17 unique combinations of SUM Scaling Factors.

*Table 8. SUM Scaling Factors experiment values.*

| Factor | Min. Value | Max. Value | Center Value |
|---|---|---|---|
| Scale_XY | 0.5 | 1.5 | 1.0 |
| Scale_Vxy | 0.5 | 1.5 | 1.0 |
| Scale_Z | 0.5 | 1.5 | 1.0 |
| Scale_Vz | 0.5 | 1.5 | 1.0 |

#### *4.2.4 Tuning Methodology*

Using SLoWC as the primary response of interest and Alert Jitter as a secondary consideration, the objective of this tuning study was to minimize both measured responses during the specified encounters. Each combination of SUM Scaling Factors in the 2-level factorial was analyzed independently. After collecting data from the encounter set described in Section 4.2.2, each response was compared. Choosing the scaling factor combinations that minimize SLoWC are first identified, then those combinations' alert jitter responses were analyzed.

The focus of this report is analysis of the SUM approach so the details of selecting the multiples used is not provided. The multipliers used are given in Table 6.

### 4.3 Guidance Band Buffer Analysis

The uncertainty associated with sensors is a source of alert jitter. Per the Phase 1 DAA MOPS [5], Corrective and Warning alerts are issued when a hazard is predicted to be on the

UA’s current trajectory. If the UA attempts to fly tangential to the hazard volume, sensor noise will likely cause a large increase in the Alert Jitter. Such a tangential flight path is associated with following the edge of the DAIDALUS guidance bands. To minimize the amount of Alert Jitter while also keeping the path deviation reasonably constrained, a trade-off study was conducted. The study measured the impact of adding a buffer to the edge of the DAIDALUS guidance bands on SLoWC and Alert Jitter. A constant buffer of 1 deg, 5 deg, and 10 deg was added to the edge of the guidance band and analysis was done to assess alert jitter for each.

#### *4.3.1 Encounter Set*

This study was performed using a full factorial of 6 factors, as detailed in Table 9. The encounter geometries are presented in Figure 5. The resulting experiment matrix consists of 54 unique encounters. To account of the stochastic response from the sensor/tracker models, several replicates were run for each encounter. A total of 21 replicates were used for each encounter: 1 Truth replicate, 10 Sensed replicate, and 10 Mitigated replicate. The resulting experiment matrix consist of 1134 runs for each Guidance Band Buffer value.

*Table 9. Factor Values for Guidance Band Buffer Analysis*

| Parameter (Units) | Values |
|---|---|
| UA Turn Rate (deg/sec) | 0 (open-loop), 1.5, 3.0 |
| UA Airspeed (KTAS) | 130 |
| Intruder Airspeed (KTAS) | 100, 200 |
| Relative Bearing (deg) | 0, ±45 |
| Sensor Configuration | RADAR, AST, ADS-B |

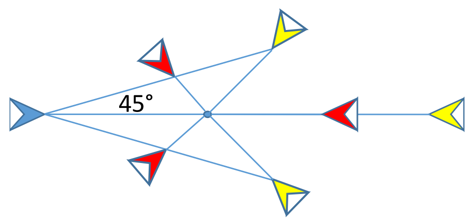


*Figure 5. Encounter Geometry for Guidance Band Buffer Analysis.*

#### *4.3.2 Results*

The results presented herein are separated based on the pilot model’s ability to respond. In other words, analysis of Open-Loop runs is considered independently from Closed-Loop analysis.

##### *4.3.2.1 Open-Loop Alert Jitter*

Simulation runs in which the pilot response model does not follow the suggested guidance and thus maintains the initially defined trajectory are referred to as Open-Loop simulation runs. Such runs are useful for analysis as they remove the influence of the pilot response model from the measure responses of interest. Alert Jitter response is of particularly interest for Open-Loop analysis, as Open-Loop runs remove influence of maneuver selection and Guidance Band Buffer value. For the defined encounter set, all Open-Loop runs result in a direct collision with a SLoWC = 100%. Figure 6 through Figure 8 shows the normalized distribution of Alert Jitter for the open-loop runs of the previously described encounter set. The figure shows the normalized distributions of Alert Jitter grouped by path of data flow, as detailed in Figure 2. Within Figure 6 through Figure 8, the histogram of runs using truth data are shown in blue, the runs using sensor/tracker degraded data are in the red, and runs which incorporate the SUM approach are in green.

As expected with perfect surveillance data, the alert jitter equals 2 for all encounters. Given that the simple, benign encounter set involves co-altitude encounters, the ideal alert

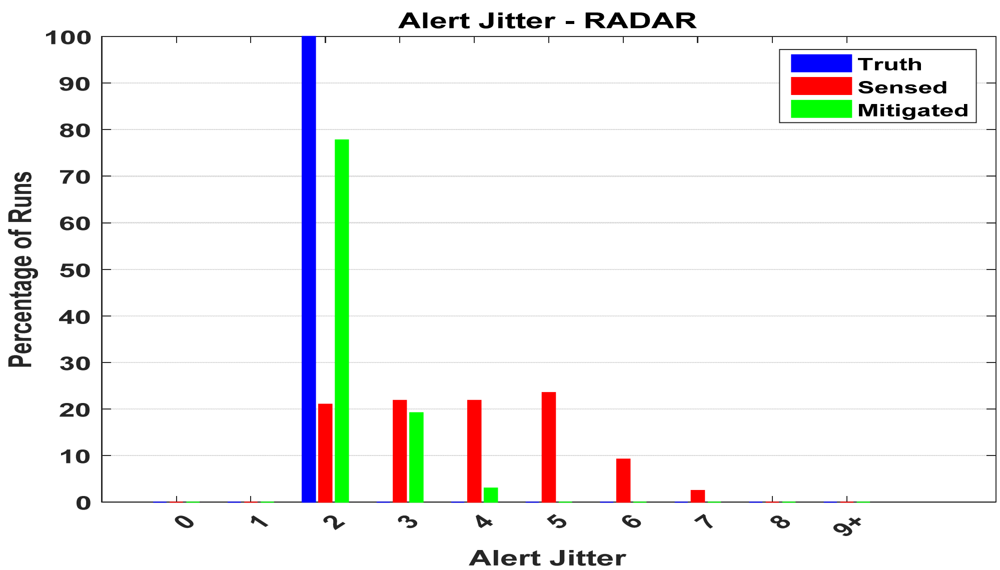


*Figure 6. Distribution of Alert Jitter: Open Loop – RADAR only*

transition is from <No Alert> to <Corrective Alert> to <Warning Alert> which is represented by an Alert Jitter value of 2. Note that there is no difference between the Truth runs with different sensors, since the limitations of each sensor are not incorporated in the Truth runs.

Figure 6 shows the Alert Jitter distribution for encounters involving a non-cooperative intruder sensed by the air-to-air radar. Comparing the Truth and Sensed distributions, the degradation of state data undesirably increases the Alert Jitter.

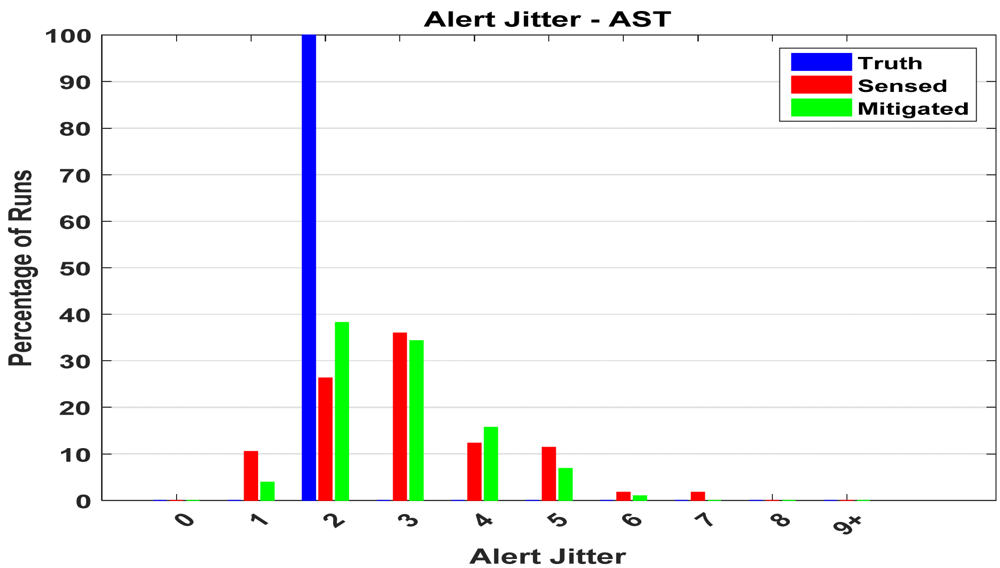


*Figure 7. Distribution of Alert Jitter: Open Loop – AST only*

Figure 7 shows the Alert Jitter distribution when equipped with AST. There is no significant improvement in Alert Jitter performance when comparing Sensed and Mitigated runs. The maximum Alert Jitter is 7. Of interest, there are occurrences of Alert Jitter equal to 1 when equipped with AST indicating that an alert was missed (e.g., UA transitioned from <No Alert> to <Warning Alert> without transitioning to <Corrective Alert>).

ADS-B-equipped Alert Jitter distribution is shown in Figure 8. As ADS-B is the most accurate sensor, the large majority of the runs resulted in Alert Jitter of 2. Even when following guidance based solely on ADS-B degraded data, the Alert Jitter performance is well contained. Even then, SUM approach increases the percentage of runs with Alert Jitter equal to 2.

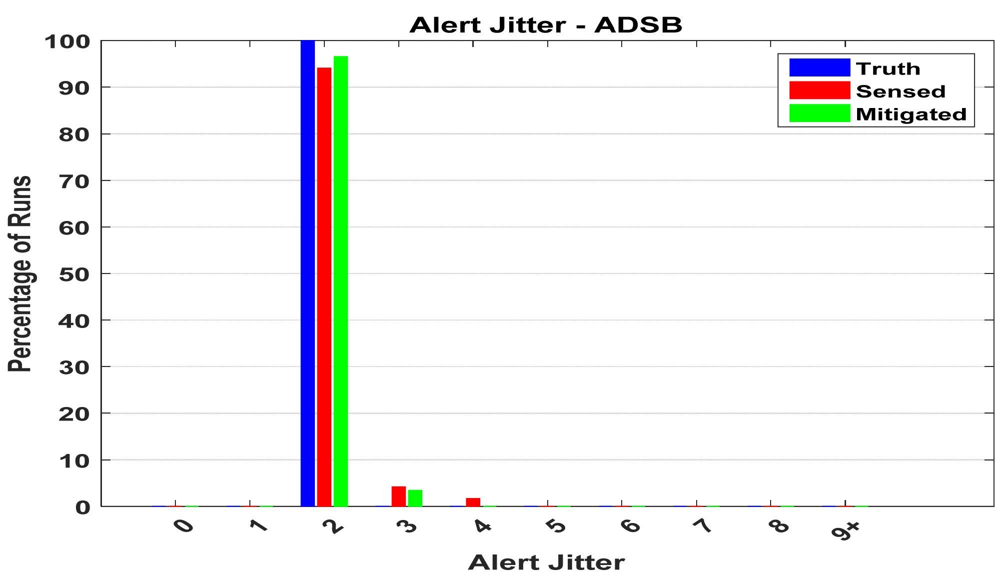


*Figure 8. Distribution of Alert Jitter: Open Loop – ADS-B only*

### *4.3.2.2 Closed-Loop SLoWC*

SLoWC response is analyzed for closed loop runs to investigate the severity of the loss of separation with the pilot in the loop responding to DAA guidance.

Figure 9 – Figure 11 show sensor-specific distributions of SLoWC for the three Guidance Band Buffer increments. Each figure contains three sub-figures with increasing Guidance Band

Buffer: 1 degree Guidance Band Buffer at the top, 5 deg in the center, and 10 deg at the bottom. Each sub-figure contains 3 distributions with different colors: Blue – Truth, Red – Sensed, Green – Mitigated. In all figures, the runs with guidance based on truth data maintain DAA Well Clear (SLoWC = 0) in all encounters. Table 10 - Table 12 contain summary statistics with the maximum SLoWC and Alert Jitter from each sensor-specific distribution.

RADAR-only distributions of SLoWC are shown in Figure 9. Independent of Guidance Band Buffer increment, the SUM mitigation approach reduces the measured SLoWC compared to following guidance based only on sensor degraded state data. There appears to be an increase in SLoWC values for runs with Guidance Band Increment greater than 1. While the figure indicates runs with a SLoWC ranging from greater than 0 to less than 10, the maximum SLoWC experienced for runs incorporating the SUM approach is 0.85% with 5 deg buffer and 6.37% with a 10 deg buffer, as shown in Table 10. These values of SLoWC are very small. Analyzing the maximum Alert Jitter response for RADAR-only runs with the SUM approach incorporated reveals a decrease in the Alert Jitter as Guidance Band Buffer increases.

*Table 10.Maximum SLoWC - RADAR.*

| Guidance Band Buffer (deg) | Guidance Type | Max. SLoWC | Max. Alert Jitter |
|---|---|---|---|
| 1 | Truth | 0 | 2 |
| 1 | Sensed | 84.67 | 8 |
| 1 | Mitigated | 0 | 8 |
| 5 | Truth | 0 | 2 |
| 5 | Sensed | 18.06 | 9 |
| 5 | Mitigated | 0.85 | 6 |
| 10 | Truth | 0 | 2 |
| 10 | Sensed | 15.65 | 9 |
| 10 | Mitigated | 6.37 | 5 |

Figure 10 shows the AST-only distributions of SLoWC. While SLoWC is reduced using the SUM approach, the performance is still not ideal. From Table 11, the Mitigated runs result in a SLoWC greater than 56% regardless of Guidance Band Buffer value. This performance is likely to be consider unacceptable. For AST, SUM approach undesirably increases the Alert Jitter measured. This is likely due to the large variations that occur in AST measurements.

ADS-B only distributions of SLoWC are shown in Figure 11 and the maximum value of SLOWC is shown in Table 12. There were minor loses of DAA Well Clear for all levels of the Guidance Band Buffer with slight improvement as the Guidance Band Buffer increases. Alert Jitter improves greatly for Guidance Band Buffer greater than 1 deg, but there is little difference between 5 deg and 10 deg buffers.

Based on this discussion, future use of this simulation tool will employ a 5 deg band buffer to optimize the trade-off between minimizing SLoWC and Alert Jitter while also minimizing the required avoidance maneuver.

*Table 11.Maximum SLoWC - AST.*

| Guidance Band Buffer (deg) | Guidance Type | Max. SLoWC | Max. Alert Jitter |
|---|---|---|---|
| 1 | Truth | 0 | 2 |
| 1 | Sensed | 96.43 | 12 |
| 1 | Mitigated | 65.87 | 20 |
| 5 | Truth | 0 | 2 |
| 5 | Sensed | 97.45 | 11 |
| 5 | Mitigated | 56.28 | 17 |
| 10 | Truth | 0 | 2 |
| 10 | Sensed | 98.70 | 13 |
| 10 | Mitigated | 76.54 | 18 |

*Table 12.Maximum SLoWC – ADS-B.*

| Guidance Band Buffer (deg) | Guidance Type | Max. SLoWC | Max. Alert Jitter |
|---|---|---|---|
| 1 | Truth | 0 | 2 |
| 1 | Sensed | 12.52 | 9 |
| 1 | Mitigated | 2.62 | 14 |
| 5 | Truth | 0 | 2 |
| 5 | Sensed | 10.41 | 8 |
| 5 | Mitigated | 1.95 | 8 |
| 10 | Truth | 0 | 2 |
| 10 | Sensed | 7.79 | 7 |
| 10 | Mitigated | 1.07 | 9 |

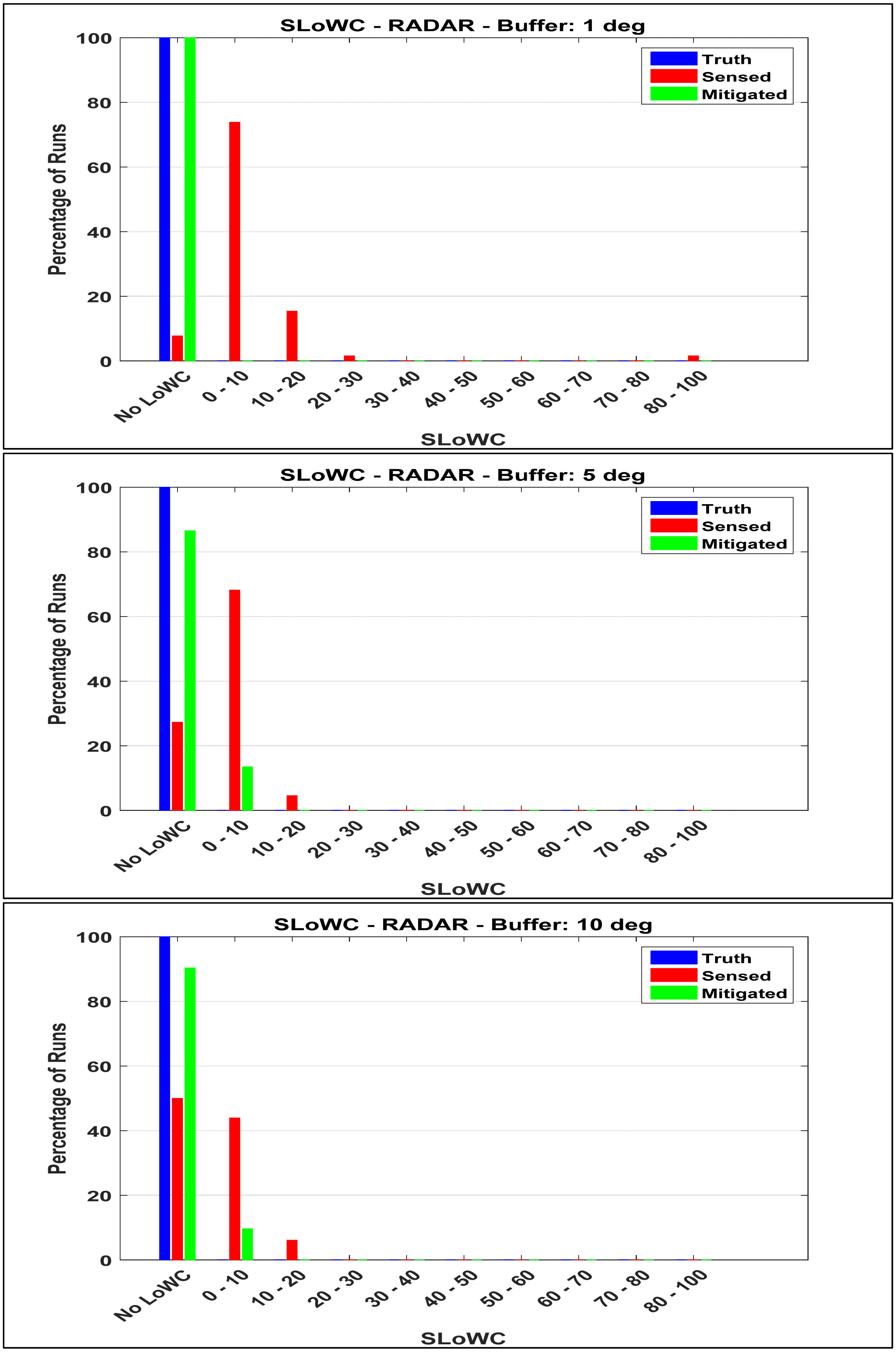


*Figure 9. Distribution of SLoWC: Closed Loop – RADAR equipped.*

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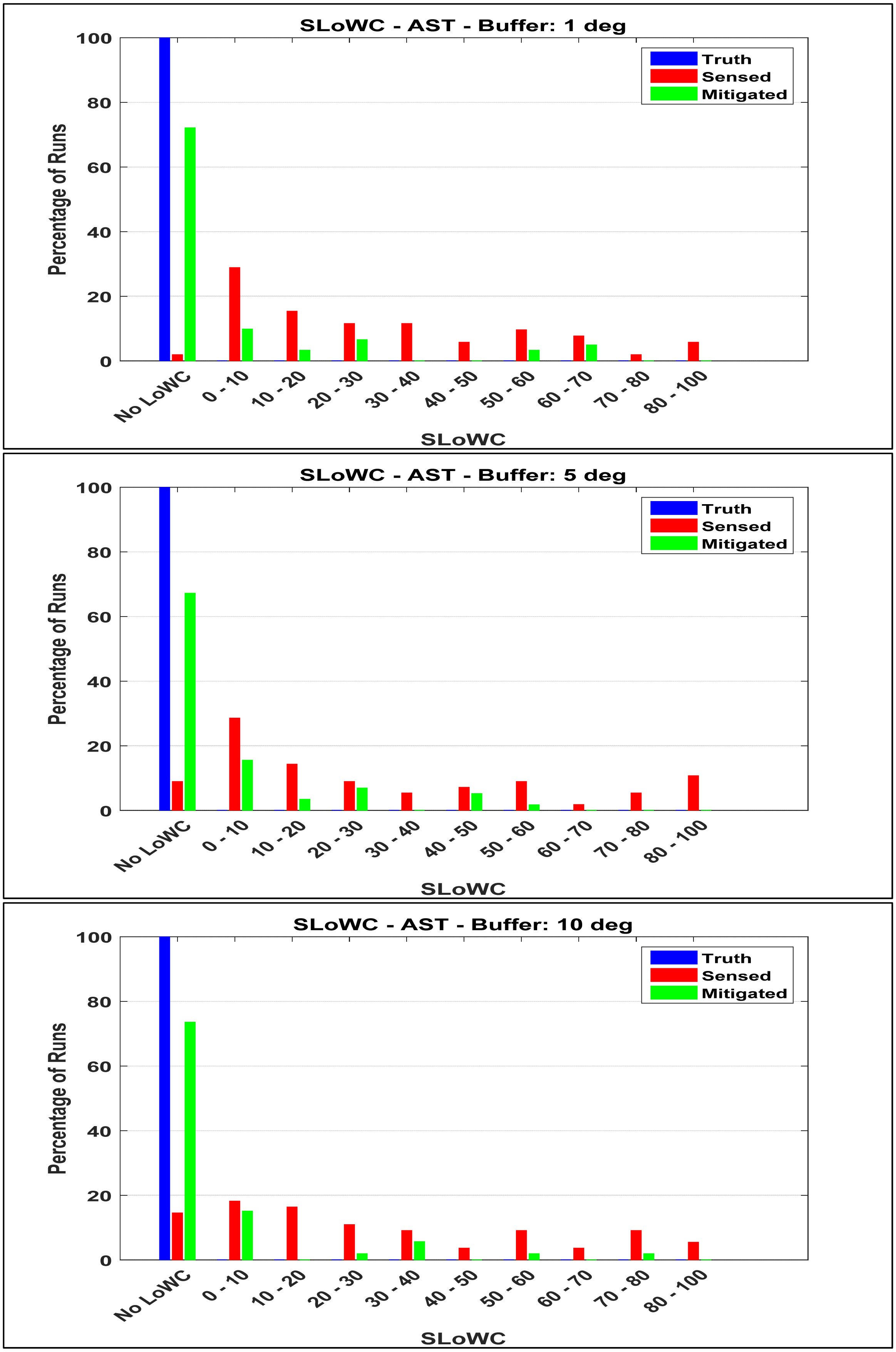


*Figure 10. Distribution of SLoWC: Closed Loop –AST equipped.*

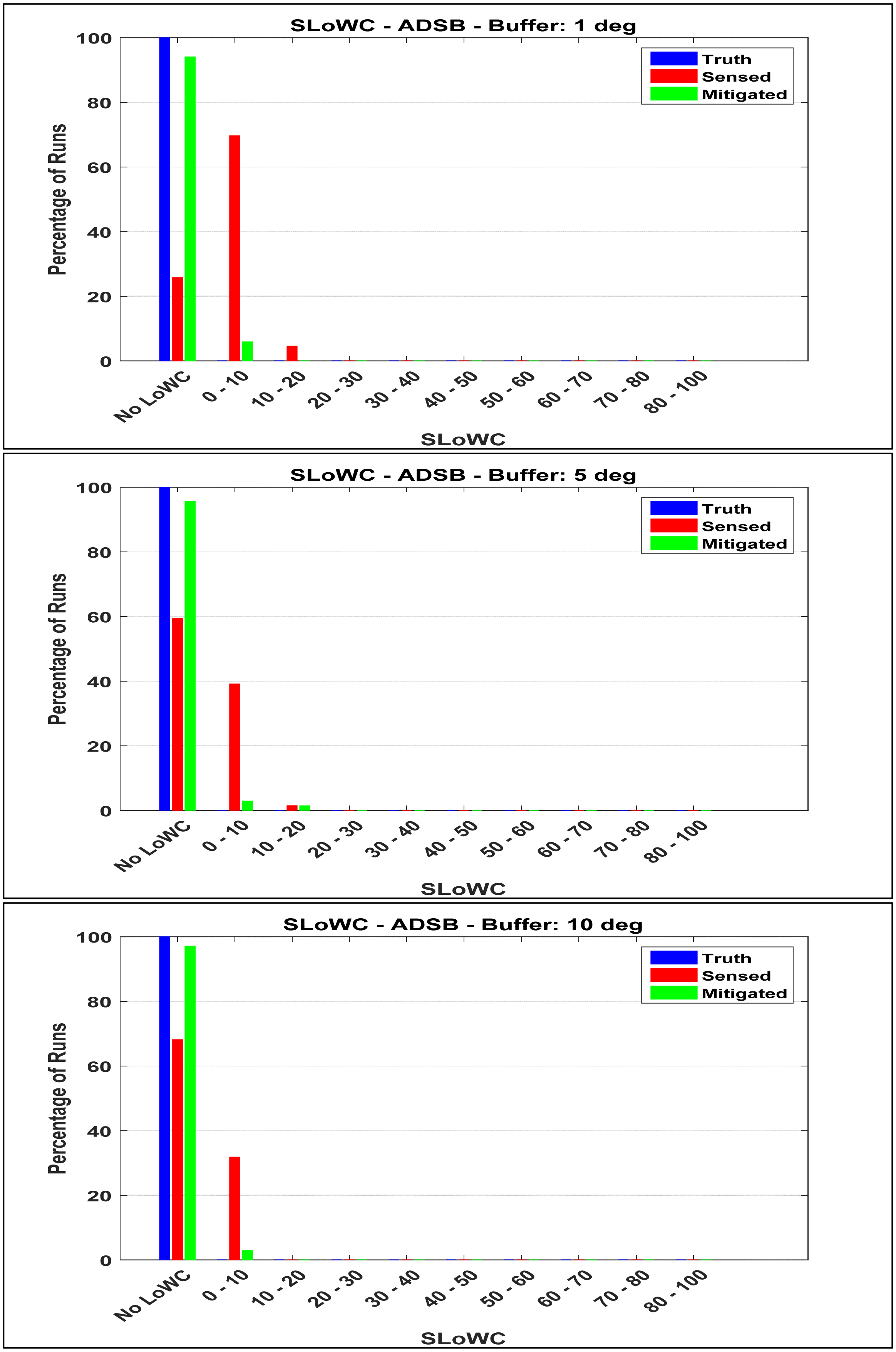


*Figure 11. Distribution of SLoWC: Closed Loop – ADS-B equipped.*

# 5 Discussion and Analysis

The introduction of additional ‘phantom’ intruders augments the DAA region by creating a physically larger volume for the DAA system to avoid as well as augmenting the perceived time at which the maneuver must begin. The following sections detail the magnitude of the change to the DAA avoidance region by analyzing the change in commanded maneuver timing as well as the change in the provided guidance bands.

## 5.1 Size of SUM Volume

The additional ‘phantom’ intruders introduced by the SUM approach expand the hazard avoidance volume. Figure 12 – Figure 14 depicts a pairwise head-on encounter with a maneuvering ownship. Within each figure, the true positions of the ownship (blue) and intruder (green) are shown as well as each sensor degraded track (black). The ‘phantom’ intruder positions (red) are also shown. Each figure shows the overhead view on the left and a profile view on the right. For each encounter shown, there would be a direct head-on collision between the two aircraft if no avoidance maneuver is performed.

Figure 12 shows the same pairwise encounter involving a non-cooperative intruder sensed only by the onboard air-to-air RADAR. The uncertainty estimate starts out very large but improves as the range between the aircraft decreases, resulting in a reduction in the size of the volume defined by the SUM phantom intruders.

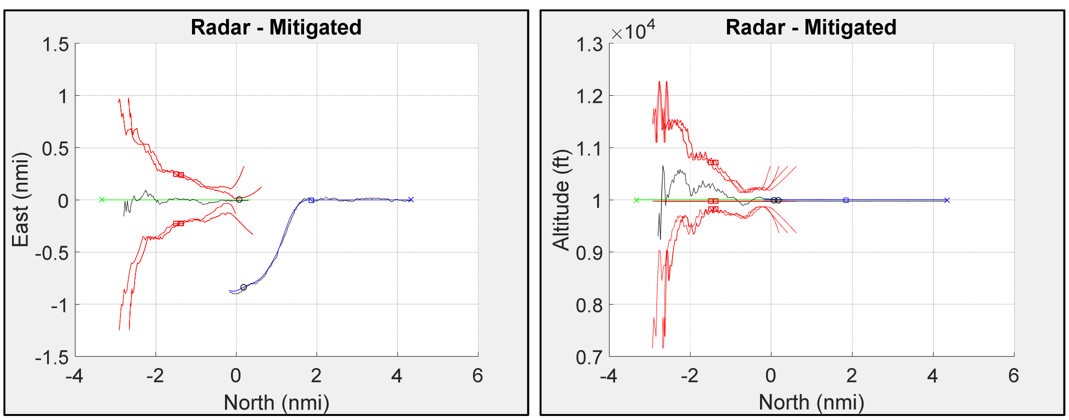


*Figure 12. Example of Sensed Position - RADAR.*

The same pair-wise encounter involving AST equipped aircraft is shown in Figure 13. The sensed position of the intruder is particularly poor in the lateral positioning. Initially, the sensed position of the intruder (shown in black) is more than 1 nmi off from the true position. With the SUM approach a ‘phantom’ intruder is roughly 3 nmi off laterally offset. This collision avoidance region is very large and may inhibit lateral maneuvers.

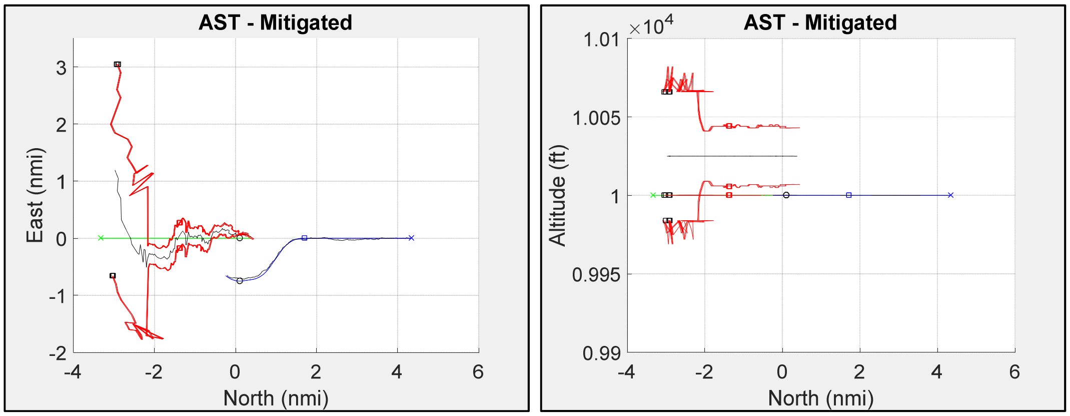


*Figure 13. Example of Sensed Position - AST.*

Figure 14 shows the pairwise encounter with ADS-B as the equipped sensor. As ADS-B is not a relative sensor, but rather a received message with high accuracy comparable to the own ship's sensed position accuracy, the estimated uncertainty is relatively small and nearly constant, shown in Figure 14 by the smoothness of the sensed intruder track (black). The figure on the right shows a constant vertical bias of ~250 ft.

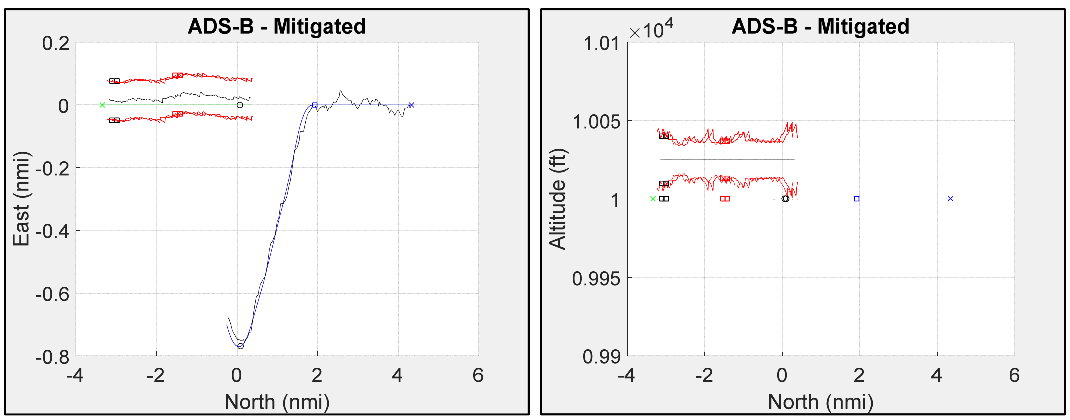


*Figure 14. Example of Sensed Position - ADS-B.*

### 5.2 Effect on Lateral Maneuvering

To illustrate the SUM approach's effect on maneuvering and the resulting SLOWC, a case study is provided. Figure 15 – Figure 17 show the maneuver performed in response to DAA guidance based on the specified sensor configuration. Each figure shows data for the same encounter scenario; a pair-wise head-on encounter involving a maneuver ownship at 130 KTAS and a constant trajectory intruder at 100 KTAS. The UAS is capable of turning at 3.0 deg/sec. Each figure contains two subplots; on the left is the overhead view of the encounter, on the right is normalized distribution of SLoWC measured for the depicted simulation runs. In each

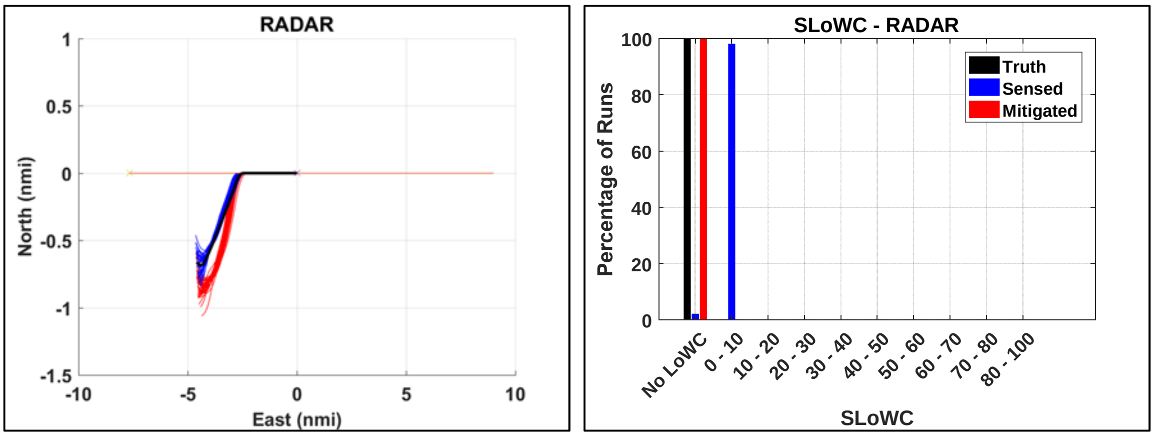


*Figure 15. Effect of Mitigation – Maneuver Selection - RADAR.*

figure, the black represents the runs following guidance based on perfect state data (i.e., Truth), the blue depicts the runs in which the maneuver is based on sensor degraded state data only (i.e., Sensed), and the red line represents runs incorporating the SUM approach (i.e., Mitigated).

Figure 15 shows the effect on maneuver selection for encounters involving non-cooperative intruders sensed solely by the air-to-air radar onboard the UA. The maneuver selection is well-contained with respect to the source of the provided guidance. In the trajectory figure, there are tight groupings of the Sensed and Mitigated runs indicating a consistent uncertainty estimate across the replicates. The Mitigated runs make a large path deviation and turn further than the Sensed runs. From the SLoWC distribution of Figure 15, all Truth runs and the majority of Mitigated runs resulted in no LoWC, while most Sensed runs failed to maintain DAA Well Clear though none exceeded 10% SLoWC.

The effect on maneuver selection for encounters involving transponder equipped aircraft is shown in Figure 16. In this example encounter, the UA displays insufficient ability to maintain

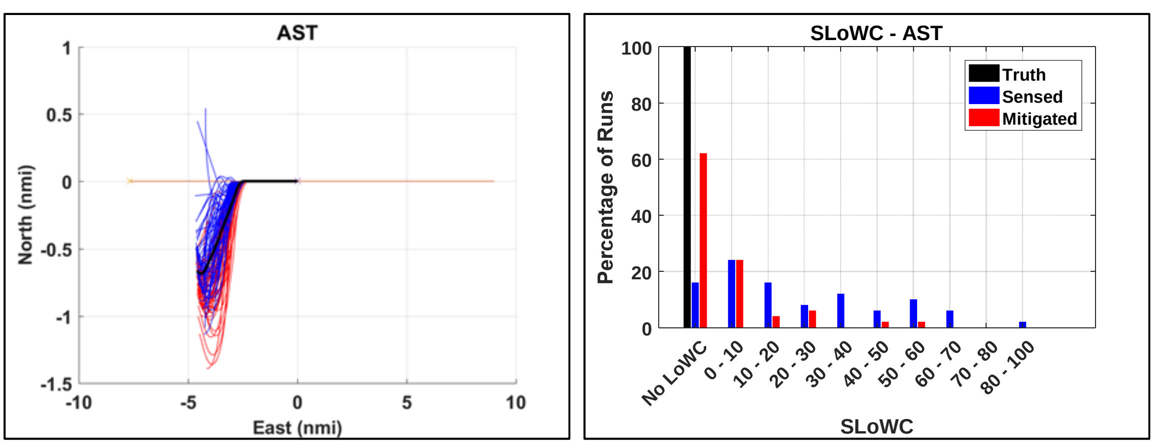


*Figure 16. Effect of Mitigation – Maneuver Selection - AST.*

DAA Well Clear. The variation in AST estimates of intruder state data and associated uncertainty are too great to maintain separation from other aircraft. Despite the poor performance when utilizing AST sensor degraded data, the normalized distribution of SLoWC shows a reduction in SLoWC for Mitigated runs compared to Sensed runs. 64% of the Sensed encounters had SLoWC greater than 10% while only 26% of the mitigated ones did: a 40% improvement.

Figure 17 shows the effect on maneuver selection for encounters involving ADS-B equipped aircraft. The trajectory subplot shows that the trajectories for all runs are closely bound. The runs incorporating the SUM approach are shown to maintain further separation from the intruder than the runs using sensor-degraded state data only. This is confirmed in the normalized distribution of SLoWC as most runs following the SUM approach-based guidance resulted in fewer losses of DAA Well Clear (i.e., SLOWC > 0).

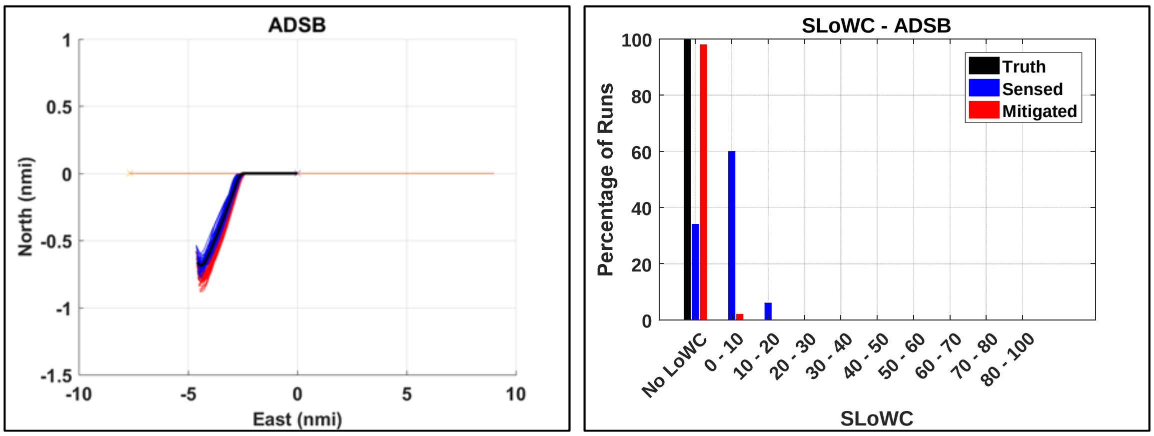


*Figure 17. Effect of Mitigation – Maneuver Selection – ADS-B.*

# Conclusion

Sensor uncertainty negatively impacts an Unmanned Aircraft System's (UAS's) ability to maintain sufficient separation from intruder aircraft and limit unnecessary alerting. An approach to compensate for sensor uncertainty for use in Detect-and-Avoid (DAA) systems was developed and presented. A methodology used to tune the SUM approach to a specific application was also introduced. Such methodology can be applied to a different system to meet the needs and operational considerations of a wide variety of UA. The SUM approach is dependent on the estimated uncertainty provided by the DAA Tracker, and thus is independent of sensor type. This allows the SUM approach to be applicable across a large number of UAS component configurations.

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**14. ABSTRACT**

Without a pilot onboard an aircraft, a Detect-and-Avoid (DAA) system, in conjunction with surveillance sensors, must be used to provide the remotely-located Pilot-in-Command sufficient situational awareness in order to keep the Unmanned Aircraft (UA) safely separated from other aircraft. To facilitate safe operations of UA within the U.S.' National Airspace System, the uncertainty associated with surveillance sensors must be accounted for. An approach to mitigating the impact of sensor uncertainty on achievable separation has been developed to support technical requirements for DAA systems.

**15. SUBJECT TERMS**
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