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RTCA Detect and Avoid Phase 2: Safety Risk Management Modeling and Simulation Final Report

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Revision History

Date	Version Number	Change	Author
11/23/2021	0.1	Initial final report from MIT Lincoln Laboratory	Christine Serres
1/29/2022	1.0	Incorporated comments received from RTCA SC-228 review	Christine Serres
5/11/2022	2.0	Added Appendix E documenting single-sensor runs and LEPR mitigation analysis, following feedback from SC-228 meeting in January 2022	Christine Serres

Abstract

The objective of this modeling and simulation safety analysis was to support the Federal Aviation Administration’s detect-and-avoid (DAA) Safety Risk Management Document (SRMD) and Technical Standard Order (TSO) by providing modeling and simulation results. The scope of the analysis, and the associated SRMD and TSO, was the RTCA SC-228 Phase 2 DAA minimum operational performance standards, and by extension, the command and control (C2) minimum aviation system performance standards. The key addition in Phase 2 was ground surveillance and the terminal environment. Three main analysis phases were performed: an integrated delay and C2 interruption sensitivity analysis in the terminal environment, a Ground Based Surveillance System (GBSS) sensor accuracy sensitivity analysis in the en route environment, and a comprehensive final safety analysis to provide data for the SRMD and TSO. The test cases for the final safety analysis were designed to represent the minimum performance of the DAA system, and may not necessarily reflect typical operating conditions. The C2 sensitivity analysis affirmed that the 3-second C2 interruption requirement in the C2 MASPS is acceptable for the DAA function. The GBSS sensitivity analysis indicated that the accuracy requirements in DO-365B result in reasonable performance. Lastly, the final safety runs provided key DAA performance information that will feed into the final safety evaluation to support the TSO and SRM.

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1 INTRODUCTION

RTCA has been developing Minimum Operational Performance Standards (MOPS) for Detect and Avoid (DAA) and Command and Control (C2) systems as part of Special Committee 228 (SC-228) activities. The Phase 1 MOPS were published in 2017 and a Phase 2 effort to revise and extend the Phase 1 MOPS was completed in 2021. In order for the MOPS to be fully utilized, they must be evaluated by the Federal Aviation Administration (FAA) employing the FAA's Safety Risk Management (SRM) process. In order to support the SRM process, there is a need for simulation data focused on the safety of DAA encounters.

This analysis focuses on gathering information to validate the use of SC-228 MOPS compliant DAA and C2 systems to enable routine UAS operations in the National Airspace System (NAS) without a chase aircraft or visual observers. The scope of this effort aligns with the SC-228 Terms of Reference that can be generally characterized as Unmanned Aircraft (UA) flying under Instrument Flight Rules (IFR) and receiving Air Traffic Control (ATC) separation services. This analysis evaluates the system safety in mixed airspace classes A, B, C, D, E, and G airspaces, and includes other IFR, Visual Flight Rules (VFR), cooperative and noncooperative aircraft in en route and terminal operations. The final safety analysis configurations and test cases were intended to represent the minimum acceptable DAA system performance, and are not necessarily a reflection of the actual operating conditions that UAS would be expected to encounter.

This final report is organized as follows: Section 2 describes the methodology used to perform the analysis. Section 3 describes the baseline results as well as results for two sensitivity analyses: the integrated delay and C2 interruption sensitivity analysis, and the Ground Based Surveillance System (GBSS) sensor accuracy sensitivity analysis. Section 4 describes the results for the final safety evaluation. Section 5 describes future work and Section 6 provides a summary of findings.

1.1 Purpose

The objective of this analysis is to support the FAA's Safety Risk Management Document (SRMD) for the RTCA SC-228 Phase 2 DAA MOPS (DO-365B) [1] and C2 MASPS (DO-377A) [2] following the FAA Office of Aviation Safety SRM process. This analysis is specifically focused on obtaining modeling and simulation results to support a safety assessment of the RTCA SC-228 DAA and C2 MASPS. The modeling and simulation assesses how well a DAA system on an IFR ownship performs when encountering an intruder in en route and terminal operations in terms of safety metrics such as risk ratio and loss of well clear ratio. The analysis consists of three main phases: an integrated delay and C2 interruption sensitivity analysis in the terminal environment, a Ground Based Surveillance System (GBSS) sensor accuracy sensitivity analysis in the en route environment, and a comprehensive final safety evaluation to provide data for the SRMD and TSO.

This analysis focuses specifically on modeling nominal conditions as opposed to equipment failures. The safety assessment itself (e.g., fault tree analysis, operational hazards assessment) is being performed by MITRE and is not part of this analysis. MITRE is also responsible for writing the SRMD. However, the modeling and simulation final safety evaluation provides values that will be used in MITRE's safety assessment.

1.2 Scope

The primary scope of this analysis is the evaluation of the Phase 2 RTCA SC-228 MOPS. The scope of this activity includes conducting modeling and simulation to assess key safety metrics for both terminal and en route operations. In general, the following configurations are assessed:

- Terminal area operations assuming a low latency networked terrestrial Command and Non-Payload Communications (CNPC) link that is aligned with the RTCA C2 MASPS and the use of a Ground Based Surveillance System (GBSS) and/or Airborne Detect and Avoid (ABDAA) system.
- En route operations that assume the use of an ABDAA system and may utilize either a low latency networked terrestrial CNPC link that is aligned with the RTCA C2 MASPS or a Ka/Ku band Satellite Communications (SATCOM) link. This includes a performance sweep of GBSS parameters vs. DAA closed loop performance (e.g., risk ratio, loss of well clear ratio) to establish a suitable set of minimum requirements for GBSS to support en route operations.

Note that urban air mobility (UAM) and small unmanned aircraft systems (sUAS) operations are out of scope of this analysis.

This analysis addresses new models for the Low-Size Weight and Power (SWaP) Non-Cooperative (LSNC) Air-to-Air Radar (ATAR) and Electro-Optical/Infrared (EO/IR) sensor performance and alerting timeline. Additionally, this analysis is applicable to operations in the en route environment and terminal area, including take-off and landing at non-airport access points. The analysis includes mixed environments which contain IFR and VFR traffic, including General Aviation (GA) and experimental aircraft, which can be non-cooperative and/or slow-moving. It should be noted that surface operations are outside the scope of this analysis.

In order to accomplish this analysis, a statistical model was developed for the availability, latency, data integrity, and Transaction Expiration Time (TET) for both a MOPS-compliant networked terrestrial C2 link and a representative Ku/Ka SATCOM link.

2 METHODOLOGY

This section describes the methodology used to produce the SRM simulation results, including the simulation method and architecture, assumed model parameters, encounter generation, and metrics.

2.1 Simulation Method

Monte Carlo simulation using MIT Lincoln Laboratory's DAA Evaluation of Guidance, Alerting, and Surveillance (DEGAS) tool was used to assess the safety of the Phase 2 RTCA SC-228 MOPS. DEGAS is the open-source version of MIT Lincoln Laboratory's Collision Avoidance System Safety Assessment Tool (CASSATT), which was used to support the Phase 1 SRMD, as well as to support SC-228 sensor requirements (e.g., EO/IR), and the specification of the noncooperative DAA Well Clear (DWC) definition. CASSATT was originally developed to support the SRMD for the Traffic Alert and Collision Avoidance System (TCAS) V7.1. The initial release (Version 1) of DEGAS (December 15, 2020) is available on GitHub. For this analysis, Version 2 of DEGAS was used. This version of DEGAS contains several new models to consider the SC-228 Phase 2 scope, including the GBSS sensor, FAA tracker, C2 latency/interruptions model, TCAS II logic, updated ATAR/EOIR models to reflect requirements for the three aircraft classes (HALE (High Altitude, Long Endurance), MALE (Medium Altitude, Long Endurance), and LEPR (Low End Performance Representative)), and trajectory-following capabilities for terminal encounters. See Appendix B for the complete change log of updates between Version 1 and Version 2.

The complexity of the DAA system response, including reference tracking, and alerting and guidance algorithms, requires Monte Carlo simulation to perform a comprehensive assessment. Monte Carlo simulation involves the evaluation of millions of encounter situations to enable computation of safety metrics with statistical significance for different sets of parameters. Figure 1 shows the functional diagram of DEGAS. Encounters containing intruder and ownship trajectories representing random, realistic airspace situations are fed into DEGAS. The intruder trajectory is simulated using an aircraft dynamic model. The intruder's true trajectory is then processed by sensor and tracker models. Next, the noisy intruder position information simulated by the sensor models is processed by the alerting and guidance algorithm. If needed, avoidance guidance will be issued and the operator model will select an appropriate maneuver. This maneuver is then executed by an aircraft dynamics model. At the end of the simulation, time histories and metrics (e.g., whether an NMAC has occurred) are saved. For this analysis, at least one million encounters were simulated for each scenario that was evaluated either as part of the scenarios run for MITRE's fault tree analysis or the C2 and GBSS sensitivity analyses. Given the resultant statistical confidence of the results, one million encounters were deemed sufficient.

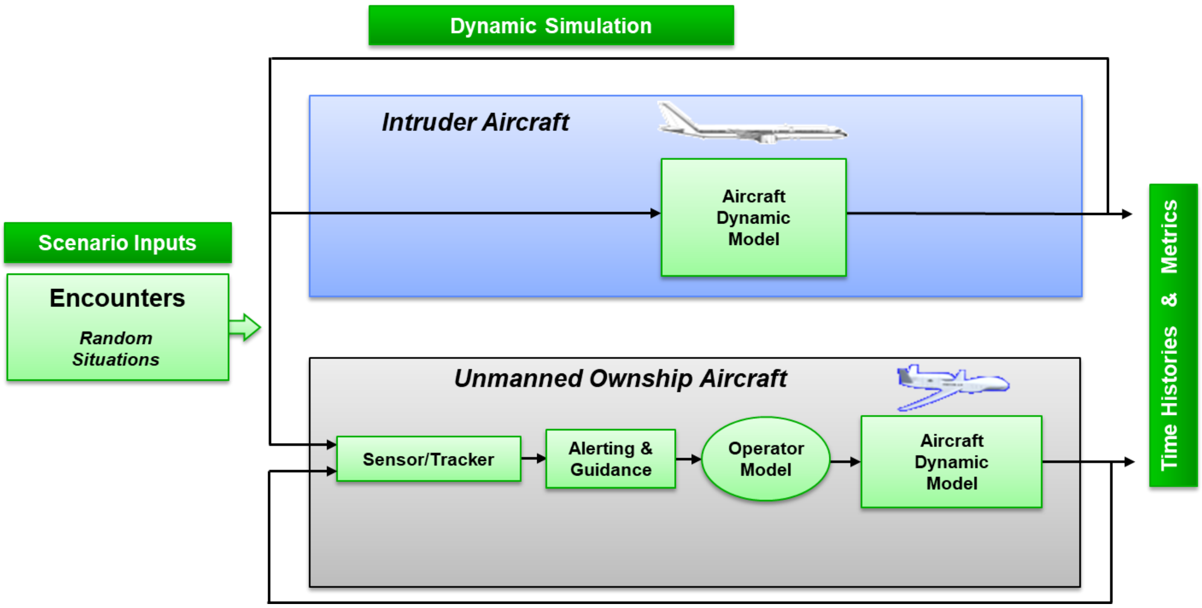

Figure 1. DEGAS functional diagram.

The following subsections describe the analysis assumptions, the models that comprise the DEGAS simulation (including sensors, dynamics, and DAA logic), the encounters that were simulated, and the metrics that were collected.

2.1.1 Assumptions

The following assumptions are used in the analysis.

2.1.1.1 General Assumptions

The analysis specifically focuses on one-on-one encounters between an ownship and both cooperative and non-cooperative intruders flying in en route and terminal environments. In Phase 1, the scope was limited to unmanned aircraft transiting through Class D, E, and G airspace. In this study, the scope was expanded to include classes A, B, C, D, E, and G airspaces, and includes IFR, VFR, cooperative, and non-cooperative aircraft for en route and terminal operations.

The ownship uses the RTCA reference algorithm Detect and AvoID ALerting for Unmanned Systems (DAIDALUS) for DAA alerting and guidance, and TCAS II collision avoidance for Class 2 equipment. In instances where both TCAS II RAs and DAIDALUS guidance are issued simultaneously, TCAS II RAs are followed. Evaluating DAA Class 3, which uses Airborne Collision Avoidance System Model X for unmanned aircraft (ACAS Xu), is out of scope. However, runs with ACAS Xu could be performed as future work (see Section 5.1.3), Collision avoidance systems on the intruder aircraft are not modeled.

2.1.1.2 Aircraft Performance Assumptions

Table 1 describes the aircraft dynamics and altitude assumptions that were used to simulate three different UA types: HALE, MALE, and LEPR. These aircraft were also used in the Phase 1 SRM studies, but there are some differences in the velocity, vertical rate, and turn rate limits used in this Phase 2 study. HALE, MALE, and LEPR aircraft are simulated with a Class A1, Class A2, or Class A3 radar, respectively.

Table 1. Aircraft categories.

Constraint	HALE	MALE	LEPR
Maximum (Max) Velocity (Knots (kts))	291 (*300*)	200	110 (*100*)
Minimum (Min) Velocity (kts)	100	40 (*80*)	40 (*50*)
Max Pitch (°)	15	15	15
Min Pitch (°)	-15	-15	-15
Correlated/Uncorrelated Max Altitude (feet (ft))	~60 thousand (k)/ 10k	~60k / 18k	18k/ 18k
Vertical Rate (feet per minute (fpm))	2,500 (*4,000*)	1,500 (*3,000*)	500
Turn Rate (degrees per second (dps))	1.5 (*3*)	3	7 (*3*)
Radar Detection Range (Nautical Miles (NM)) (For Large Intruders)	5.9	4.6	3.5

(When different, limits for HALE/MALE/LEPR from Phase 1 are noted in parentheses)

2.1.1.3 DAA Classes

Table 2 lists the DAA equipment classes from RTCA Document 365B (DO-365B). Not all of these classes need to be individually assessed for the SRMD safety case. For example, it does not make sense to evaluate Class 5 with Class 1, 2, or 3 equipment alone, because most ATAR will not perform within MOPS requirements close to the ground due to ground clutter (hence the need for a GBSS solution). If ATAR is not performing according to the MOPS and there is no GBSS, an associated simulation is not necessary because the DAA would lack the minimal sensor requirements. Additionally, it is not necessary to simulate Class 7 given that Class 6 is the stressing case from a latency perspective (greatest latency). The run matrix in Section 2.2 shows the DAA classes that were simulated in this effort.

Table 2. DAA classes.

Class	Description	DAA Logic†/Sensors‡ Used
1	DAA Remain Well Clear (RWC) function only, en route	DAA Logic/Active Surveillance (AST), Automatic Dependent Surveillance-Broadcast (ADS-B), ATAR, EO/IR
2	DAA RWC and TCAS, en route	DAA Logic & TCAS II/AST, ADS-B, ATAR, EO/IR
3	ACAS Xu, en route	ACAS Xu/AST, ADS-B, ATAR
4	Not defined	Not defined
5	Terminal (enabled terminal RWC and alerting standards) for Classes 1, 2, 8. Must use Classes 6 or 7	See Class 6 or Class 7.
6	GBSS data processed at UA, en route. Used with Classes 1, 2, 5	DAA Logic/AST, ADS-B, EO/IR, GBSS
7	GBSS data processed at the control station (CS), en route. Used with Classes 1, 2, 5	DAA Logic/AST, ADS-B, EO/IR, GBSS
8	GBSS as the only noncooperative sensor	DAA Logic/GBSS, ADS-B

† Note: Unless otherwise specified, DAIDALUS is used as a representative DAA logic.

‡ Note: This list includes all sensors applicable to each class, but does not imply that all sensors will be employed simultaneously.

2.1.2 Tools/Models

DEGAS is an open-source simulation framework created by MIT LL to perform simulations of DAA systems and is available on GitHub: https://github.com/mit-ll/degas-core. DEGAS is written in Matlab/Simulink, and contains all the necessary components to simulate pairwise encounters. As mentioned in Section 3.1, Version 2 of DEGAS was used for this analysis. (Note: Version 2 is not yet available publicly; the latest public release was Version 1).

2.1.2.1 Sensor Models

For this analysis, the simulation includes five sensor models: ATAR (A1, A2, A3), GBSS, ADS-B, AST, and EO/IR. The ATAR, ADS-B, and EO/IR models were already part of Version 1 of the DEGAS framework; however, additional ATAR model parameters were added to the simulation to represent all three radar classes: A1, A2, and A3 (a.k.a. LSNC ATAR). While the error modes are the same for the three radar classes, the tracking range/detection range parameters are different, as shown in Table 5. GBSS is a new model that was developed for this effort. These sensors represent different potential intruder equipages. These sensor models were simulated using the error distributions described in Appendix Q of RTCA DO-365B. A model of ownship sensor noise was also included. The default parameters for these sensors are shown in the tables below.

Table 3. ADS-B model parameters (Table Q-1 in DO-365B).

Parameter	State	Absolute Error (per Aircraft) 1 sigma	Bias	Time Correlation	Notes
Navigation Accuracy Category for Position (NACp) = 7	Horizontal Position	75.6 meters (m)	0	300 seconds (sec)	NACp = 185.2 m (95%) / 2.45 = 75.6 m
	Barometric (Baro) Altitude	–	Per Traffic Situation Awareness with Alerts (TSAA) model		International Civil Aviation Organization (ICAO) Annex 10 Bias model used in TSAA. Quantization 25 ft/ 100 ft.
Navigation Accuracy Category for Velocity (NACv) = 2	Horizontal Velocity	1.22 m/s	0	300 sec	NACv = 3 m/s (95%) / 2.45 = 1.22 m/s horizontal
	Vertical Velocity	1.707 m/s (95%)			Per TSAA model. Laplacian distribution. 95% bound = 5.6 ft/s. Equivalent to 95% bound of 366 fpm as determined empirically by analysis of installed Version 2 ADS-B avionics.

Parameter	State	Notes
Update Rate (dt)	dt = 1 second	
Latency Effects (Uncompensated)	< .4 seconds	Bias transport delay with uniform distribution up to 400 milliseconds (ms). This does not address the Automatic Dependent Surveillance-Rebroadcast (ADS-R) latency effects/contributions.
Detection Range (DR)	DR ≤ 20 NM	Based on Active Surveillance DR.
Probability of Reception/Detection (PD)	PD = 0.95	Over any 3 secs ≤ 10 NM (Based on the reception of both position and velocity) Over any 7 secs > 10 NM

Table 4. ATAR model parameters (Table Q-2 in DO-365B).

State	Relative Error 1 sigma	Bias	Notes
Range	21.34 m (70 ft)	15.24 m (50 ft)	White noise model, with bias drawn from a [+/- bias] uniform distribution for each encounter.
Range Rate	3.0 m/s (10 ft/sec)	2.4 m/s (8 ft/sec)	White noise model, with bias drawn from a [+/- bias] uniform distribution for each encounter.
Angle (Azimuth (Az)/Elevation (El))	1 degree (deg)	0.5 deg	White noise model, with bias drawn from a [+/- bias] uniform distribution for each encounter

Parameter	State	Notes
Update Rate (dt)	dt = 1 second	
Field of Regard (FOR)	+/- 15° Elevation (Stabilized with respect to velocity vector) +/- 110° Azimuth	
Probability of Track (P(Track))	P(Track) = 1	Assume perfect detection when inside the DR and FOR

Table 5. ATAR tracking range/detection range parameters (from Table 2-7, Table 2-8, Table 2-8, Table 2-10, Table 2-11, and Table 2-12 in DO-366A).

Parameter	State		Notes
Class A1 Tracking Range / Detection Range (DR)	DR = 5.08 NM (<100 kts small intruder) DR = 5.47 NM (100-130 kts medium intruder) DR = 5.98 NM (>130 kts large intruder)	DR Scale Factor (Small, Medium, Large) Az: [0, 30], (1.0, 1.0, 1.0) Az: (30, 60], (0.57, 0.65, 0.75) Az: (60, 90], (0.31, 0.49, 0.64) Az: (90, 110], (0.16, 0.24, 0.39)	Assumption is intruder size is loosely correlated to speed, hence DR is determined by max speed across the entire encounter. For additional detail, see the ATAR MOPS. Once the track is established, scale factor correction is not performed; however, the track would drop upon the intruder leaving the FOR. DR scale factors are linearly interpolated between levels where the max value in each bin is given. (Table Q-2 in DO-365B)
Class A2 Tracking Range / Detection Range (DR)	DR = 3.75 NM (<100 kts small intruder) DR = 4.12 NM (100-130 kts medium intruder) DR = 4.61 NM (>130 kts large intruder)	DR Scale Factor (Small, Medium, Large) Az: [0, 30], (1.0, 1.0, 1.0) Az: (30, 60], (0.68, 0.77, 0.84) Az: (60, 90], (0.62, 0.71, 0.79) Az: (90, 110], (0.44, 0.56, 0.69)	
Class A3 Tracking Range / Detection Range (DR)	DR = 2.57 NM (<100 kts small intruder) DR = 2.93 NM (100-130 kts medium intruder) DR = 3.42 NM (>130 kts large intruder)	DR Scale Factor (Small, Medium, Large) Az: [0, 30], (1.0, 1.0, 1.0) Az: (30, 60], (0.85, 0.89, 0.92) Az: (60, 90], (0.69, 0.77, 0.85) Az: (90, 110], (0.56, 0.66, 0.75)	

Table 6. Ground-based surveillance (GBSS) model (Table P-16 in DO-365B).

Metric	Model Type	Parameters	Notes
Heading	N/A	Derived from degraded velocity	Noise, no bias
Position (x, y, z)	Gauss Markov	98-second decorrelation 2σ = 555.6 meters	Since using (3D) Gauss Markov Model (GMM), sigma is the 95% bound/2.1; 2.448 if 2D
Velocity (EWV, NSV, Vertical rate)	Gauss Markov	45-second decorrelation 2σ = 3 meters per second	Since using 3D GMM, sigma is the 95% bound/2.1; 2.448 if 2D

Note: GBSS horizontal errors are represented using a 2D Gauss Markov Model and GBSS vertical errors are represented using a 1D Gauss Markov model, using the decorrelation parameters described in Table 6, and the vertical and horizontal error values described in Table 7. The values in Table 7 include ownship error contributions. Note that the required track accuracy values in DO-381 do not include ownship noise and thus, are slightly lower than the values in Table 7; ownship noise is included in this analysis. Detection range limitations are not considered (i.e., it is assumed that the ownship and intruder are always within range of the GBSS), and it is assumed that the track is always valid (i.e., no track drops). The model is run at 1 Hz and perfect latency compensation is assumed.

Table 7. Ground-based surveillance (GBSS) parameters (based on Paragraph Q.4.3 in DO-365B).

State	Radar 1-σ	Ownship 1-σ	Total Error 1-σ	95% Error
Horizontal Position	71.54 m	37.8 m	80.91 m	198.24 m
Vertical Position	52.49 m	16.08 m	68.57 m	134.4 m
Horizontal Velocity	2.62 m/s	1.22 m/s	2.89 m/s	7.08 m/s
Vertical Rate	2.62 m/s	0.87 m/s	2.76 m/s	5.41 m/s

Table 8. Active surveillance parameters (Table Q-3 in DO 365B).

State	Absolute Error 1-sig	Bias	Quantization	Notes
Range	15.24m (ft)	38.1m (125 ft)		250 ft bias for Mode C
Bearing	[-10, 10 deg]: 9 deg Root Mean Square (RMS), 27 deg max [-15, -10] or [10, 20 deg]: 15 deg RMS, 45 deg max			Assume RMS value = sigma in white noise model
Altitude	0	Per TSAA model	Intruder: 25 ft/ 100 ft Ownship: 1 ft	

Parameter	State	Notes
Update Rate	1 Hertz (Hz) / 0.2 Hz (Tau > 60)	
Detection Range (DR)	DR ≤ [20.6, 14.3, 8.0] NM (Mode C) DR ≤ 15.6 NM (Mode S)	Front: [0, ± 45 deg], Side: [0, ± 45 deg], Rear: [0, ± 45 deg]
Probability of Detection (PD)	PD: 0.90 (Mode C) PD: 0.95 (Mode S)	Per 1 second epoch
Field of Regard (FOR)	360 deg Azimuth [-15, +20 deg] Elevation Angle	

Table 9. EO/IR parameters (from Appendix E in DO-387).

State	Model	Minimum Requirement	Parameter Used in Simulation	Correlation Time
Bearing and Elevation Error	Gaussian white noise with standard deviation σ	Not Applicable	σ = 1 milliradian (mrad)	None
Bearing and Elevation Rate Error	Gauss Markov noise with standard deviation σ	Maximum σ < 2.1 mrad/s	σ = 1.4 mrad/s	1 second (10 samples with model executed at 10 Hz)
Detection Range	Constant value	Minimum range of 2 NM	2.5 NM	Not Applicable
Range Error	Colored random error with standard deviation σ (see EO/IR appendix for details).	σ should not exceed 12% of true range	σ = 0.03 × true range	5 seconds
Range-Rate Error	Gauss Markov noise with standard deviation σ	σ should not exceed 20% of true range-rate	σ = 0.05 × true range rate	2 seconds (EO/IR sensor needs 5 seconds since the time of first detection to start outputting a valid range rate)

Table 10. Ownship navigation (NAV) model parameters (from DO-365B Table Q-4).

Parameter	State	Absolute Error (per Aircraft) 1 sigma	Bias	Time Correlation	Notes
Navigation Accuracy Category for Position (NACp) = 8	Horizontal Position	37.8 meters (m)	0	300 seconds (sec)	NACp = 92.6 m (95%) / 2.45 = 37.8 m
	Barometric (Baro) Altitude	0	Per Traffic Situation Awareness with Alerts (TSAA) model		International Civil Aviation Organization (ICAO) Annex 10 Bias model used in TSAA. Quantization 1 ft.
Navigation Accuracy Category for Velocity (NACv) = 2	Horizontal Velocity	1.22 m/s	0	300 sec	NACv = 2 (3 m/s (95%) / 2.45 = 1.22 m/s horizontal)
	Vertical Velocity	1.707 m/s (95%)	N/A	N/A	Per TSAA model. Laplacian distribution. 95% bound = 5.6 ft/s. Equivalent to 95% bound of 366 fpm as determined empirically by analysis of installed Version 2 ADS-B avionics.
	Attitude	[0.2, 0.2, 0.4] degs	N/A	N/A	[Roll, Pitch, Yaw/Heading]. Note the heading error is with respect to true north. White Noise Model, no bias.

Data from different sensors are processed using the FAA Tech Center Phase 2 tracker (Version 7.5.1, April 2, 2021), which outputs a track using best source selection based on horizontal position error. Note that Version 7.5.1 of the Phase 2 tracker does not accept EO/IR sensor data as input. Version 8 of the FAA Tech Center was updated to include EO/IR data (received May 24, 2021). This updated tracker does not filter or perform state estimation on the EO/IR track, but rather, correlates it with other surveillance sources and selects the best source.

Unless otherwise stated, all of the analysis runs without EO/IR were performed using Version 7.5.1 of the Phase 2 tracker. A few scenarios with EO/IR were performed using Version 8 of the FAA Tech Center tracker and the results are documented in Section 4.13.1.

2.1.2.2 Pilot Model

In addition to the sensors, the simulation also contains the Lincoln Laboratory pilot model [3] which includes representative pilot delays, such as an ATC coordination time and a maneuver decision delay, as shown in Figure 2. This is the same model that was used in Phase 1 (Study 5).

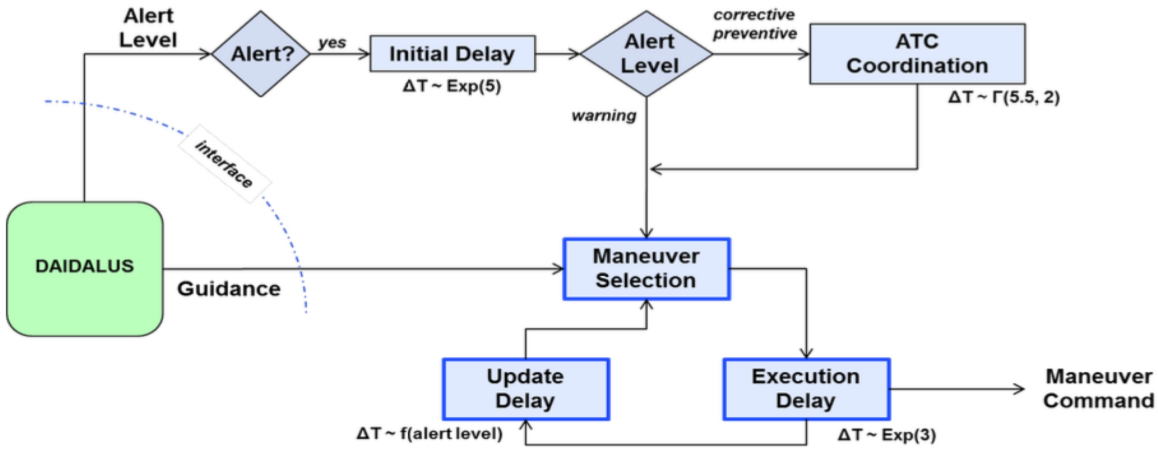

Figure 2. Pilot model architecture.

The pilot model was run in stochastic mode, which means the model uses the probabilistic delay durations described in Table 11.

Table 11. Pilot model delays.

Delay Type	Distribution
Initial Delay	Exponential distribution with mean 5 sec
ATC Coordination	Gamma distribution with mean 11 sec
Execution Delay	Exponential distribution with mean 3 sec
Update Delay	Exponential distributions with mean 25 sec (no alert update), mean 10 sec (preventive/corrective) and mean 8 sec (warning)

The maneuver selection is based on DAIDALUS horizontal and vertical suggestive guidance, with the maneuver magnitude drawn from a gamma distribution with parameters shown in Table 12. In Table 12, compliant maneuvers are those that are in the direction of the minimum suggested maneuver, and non-compliant maneuvers are those that are in the opposite direction. For example, if the bands indicate that safe headings can be achieved by either turning 30° to the left or 20° to the right, then the minimum suggested maneuver is turning 20° to the right. In this example, the compliant maneuver is turning right and the non-compliant maneuver is turning left.

The distributions in Table 12 are relative to the minimum suggested maneuver. That is, a positive sample from the distribution would result in a maneuver equal to the minimum suggestion plus a buffer, and a negative sample would result in a maneuver smaller than the minimum suggestion—i.e., within the DAIDALUS band. This range of maneuvers reflects actual operator behavior observed in human-in-the-loop (HITL) experiments. Because gamma distributions have domain $x \geq 0$, thirty degrees are subtracted from the sampled horizontal maneuver and 1500 ft is subtracted from the sampled vertical maneuver in order to shift the distributions to the left to allow for maneuvers that are less than the minimum suggestion. Plots of the modeled turn and climb/descend magnitude distributions are available in the pilot model report [3].

Table 12. Pilot model maneuver magnitudes (relative to minimum suggested maneuver).

Maneuver Type	Distribution
Horizontal (Compliant)	Change in heading ~ Γ(6.21, 9.67) – 30°
Horizontal (Non-Compliant)	Change in heading ~ Γ(5.47, 8.25) – 30°
Vertical	Change in altitude ~ Γ(9.37, 207.98) – 1500 ft

Table 13 describes the dynamics capability assumptions used in the pilot model.

Table 13. Pilot model aircraft dynamics assumptions.

Constraint	A1 (HALE)	A2 (MALE)	A3 (LEPR)
Turn Rate (°/sec)	1.5	3	7
Vertical Rate (feet per minute (fpm))	2500	1500	500

The pilot model does not model return to course.

Note that the pilot model was modified for terminal area operations. The Terminal DWC definition is applied within a predefined region known as the DAA Terminal Area (DTA). According to DO-365B, the DTA shall be "a cylinder with a minimum radius of 4 NM, a maximum radius of 5 NM, a minimum height of 1800 ft, and a maximum height of 2700 ft above the runway center point or airport elevation, and be located with the center of the bottom surface of the cylinder at the appropriate departure or arrival runway center point." For this analysis, the DTA is a cylinder with a radius of 4.2 NM and height of 2000 ft; these are the default DAIDALUS DTA parameters provided by NASA and represent the minimum requirements plus a buffer. DTA logic is enabled when the intruder is within the DTA. When the intruder is inside the DTA, DAIDALUS only issues warning alerts, consistent with the requirements in DO-365B. However, when transitioning in and out of the DTA, DAIDALUS may issue en route corrective alerts for intruders outside the DTA. As tracks generated by the terminal encounter model can extend as far out as 8 NM from the airport, the ownship can potentially transition in and out of the DTA during a terminal encounter. Note that the TCAS low alerting threshold (inhibit) is 900 ft AGL so there is a limited area of collision avoidance protection within the DTA for Class 2 equipment (considering a standard three-degree glideslope).

According to the Terminal Operations 2 (TOPS2) human-in-the-loop (HITL) experiment performed by NASA [4], the most frequent maneuver performed by pilots in response to lower level alerts up to en route DWC corrective alerts is a change in the commanded speed. For warning alerts and higher, pilots preferred to execute a missed approach procedure, in which the pilot climbs to remain within the protected approach corridor. For this analysis, since speed maneuvers are not considered by DO-365B and only warning alerts are permitted, the pilot model always follows vertical bands guidance from DAIDALUS in the DTA when warning or recovery guidance is received. If the ownship is landing, DAIDALUS produces guidance to allow the pilot to continue to descend or start a missed approach maneuver. If the ownship is taking off, DAIDALUS produces guidance to allow the pilot to level off or continue to ascend. The pilot model will then maneuver to an altitude that is conflict free; the distribution of altitudes selected by the pilot model (relative to the guidance altitude) is the same as in the Phase 1 en route model. If there is an equivalent option to climb or descend, the pilot model will choose to climb. In the event that the vertical guidance is saturated, meaning that none of the bands are indicated as safe, the pilot model will level off; however, saturated guidance is not expected to occur. In the baseline simulations (Section 4.3.1), all-red saturated vertical guidance occurs in 4% of terminal encounters, and around 5% of en route correlated and uncorrelated encounters that have an alert. However, vertical saturation is less of an issue for en route correlated and uncorrelated encounters, because it is possible for horizontal guidance to not be saturated when vertical guidance is saturated. All maneuvers are performed at the maximum vertical rate for each platform type as shown in Table 13. Although horizontal guidance may optionally be used with caution during takeoffs per DO-365B, no horizontal maneuvers are modeled in this analysis. However, if a nominal—i.e., without DAA—horizontal maneuver is being performed while the ownship is entering the DTA and a warning alert occurs, the ownship will continue the horizontal maneuver.

In the en route model, the initial delay is modeled by an exponential delay with a mean of 5 seconds and the execution delay is modeled by an exponential distribution with a mean of 3 seconds such that the mean time to first maneuver from an initial warning alert is 8 seconds. However, TOPS2 results showed that pilots respond very quickly to DTA alerts (average response and execution results was 5 seconds), so for the terminal pilot model, the initial delay is modeled by an exponential delay with a mean of 2 seconds such that the mean time to first maneuver from an initial warning alert in the DTA is 5 seconds.

2.1.2.3 DAA Logic

The pilot model responds to DAA guidance from NASA's DAIDALUS. The simulation uses DAIDALUS Version 2.0.2 [5]. Guidance from DAIDALUS is based on the turn rate appropriate for each class as shown in Table 13. The model also includes 4-second alert level persistence and a 2-of-4 (m of n) alert filter, consistent with the Phase 1 analysis. Table 14 and Table 15 show the DAIDALUS parameters that were used in Phase 2. The parameters in Table 14 assume that DAIDALUS's Sensor Uncertainty Mitigation (SUM) logic is used, and the parameters in Table 15 assume that SUM is not used—note that there are slight differences in the alerting time parameters compared to what was used in Phase 1 MITRE Study 5A. The SUM logic parameters that were used are documented in Table G-11 of DO-365B.

To assess the effect of SUM, a few baseline cases were run with SUM without buffers on the DWC (Table 14 parameters) and without SUM with buffers on the DWC (Table 15 parameters); see Section 4.3.1 for baseline run results. Without SUM, a horizontal buffer that is 1.52 times the default HMD is applied (consistent with that used in Phase 1), and for non-cooperative intruders, a vertical buffer of 4000 ft is used instead of the default ZTHR. The horizontal buffer is similar to the one used in Phase 1 and the 4000 ft buffer follows the MOPS suggestion of treating non-cooperative intruders as co-altitude if they are vertically within 4000 ft of the ownship. Since the differences in the results were negligible, the final safety analysis was performed with SUM, which is consistent with the recommendation received from NASA.

Table 14. DAIDALUS parameters with SUM.

En route Cooperative Environment			
Parameter	**Preventive Alert**	**Corrective Alert**	**Warning Alert**
Tau Threshold (TTHR) (s)	35	35	35
Horizontal Threshold (DTHR) (nmi)	0.66	0.66	0.66
Vertical Threshold (ZTHR) (ft)	700	450	450
Time to Co-Altitude (TCOA) (s)	0	0	0
Alerting Time (s)	50	50	25
Terminal Environment (Note: Only warning alerts are issued in a DTA [1]**)**			
Parameter	**Preventive Alert**	**Corrective Alert**	**Warning Alert**
Tau Threshold (TTHR) (s)	--	--	0
Horizontal Threshold (DTHR) (ft)	--	--	1500 ft
Vertical Threshold (ZTHR) (ft)	--	--	450
Time to Co-Altitude (TCOA) (s)	--	--	0
Alerting Time (s)	--	--	40
Noncooperative Environment			
Parameter	**Preventive Alert**	**Corrective Alert**	**Warning Alert**
Tau Threshold (TTHR) (s)	0	0	0
Horizontal Threshold (DTHR) (ft)	2200 ft	2200 ft	2200 ft
Vertical Threshold (ZTHR) (ft)	450	450	450
Time to Co-Altitude (TCOA) (s)	0	0	0
Alerting Time (s)	50	50	20

Table 15. DAIDALUS parameters without SUM (includes buffer on the DWC).

En route Cooperative Environment			
Parameter	**Preventive Alert**	**Corrective Alert**	**Warning Alert**
Tau Threshold (TTHR) (s)	35	35	35
Horizontal Threshold (DTHR) (NM)	1 (≈ 1.52 * 0.66)	1	1
Vertical Threshold (ZTHR) (ft)	700	450	450
Time to Co-Altitude (TCOA) (s)	0	0	0
Alerting Time (s)[1]	55	55	25
Terminal Environment (Note: Only warning alerts are issued in a DTA [1]**)**			
Parameter	**Preventive Alert**	**Corrective Alert**	**Warning Alert**
Tau Threshold (TTHR) (s)	--	--	0
Horizontal Threshold (DTHR) (NM)	--	--	0.375 (≈1500 ft *1.52)
Vertical Threshold (ZTHR) (ft)	--	--	450
Time to Co-Altitude (TCOA) (s)	--	--	0
Alerting Time (s)	--	--	45
Noncooperative Environment			
Parameter	**Preventive Alert**	**Corrective Alert**	**Warning Alert**
Tau Threshold (TTHR) (s)	0	0	0
Horizontal Threshold (DTHR) (NM)	0.55 (≈2200 ft * 1.52)	0.55	0.55
Vertical Threshold (ZTHR) (ft)	4000	4000	4000
Time to Co-Altitude (TCOA) (s)	0	0	0
Alerting Time (s)	55	55	25

2.1.2.4 Communications Latency and Interruptions Models

Communications latency and interruptions are expected to have an effect on the ability to conduct timely DAA maneuvers to remain well clear of and avoid collisions with other aircraft. In order to support the SRM process, it is necessary to model communications latency and interruptions and their impact on DAA system risk ratios and overall safety. Latency can be caused by DAA alerting, pilot decision making, coordination with ATC, and implementing a maneuver to remain well clear. The integrated delay model in DEGAS accounts for the latencies below, from Table E-1 in DO-365B:

[1] In Phase 1 MITRE Study 5A, the preventive and corrective alerting times were 60 seconds, and the warning alert alerting time was 30 seconds.

Table 16. Allowable latency contributions for DAA subsystems (Table E-1 in DO-365B).

Subsystem/ Function	Maximum Total Latency Contribution (milliseconds)	Uncompensated Latency (ms)	Maximum Latency Compensation Error (ms)	Source of Requirement
ADS-B (1090 Megahertz Extended Squitter (1090ES)/Universal Access Transceiver (UAT))	2500	--	-200/+400	DO-260B/C DO-282B/C
ADS-R	3500	--	-300/+500	DO-260B/C DO-282B/C
ATAR	500	500	--	DO-366
GBSS	100	100	--	DO-381
Active Surveillance (Mode C/S)	1000	--	500	DO-185B
DAA Tracker	1000	--	100	DO-365B §2.2.3.2.3.1
DAA Alerting Algorithm	1000	1000	--	DO-365B §2.2.4.3.5.4
C2 Link System (Downlink)	1000	1000	--	DO-377
DAA Guidance Processing	1000	1000	--	DO-365B §2.2.4.4
DAA Traffic Display	500	500	--	DO-365B §2.2.5.4.1
C2 Link System (Uplink)	1000	1000	--	DO-377
CS GBSS Track Forwarding (Class 6 Only)	1000	1000	--	DO-365B §2.2.2.4.2
CS Track Data Association (Class 7 and 8 Only)	1500	--	100	DO-365B §2.2.3.2.3.1

As in the Phase 1 study, the delays from the sensors (ADS-B, ADS-R, ATAR, GBSS, and AST) are modeled as 500 ms (based on the uncompensated latency and maximum latency compensation error columns in Table 16). Delays from the DAA alerting algorithm, C2 Link system (downlink), DAA guidance processing are 1000 ms each, and the DAA traffic display is 500 ms. Note that the C2 Link system (downlink) delay does not apply to Class 8, and the 1000-ms DAA tracker delay itself is modeled by the FAA tracker. When modeling Class 6, there is an additional 1000-ms GBSS track forwarding delay. When modeling Class 7 and 8, there is an additional 100-ms track data association delay, which is rounded to 0 sec. The components of the C2 delay are summarized in Table 17.

Table 17. Components of the integrated system delay.

Subsystem/Function	Modeled Latency (milliseconds)	Applicable Classes	Delay Component in Figure 3
Sensors	500	All	Delay 1
DAA Alerting Algorithm	1000	All	Delay 1
C2 Link System (Downlink)	1000	Class 1-7	Delay 1
C2 Uplink Delay*	1000	All	Delay 2
DAA Guidance Processing	1000	All	Delay 1
DAA Traffic Display	500	All	Delay 1
GBSS Track Forwarding	1000	Class 6	Delay 1
Track Data Association	100 (rounded to 0)	Class 7 and 8	Delay 1

* Note: The C2 Uplink Delay could be added to Delay 1 (as it would have the same effect in the simulation). However, it is accounted for separately to be consistent with the Phase 1 analysis.

The integrated delay (Delay 1) for each class is the sum of all delay components applicable to that class. Because DEGAS runs in 1-second time steps, the integrated delays are rounded to the nearest whole second. For example, the delay for Class 8 is 3 seconds (the sum of delays from sensors, the DAA alerting algorithm, DAA guidance processing, DAA traffic display, and track data association). In addition, there is a 1000-ms C2 Uplink Delay (i.e., command-to-execute delay, Delay 2) and a 5000-ms initial Resolution Advisory (RA) Response delay (Delay 3). Note that the RA Response delays is 3000 ms for subsequent RAs. For comparison, in Phase 1 (Study 5, Spiral 3), the integrated delay was 2 seconds, the C2 uplink delay was 1 second, and the RA response delay was 5 seconds [6].

These are all uncompensated delays (meaning the DAA system makes no attempt at compensation), and are summarized in Table 18. Additionally, consistent with the Phase 1 analysis, the compensation that the system does perform is assumed perfect, such that the compensation (latency compensation error) does not need to be modeled. Note that these are the default delays that are modeled, but a parameter sweep over integrated delay was performed to understand the maximum allowable delay before there is a negative impact on safety. See Section 3.2.2 for the results of the integrated delay sensitivity analysis.

Table 18. Modeled delays.

<table>
<tr><th>Function</th><th>Delay (milliseconds)
for Phase 2</th><th>Delay (milliseconds)
for Phase 1 [7]</th></tr>
<tr><td>Integrated Delay (Delay 1) for Class 1-5</td><td>4000</td><td rowspan="4">2000
for all classes</td></tr>
<tr><td>Integrated Delay (Delay 1) for Class 6</td><td>5000</td></tr>
<tr><td>Integrated Delay (Delay 1) for Class 7</td><td>4000</td></tr>
<tr><td>Integrated Delay (Delay 1) for Class 8</td><td>3000</td></tr>
<tr><td>C2 Uplink Delay (Delay 2)</td><td>1000</td><td>1000</td></tr>
<tr><td>RA Response Delay (Delay 3)</td><td>5000</td><td>5000</td></tr>
</table>

In DEGAS, the C2 uncompensated delays are modeled as a set of delays corresponding to the delays in Table 18, as shown in Figure 3. The integrated delay accounts for delays up to displaying traffic, alerts, and guidance on the traffic display and is applied before sensor data is passed to the pilot response model. The pilot response delay accounts for maneuver execution delays and is applied before the maneuver chosen by the pilot response model is passed to the aircraft dynamics model: note that the pilot response delay is represented within the pilot response model. The RA response delay represents delays in receiving and following TCAS II logic guidance and is applied before TCAS II RAs are passed to the aircraft dynamics model.

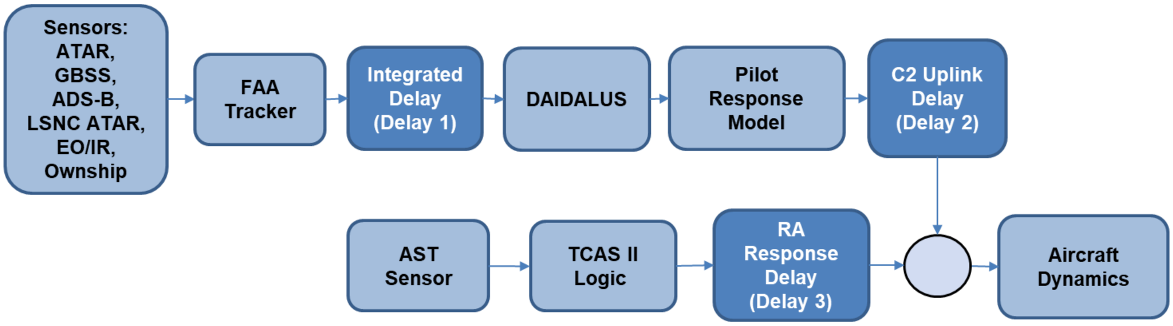

Figure 3. C2 model block diagram.

In terms of compensated latency, the FAA tracker extrapolates state and uncertainty information from the last track update time to the next one-second epoch time at which track information is sent out to the DAA algorithm. However, DO-365B limits the delay compensation error introduced by the tracker to 100 ms. This negligible compensated error is not modeled.

The C2 model also accounts for interruptions. Interruptions are modeled as a pause after an alert is received as illustrated in Figure 4. The pause prohibits an action by the pilot model during the interruption, but after the pause, the pilot model acts on up-to-date information. This is different from a delay, where the pilot model would act on stale information. As in the Phase 1 analysis [7], two methods were assessed:

1. Interruption on the first alert triggering a maneuver (i.e., corrective or warning), and
2. Interruption on the first warning alert.

The interruption pause is a fixed value for each run of one million encounters for the sensitivity analysis; for the final safety analysis, a distribution was sampled for each encounter (see Section 3.2.4 for details). Note that this interruption pause occurs as soon as an alert is received, so all pilot model delays are applied after the pause. If the interruption occurs before the first maneuver in the simulation, there is an initial delay before a maneuver is selected. If the interruption occurs before a subsequent maneuver in the simulation (a possibility when Method 2 is applied) and the interruption lasts longer than 8 seconds, there is a new initial delay after the pause. This is due to traffic, alerts, and guidance information being removed from the traffic display if not updated for 5 seconds (as defined in DO-365B), such that it is assumed that the remote pilot would need to reassess the situation if there is no traffic display information for 3 seconds. Otherwise, if the interruption is less than 8 seconds, then there is not a new initial delay before subsequent maneuvers.

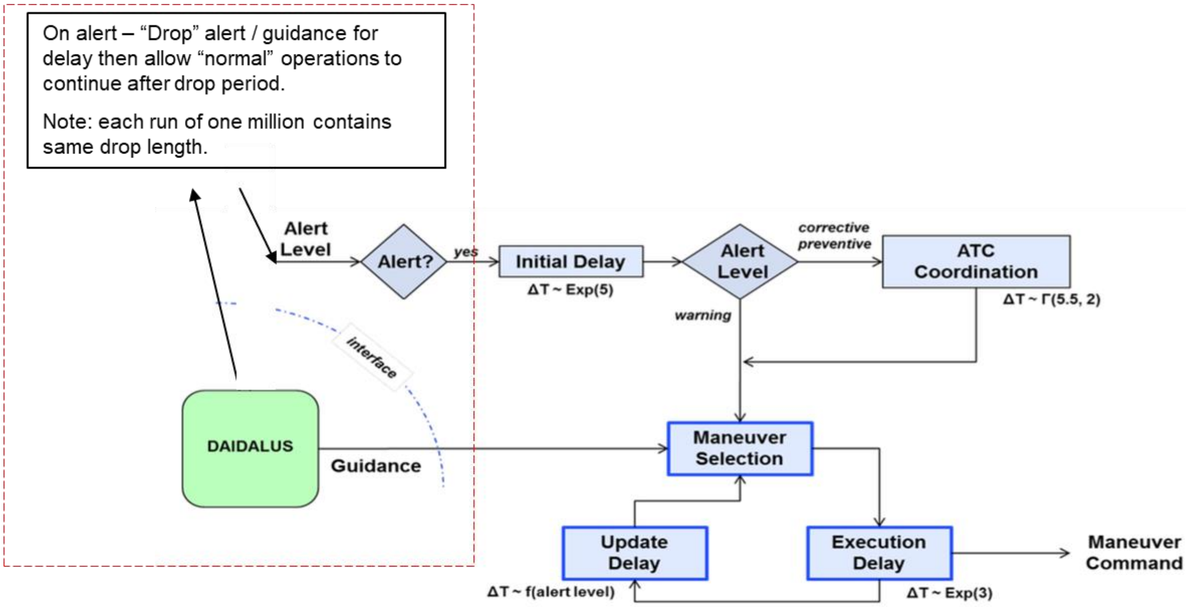

Figure 4. C2 interruption model.

2.1.3 Encounters

Three different encounter sets (uncorrelated, correlated, and terminal) were generated for each of the three ownship classes (HALE, MALE, LEPR) for a total of nine encounters sets. Correlated encounters assume ATC involvement, whereas uncorrelated encounters are those that do not include ATC intervention: e.g., between a cooperative (transponder equipped) and noncooperative aircraft. Terminal encounters are those that take place within an 8 NM radius of an airport, up to 3000 ft altitude. In terminal encounters, the ownship is taking off or landing.

The uncorrelated and correlated encounters were generated using the encounter generation tool (October 2, 2020 Update version) [8], which is available on GitHub. This tool has been updated internally to generate correlated encounters. (The ability to generate correlated encounters is not yet publicly available). Terminal encounters were generated using the terminal encounter model [9].

2.1.3.1 Correlated Encounter Assumptions

Correlated encounters are 120 seconds in length with the Closest Point of Approach (CPA) around 110 seconds in order to provide sufficient time to initiate the intruder track and provide alerts and guidance. Table 19, Table 20, and Table 21 contain the airspeed distributions that are used to generate correlated encounters for the three UA classes. The altitude bins for HALE and MALE aircraft correspond to those in the extended correlated encounter model (ECEM) [10]. The likelihood of sampling an individual altitude bin is based on the frequency of aircraft observed for that bin in the radar data used to develop the ECEM. Encounter altitudes are sampled uniformly in each altitude layer bin. Likewise, airspeed in also sampled uniformly within an individual airspeed bin.

Table 19. HALE correlated airspeed distribution.

Airspeed (kts) → **Altitude Layer (ft) ↓**	**100-150**	**150-200**	**200-250**	**250-291**
1000-3000	37.5%	50%	12.5%	0%
3000-5000	12.5%	50%	37.5%	0%
5000-10000	12.5%	50%	37.5%	0%
10000-18000	0%	25%	50%	25%
18000-29000	0%	0%	50%	50%
29000-40000	0%	0%	25%	75%

Table 20. MALE correlated airspeed distribution.

Airspeed (kts) → **Altitude Layer (ft) ↓**	**40-100**	**100-150**	**150-200**
1000-3000	50%	50%	0%
3000-5000	37.5%	50%	12.5%
5000-10000	37.5%	50%	12.5%
10000-18000	0%	50%	50%
18000-29000	0%	25%	75%
29000-40000	0%	0%	100%

Table 21. LEPR correlated airspeed distribution.

Airspeed (kts) → **Altitude Layer (ft) ↓**	**40-110**
500-1200	100%
1200-3000	100%
3000-5000	100%
5000-18000	100%

There is only one airspeed bin for LEPR aircraft. Table 22, Table 23 and Table 24 contain the vertical rate distributions that are used to generate encounters for the three radar classes. The same vertical rate distributions are used for correlated and uncorrelated encounters.

Table 22. HALE vertical rate distribution.

Vertical Rate (fpm)→ **Altitude Layer ↓**	**-2500** **-2000**	**-2000** **-1000**	**-1000** **-400**	**0**	**400** **1000**	**1000** **2000**	**2000** **2500**
500-1200 (ft)	7.5%	20%	7.5%	15%	5%	15%	30%
1200-3000 (ft)	7.5%	20%	7.5%	15%	5%	15%	30%
3000-5000 (ft)	10%	25%	10%	20%	5%	15%	15%
5000-18000+ (ft)	10%	25%	10%	20%	5%	15%	15%

Table 23. MALE vertical rate distribution.

Vertical Rate (fpm) → Altitude Layer ↓	-1500 -1000	-1000 -400	0	400 1000	1000 1500
500-1200 (ft)	27.5%	7.5%	15%	5%	45%
1200-3000 (ft)	27.5%	7.5%	15%	5%	45%
3000-5000 (ft)	35%	10%	20%	5%	30%
5000-18000+ (ft)	35%	10%	20%	5%	30%

Table 24. LEPR vertical rate distribution.

Vertical Rate (fpm) → Altitude Layer ↓	-500 -400	0	400 500
500-1200	20%	55%	25%
1200-3000	20%	55%	25%
3000-5000	30%	55%	15%
5000-18000	30%	55%	15%

Table 25 lists the dynamics constraints for each aircraft class. These are the minimum and maximum constraints that the ownship cannot exceed at any point during the encounter and are taken into account when generating and simulating encounters.

Table 25. Dynamics constraints by aircraft class.

Constraint	HALE	MALE	LEPR
Max Velocity (kts)	291	200	110
Min Velocity (kts)	100	40	40
Max Bank Angle	20	20	45
Min Bank Angle (°)	-20	-20	-45
Max Cumulative Turn (°)	180	180	180
Max Pitch (°)	15	15	15
Min Pitch (°)	-15	-15	-15

2.1.3.1.1 Correlated Encounter Sampling Technique

HALE, MALE and LEPR correlated encounter sets are built up by rejection sampling. First, ten million encounters are generated from the correlated encounter model using the encounter generation tool. The default model distributions (which are built from observed radar data) are used. The encounter generation tool uses a statistical technique known as importance sampling [11] to oversample encounters of interest (e.g., NMACs) based on proposed joint distributions of Vertical and Horizontal Miss Distance (VMD and HMD).

The number of desired encounters (out of one million total) for each airspeed/vertical rate/altitude layer combination is computed based on the distributions in Table 19-Table 24. Encounters are drawn from the ten million generated encounters to fill in each airspeed/vertical rate/altitude layer bin as much as possible. Bins for which there are not enough encounters with the desired characteristics are filled by randomly selecting encounters from the remaining encounters that have not already been assigned to a bin in order to obtain 1 million unique encounters. Approximately 40% of the encounter sets are comprised of these randomly selected encounters. Because of this sampling technique, the resulting distributions of airspeed, vertical rate, and altitude layer are somewhat different from the distributions that were used for sampling (Section 2.1.3.1). However, the resulting distributions have been reviewed and vetted by MITRE for use in the final safety evaluation, and all of the encounters are still within the desired minimum/maximum limits for airspeed, vertical rate, and altitude layer. Two separate sets of 1 million encounters were generated for Class A and for Class B/C/D/E/G airspaces.

2.1.3.2 Uncorrelated Encounter Assumptions

Uncorrelated encounters are 240 seconds in length with CPA around 210 seconds. Table 26, Table 27, and Table 28 contain the airspeed distributions that were used to generate uncorrelated encounters for the three radar classes.

Table 26. HALE uncorrelated airspeed distribution.

Airspeed (kts) → Altitude Layer (ft) ↓	100-150	150-200	200-250	250-291
500-1200	50%	50%	0%	0%
1200-3000	50%	50%	0%	0%
3000-5000	50%	50%	0%	0%
5000-10000	10%	60%	15%	15%

Table 27. MALE uncorrelated airspeed distribution.

Airspeed (kts) → Altitude Layer (ft) ↓	40-100	100-150	150-200
500-1200	50%	50%	0%
1200-3000	50%	50%	0%
3000-5000	50%	50%	0%
5000-18000	25%	50%	25%

Table 28. LEPR uncorrelated airspeed distribution.

Airspeed (kts) → Altitude Layer (ft) ↓	40-110
500-1200	100%
1200-3000	100%
3000-5000	100%
5000-18000	100%

The vertical rate distributions for uncorrelated encounters are the same as those used for correlated encounters (Table 22, Table 23, and Table 24)

2.1.3.2.1 Uncorrelated Encounter Sampling Technique

Uncorrelated encounters are sampled from the uncorrelated encounter model [12] using the encounter generation tool. Similar to the correlated encounters, importance sampling is used to oversample encounters of interest (e.g., NMACs). First, rejection sampling is used to sample a pair of trajectories. The tool repeatedly samples a pair of trajectories and computes the VMD at the desired time of CPA. The sample is kept or rejected based on the probability associated with the VMD bin that the computed VMD falls in. Once a pair of trajectories has been sampled successfully, HMD is sampled from a uniform distribution and the trajectories are rotated horizontally so that the encounter's HMD matches the sampled values. Rejection sampling is performed to obtain VMD (whereas HMD is sampled directly) because the nominal VMD distribution is not known a priori, as it is defined by the altitude distributions of both aircraft.

For this analysis, a large number of NMACs were generated through the importance sampling process to compute risk ratios with statistical significance. However, since this many NMACs do not naturally occur in the airspace, the encounters were reweighted to match the actual (or nominal) distributions of VMD and HMD observed or expected in the real world when computing metrics. Each uncorrelated encounter set contains one million encounters.

2.1.3.3 Terminal Encounter Assumptions

The terminal encounter model is based on terminal area radar (ASR-9) observations of altitude reporting transponder equipped aircraft as well as OpenSky Network crowdsourced observations of ADS-B equipped aircraft. The terminal area is defined as cylinder with an 8-NM radius from a runway up to 3000 ft. An encounter is defined as a separation between aircraft within 4 NM horizontally and 2000 ft vertically. The length of the encounters varies depending on the sampled CPA characteristics from the model. The C2 sensitivity analysis (Section 4.1), GBSS sensitivity analysis (Section 4.2), and baseline runs (Section 4.3.1) were performed using Version 2 of the terminal encounter model (completed in March 2021). This version of the model pairs ownship landings and takeoffs with intruders that are landing, taking off, or transiting at single runway airports in Class D, E, and G airports. Note that transiting intruders do not include intruders that are currently in the process of taking off or landing at a different airport than the ownship—i.e., all transiting intruders are aircraft that are passing through the airspace and are not involved in terminal operations. The ownship is assumed to be a fixed-wing aircraft landing straight-in or taking off straight-out, whereas the intruder can be landing or taking off by any means. The intruder can be fixed-wing or rotorcraft.

Version 3 of the terminal encounter model (completed in June 2021) incorporates ownship pattern operations, multi-runway airports, and Class C airports. The terminal area definition cylinder was also extended to 8 NM laterally and 5000 ft vertically from a runway. In addition, significant updates to how the encounter geometry is sampled were made to Version 3. The final safety scenario runs (Section 4) were performed using Version 3 of the terminal encounter model.

2.1.3.3.1 Terminal Encounter Sampling Technique

The terminal encounter model is composed of two components: the encounter geometry model and the trajectory generation models. Terminal encounters are generated by first sampling the encounter geometry model for CPA location relative to the runway. Unlike the uncorrelated encounter model, HMD and VMD are not sampled directly; instead, the positions of the two aircraft (relative to the runway) are sampled using model variables such as ownship/intruder intent (i.e., landing, departing), the intruder type, the intruder runway, etc. The ownship and intruder trajectories are then propagated forward and backwards from CPA using the trajectory generation models. Importance sampling is not supported by Version 2 of the terminal encounter model; instead, encounters and conflicts (e.g., LoWC and NMAC) are sampled at the rate at which they appear in the airspace data. In the HALE, MALE, and LEPR terminal encounter sets, approximately 3.6%, 5.9%, and 8.7% of the encounters are NMACs, respectively. Version 3 of the terminal encounter model has been updated to sample equal numbers of encounters for all combinations of airspace class and ownship intent. Each encounter set from Version 2 of the model contains one million encounters and each encounter set from Version 3 of the model contains approximately two million encounters. In all of the terminal encounter sets, half of the encounters are sampled using OpenSky data and the other half are sampled using radar data.

2.2 Run Matrix

The analysis was performed by sweeping over different parameters that affect system safety, including aircraft class (HALE, MALE, LEPR), DAA class, and intruder equipage. Each parameter sweep run was performed using a set of one million encounters, each sampled from either the uncorrelated, correlated, or terminal encounter model. See Appendix A for the complete set of scenarios.

To reduce the number of runs performed, a few baseline cases were evaluated with ADS-B 100-ft altitude quantization and ADS-B 25-ft quantization to assess whether both needed to be evaluated or whether they were sufficiently similar such that only one was needed. Since the ADS-B 100 ft quantization results were similar to the ADS-B 25 ft quantization results, all safety runs where the transponder type of the intruder was not specified were performed with ADS-B 25ft quantization. See Section 3.1 for the baseline quantization run results. Note: in actuality, altitude quantization is dependent on aircraft installation and operation; most aircraft en route in Class A, B, C, and D airspace have 25 ft quantization while there are more 100 ft quantization in Class E and G.

In addition to these runs, a parameter sweep over integrated delay and C2 interruption time was performed as part of a sensitivity analysis to understand the impact of these parameters on system safety. The results of the C2 sensitivity analysis are discussed in Section 3.2.

Lastly, since GBSS is a new sensor for Phase 2 that was not evaluated in Phase 1, a parameter sweep over the GBSS parameters from Table 7 was performed to evaluate the sensitivity to GBSS errors. The results of the GBSS parameter sweep are discussion in Section 3.3.

2.3 Metrics

The following metrics were collected and analyzed. Note that for the final safety assessment, it may be necessary to collect metrics normalized by some nominal encounter definition to support the estimation of the rate of the event (if the rate of the nominal encounter definition is known). This may be as simple as dividing by the probability of having a nominal encounter. However, to do this, a nominal encounter definition must be agreed upon. The metrics presented in this final report are *not* normalized by such a nominal encounter definition. For conciseness, only risk ratio and loss of well clear ratio results are discussed in Sections 3 and 4. However, all metrics are documented in Appendix D.

2.3.1 Risk Ratio and Loss of Well Clear Ratio

The primary metrics used to evaluate safety are risk ratio and loss of well clear ratio. Risk ratio is defined as the relative probability of a collision between two different systems or configurations. It is a useful metric for comparing, for example, the relative performance in encounters between aircraft equipped with a DAA system to aircraft without DAA: the situation without DAA is referred to as the nominal case. The relative benefit of equipping with a DAA system compared to using no DAA system is estimated as:

$$\frac{P(NMAC|encounter, with\ DAA\ mitigation)}{P(NMAC|encounter, without\ DAA\ mitigation)}$$

An NMAC occurs when the separation between two aircraft is less than 500 ft horizontally and 100 ft vertically, and is used as a surrogate for collisions in order to avoid modeling individual aircraft geometries. If the ratio is less than one, then the mitigated system reduces the risk of NMAC. For example, a risk ratio of 0.1 indicates a 90% reduction in risk. If the ratio is greater than one, then the system increases the collision risk.

This metric includes a 95% confidence interval computed via bootstrapping [13]. One hundred random resamples are used to compute each confidence interval.

In addition to risk ratio, a similar metric was computed for encounters with a LoWC:

$$\frac{P(LoWC|encounter, with\ DAA\ mitigation)}{P(LoWC|encounter, without\ DAA\ mitigation)}$$

For this analysis, ratios were computed for the DO-365B LoWC volumes indicated in Table 29. LoWC volumes are defined by three parameters: HMD (the predicted minimum horizontal miss distance between the ownship and intruder), h (the current vertical distance (height) between the ownship and intruder), and τ_{mod}. The definition of τ_{mod} is

$$\tau_{mod} = \begin{cases} -\frac{r^2 - D_{mod}^2}{r\dot{r}}, r > D_{mod}, \\ 0, r \leq D_{mod} \end{cases} \tag{1}$$

where r and $\dot{r}$ are horizontal range and range rate, respectively, between the UAS and the intruder. D_{mod} is the distance modification and defines the radius of a cylinder around the UAS. In this analysis, D_{mod} is set equal to the horizontal miss distance threshold, HMD*. A LoWC for a particular aircraft class occurs if all three parameters fall below the thresholds listed in Table 29, from DWC Alerting Requirements in DO-365B.

Table 29. DWC volumes of interest.

Aircraft Class	HMD*	h*	τ_{mod}*
En route cooperative	4000 ft	450 ft	35 sec
En route noncooperative	2200 ft	450 ft	0 sec
Terminal	1500 ft	450 ft	0 sec

Similar to risk ratio, if the LoWC ratio is less than one, then the mitigated system reduces the risk of LoWC. As with risk ratio, this metric includes a 95% confidence interval computed via bootstrapping [13]. One hundred resamples are used to compute each confidence interval.

The risk ratios and LoWC ratios are separated into risk from unresolved encounters (encounters that triggered an NMAC/LoWC, with and without the DAA mitigation system) and induced encounters (encounters that had no NMAC/LoWC until a DAA mitigation system was introduced).

2.3.2 Severity of the Encounter: SLoWC (Severity of Loss of Well Clear)

Another key metric that was included in the Phase 1 SRMD [14] is the severity of an encounter, measured on a scale of 1-5:

- Minimum Severity (5) = LoWC
- Minor Severity (4) = SLoWC >= 50% OR relative velocity >= 205 kts
- Major Severity (3) = SLoWC >= 50% AND relative velocity >= 205 kts
- Hazardous Severity (2) = NMAC
- Catastrophic Severity (1) = MAC

This metric makes use of SLoWC, which is a measure of the extent of a well-clear violation. According to DO-365 §L.5.1.5: "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." See DO-365 L.6.1 for the specific calculation.

As described in Section 2.3.1, a LoWC is determined by three parameters: *HMD*, *h*, and τ_{mod}. A LoWC for a particular aircraft class occurs if all three parameters fall below the thresholds listed in Table 29. An NMAC occurs if the horizontal separation is less than 500 ft and the vertical separation is less than 100 ft. A MAC is estimated to occur if the horizontal separation is less than the sum of the half wing spans for the ownship and intruder and if the vertical separation is less than the sum of the half height for the two aircraft. Note that MAC was not computed as part of this analysis.

For this analysis, the specific metrics computed to evaluate the severity of the encounter were:

- Numbers of LoWC, SLoWC1s, SLoWC2s, and NMACs
- P(LoWC|ENC), where ENC is defined as the start of the simulation
- P(SLoWC1|LoWC)
- P(SLoWC2|SLoWC1)
- P(NMAC|SLoWC2)

2.3.3 Alert Ratio

The alert ratio compares the numbers of alerts that occur with a DAA system to the number of NMACs that occur nominally:

$$\frac{P(Alert|encounter, with\ mitigation)}{P(NMAC|encounter, without\ mitigation)}$$

Given the same risk ratio, systems with lower alert ratios are desirable, since fewer alerts indicate fewer unnecessary maneuvers.

2.3.4 Additional Metrics

Additional metrics that are captured include:

- Numbers of preventive, corrective, and warning alerts
- Number of TCAS Resolution Advisories
- Best sensor metrics as selected by the tracker, including:

- Percent of encounters for which each sensor (ADS-B/ATAR/AST/GBSS) was the majority best sensor (i.e., the sensor selected most often by the FAA Tech Center Tracker during the encounter). Note: this metric is not available for runs performed with the Phase I tracker.
- Percent of preventive/corrective/warning alerts that were issued when ADS-B was chosen as the best sensor
- Percent of preventive/corrective/warning alerts that were issued when ATAR was chosen as the best sensor
- Percent of preventive/corrective/warning alerts that were issued when AST was chosen as the best sensor
- Percent of preventive/corrective/warning alerts that were issued when GBSS was chosen as the best sensor

3 BASELINE AND SENSITIVITY ANALYSIS RESULTS

This section describes the analysis results. Section 3.1 describes baseline runs that were performed to determine default parameter values to use in the final safety runs. Section 3.2 describes the integrated delay and C2 interruption sensitivity analysis. Section 3.3 describes the GBSS sensitivity analysis. These sections focus on the primary safety metrics: risk ratio and loss of well clear ratio.

3.1 Baseline Runs

Before performing the final safety scenario runs, baseline runs were performed to determine the default parameter values of the following configurations:

- DAIDALUS SUM vs. No SUM (Sensor Uncertainty Mitigation). SUM is an algorithm in DAIDALUS that accounts for sensor uncertainty rather than applying a buffer to the DWC volume. [15]
- ADS-B altitude quantization of 100 ft vs. 25 ft

These baseline runs were performed using all of the encounter sets (terminal Version 2, uncorrelated, and correlated). Both a 4-second integrated delay (corresponding to Class 1-5, and 7), and a 5-second integrated delay (corresponding to Class 6) were tested; no C2 interruptions were simulated. All of the baseline runs were performed with the MALE platform and ADS-B sensor. Even though the uncorrelated set represents noncooperative intruders, ADS-B was used for consistency and to isolate any differences that might be due to the encounter sets. Testing SUM vs. no SUM for noncooperative intruders detected by ATAR only or GBSS only can be performed as future work as described in Section 5.1.5.

For the terminal encounter set, encounters with the following criteria were filtered out when computing metrics in order to provide a fair analysis:

- Any encounters that start in an NMAC or LoWC, or any that issue a warning alert in the first 10 seconds of the simulation, as these encounters do not give the DAA system enough time to initialize and respond.
- Any encounters that had red (warning) DAIDLAUS vertical guidance saturation, meaning that none of the vertical bands were safe. This occurs in approximately 4% of encounters with alerts that do not start in an NMAC or LoWC. These encounters were filtered out because saturated warning guidance is not expected to occur operationally. Note that green (recovery) guidance saturations occur in approximately 2-3% of encounters with an alert, but these were not filtered out.

No filtering was performed on the uncorrelated and correlated encounter sets, as the ownship and intruder start further apart in these encounters, and thus, filtering is unnecessary.

Figure 5 shows the baseline results for the correlated encounters. The plots on the left compare results with and without SUM for different integrated delays. The plots on the right compare results with 25 ft vs. 100 ft ADS-B altitude quantization for different integrated delays. The top row shows risk ratios, whereas the bottom row shows loss of well clear ratios. The results indicate that quantization does not make a significant difference. Similarly, the results with and without SUM are comparable. The risk ratios are comparable to the Study 5 MALE risk ratio, which was approximately 0.10 when run with ADS-B, AST, and ATAR [6]. However, the loss of well clear ratios are higher than the Study 5 MALE LoWC ratio, which was approximately 0.30. This difference could be due to a number of factors, including updates to the DAIDALUS implementation, encounter sets, etc.

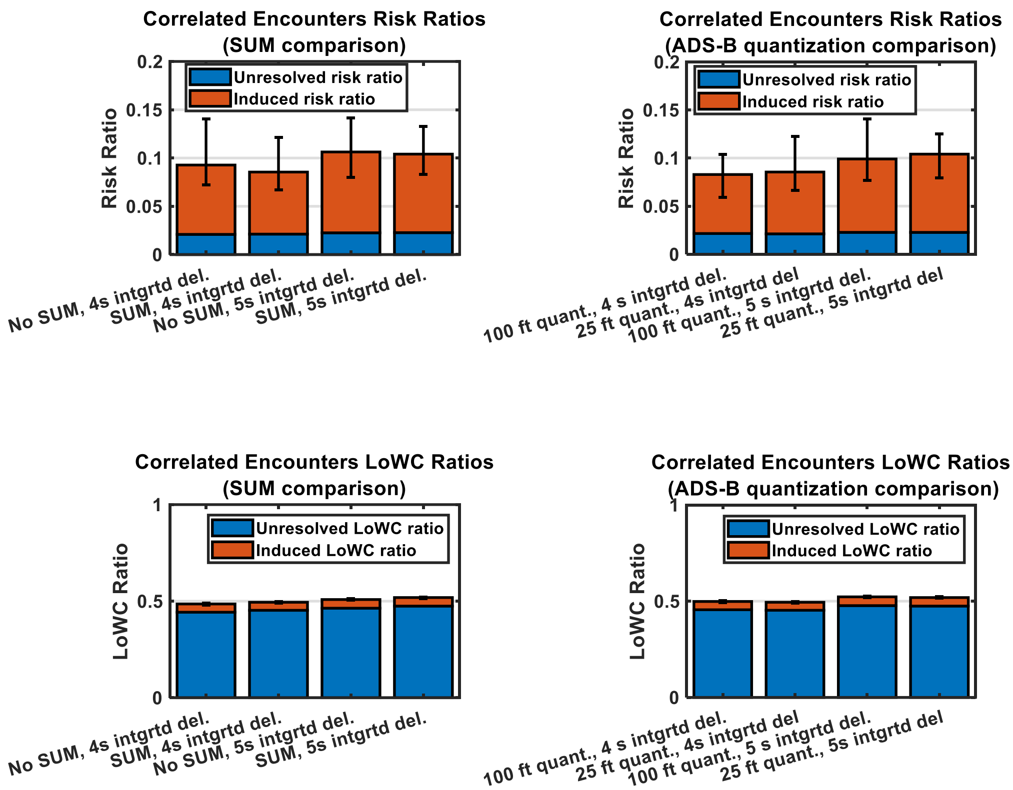

Figure 5. Correlated baseline results.
(LoWC volume = 4000 ft horizontally, 450 ft vertically, 35 sec modTau)

Figure 6 shows the baseline results for the uncorrelated encounters. The risk ratios and LoWC ratios are lower than the correlated results (Figure 5). The trends are similar to the correlated encounters in that the quantization does not make a significant difference and the results with and without SUM are comparable. The risk ratios ATAR are lower than the Study 5 results run with AST and (approximately 0.30), as are the LoWC ratios (Study 5 results were approximately 0.2) [6]. Note that Study 5 used a different LoWC definition (i.e., the "en route cooperative" definition from Table 29). Again, this could be due to differences in the encounter sets used in each study as well as the fact that ADS-B was used in these baseline runs; ADS-B is not as noisy as AST and ATAR. One difference between Figure 5 and Figure 6 is that the majority of the risk ratios in Figure 5 are due to induced NMACs, whereas the induced risk is a significantly smaller portion of the risk ratios in Figure 6. The large amount of induced risk in Figure 5 could be due to the fact that correlated encounters are more difficult to resolve due to high intruder performance relative to the UAS ownship. Additionally, the correlated model reflects prior mitigation—i.e., the nominal vertical and horizontal miss distances are skewed away from NMAC—such that DAA maneuvers are more likely to induce NMACs.

Figure 7 shows the baseline results for the terminal encounters. The results are similar to the uncorrelated results, although the terminal encounters are filtered when computing results as described above, whereas the uncorrelated results are not. The trends are similar to both the uncorrelated and correlated results in that the quantization does not make a significant difference and the results with and without SUM are comparable.

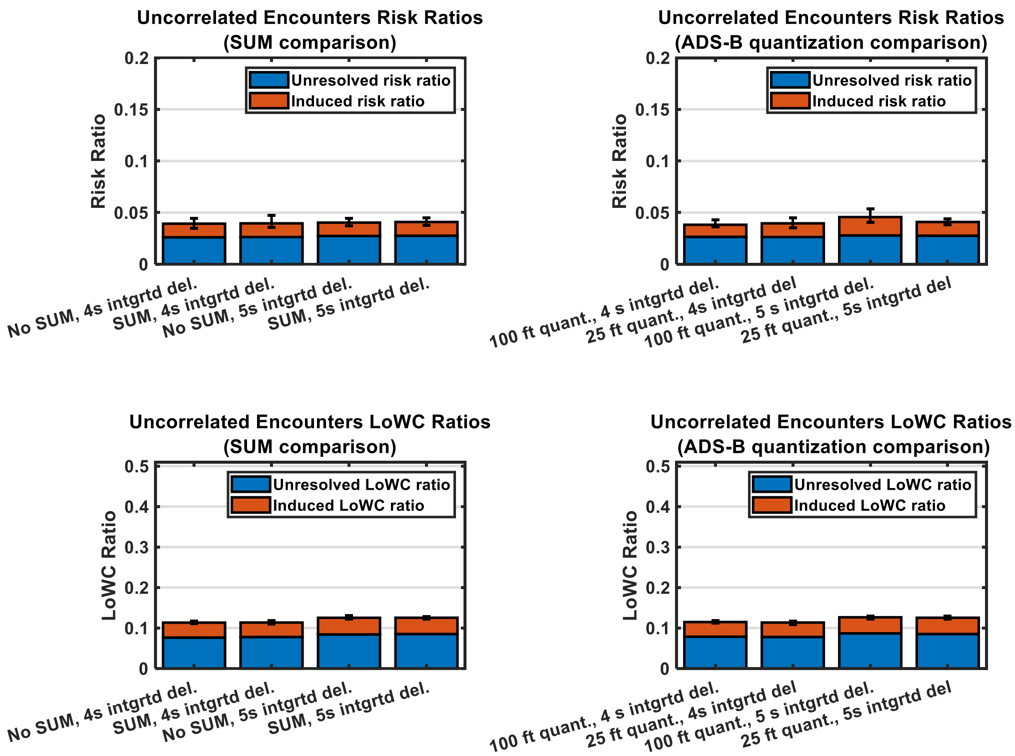

Figure 6. Uncorrelated baseline results.
(LoWC volume = 2200 ft horizontally, 450 ft vertically, 0 sec modTau)

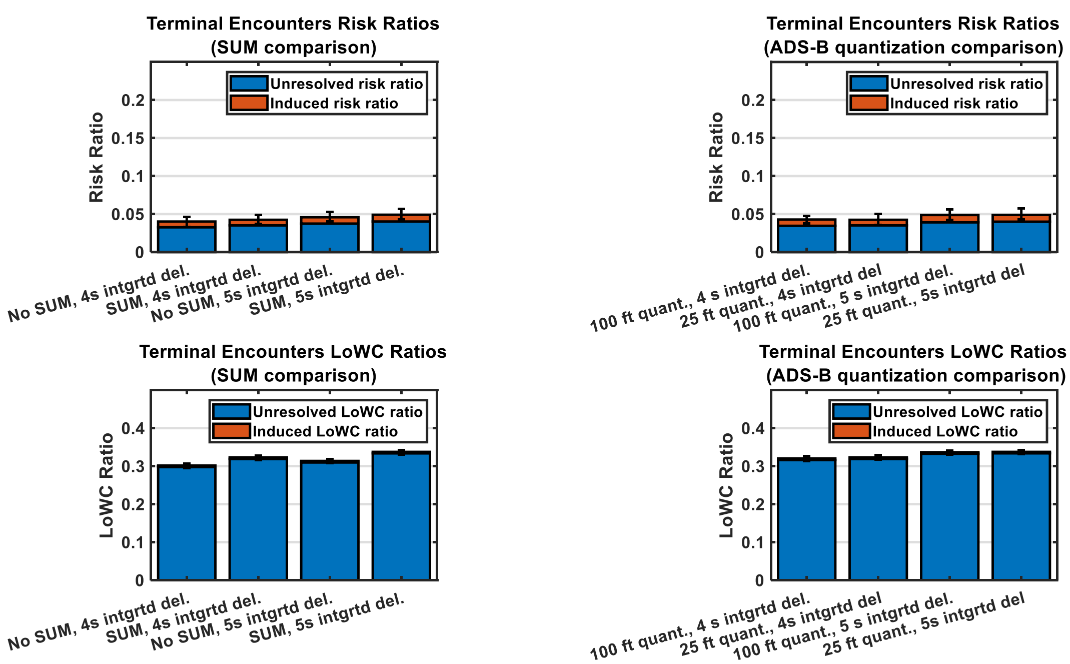

Figure 7. Terminal baseline results.
(LoWC volume = 1500 ft horizontally, 450 ft vertically, 0 sec modTau)

Because the results indicate that altitude quantization does not make a significant difference, the final safety scenario runs default to using a 25 ft ADS-B quantization unless otherwise specified by a final safety scenario. Likewise, as the results with and without SUM are comparable, the final safety scenarios were run with SUM enabled in DAIDALUS, in line with the recommendation received from the NASA DAIDALUS developers.

3.2 Integrated Delay and C2 Interruption Sensitivity Analysis

The purpose of the integrated delay and C2 interruption sensitivity analysis was to assess the sensitivity of the DAA system performance (safety and operational suitability) to C2 performance levels, and to evaluate the impact of varying C2 performance requirements. This analysis was performed using one million MALE encounters from the terminal encounter model (Version 2), and the ADS-B sensor, which was processed through the Phase I FAA Tech Center Tracker. The Phase 1 tracker was used because the Phase II tracker was not yet integrated at the time the C2 sensitivity analysis was performed. However, ADS-B performance is consistent between the Phase I and Phase II trackers.

Figure 8 shows the configuration of the C2 model that was used for the sensitivity analysis. The TCAS II RA logic is not enabled in order to focus on the effects of the DAA specific integrated delays and C2 interruptions.

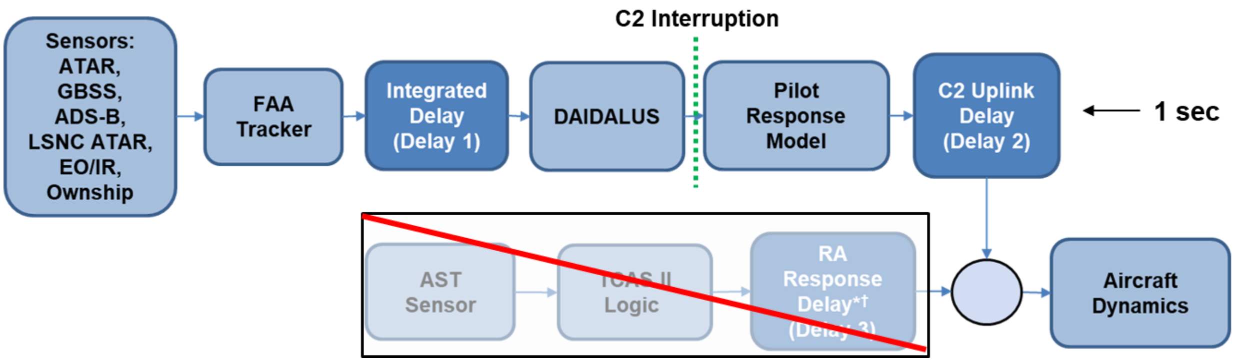

Figure 8. C2 sensitivity analysis model configuration.

Table 30 shows the values that were used for this parameter sweep. C2 interruptions can also be referred to as the Transaction Expiration Time (TET).

Table 30. C2 model parameter sweep values.

Parameter	Values
Integrated Delay (Delay 1)	0, 2, 4*, 5, 10, 15 sec
C2 Interruption Time (from [7])	0* (no interruptions) 2, 5, 10, 15, 20, 25, 30, 60 sec (Method 1 in Section 2.1.2.4) 2, 3, 5, 10, 20 sec (Method 2 in Section 2.1.2.4)

The default configuration (denoted by *) is an integrated delay of 4 sec (corresponding to Class 1-5, and 7), and a C2 interruption of 0 seconds (i.e., no interruptions). The default configuration is used as a baseline for comparing the other sweep values. While sweeping over a parameter, the other parameter is held constant at its default configuration—i.e., when sweeping over integrated delay, the C2 interruption time is 0 seconds, and when sweeping over the C2 interruption delay, the integrated delay is 4 seconds. In all runs, the C2 uplink delay (delay 2 in Figure 3) is 1 second. Note that the pilot response latencies are defined within the pilot model, so they were not evaluated explicitly as part of the parameter sweep.

3.2.1 Integrated Delay and C2 Interruption Sensitivity Analysis Methodology

The primary metrics for the C2 analysis were risk ratios and loss of well clear ratios. Recall that the loss of well clear volume for the terminal area is 1500 ft horizontal and 450 ft vertical with a 0 sec modTau. To provide a fair and consistent analysis of the C2 system, the same filtering that was applied to the terminal encounters in the baseline runs (Section 3.1) was also applied here.

3.2.2 Integrated Delay Sensitivity Results

Figure 9 shows the risk ratios and loss of well clear ratios for the integrated delay sweep. As expected, the risk increases as the integrated delay increases. The default integrated delay is 4 seconds, which corresponds to Class 1-5 and 7. (In Phase I (Study 5, Spiral 3), the integrated delay was 2 seconds [6]). The results for this default delay are shown by the dashed green line. The maximum integrated delay for any class is 5 seconds, corresponding to Class 6. The risk ratio for a delay of 5 seconds is approximately 60% over the default. Class 8 has an integrated delay of 3 seconds; based on the trends, the risk ratio for Class 8 is expected to be below the default. The results for 0- and 2-second delays are significantly lower than the default. These results indicate that the DAA performance is highly sensitive to response delay in the terminal environment. Appendix C (Section C.1.1) shows an example encounter that has a 4-second integrated delay.

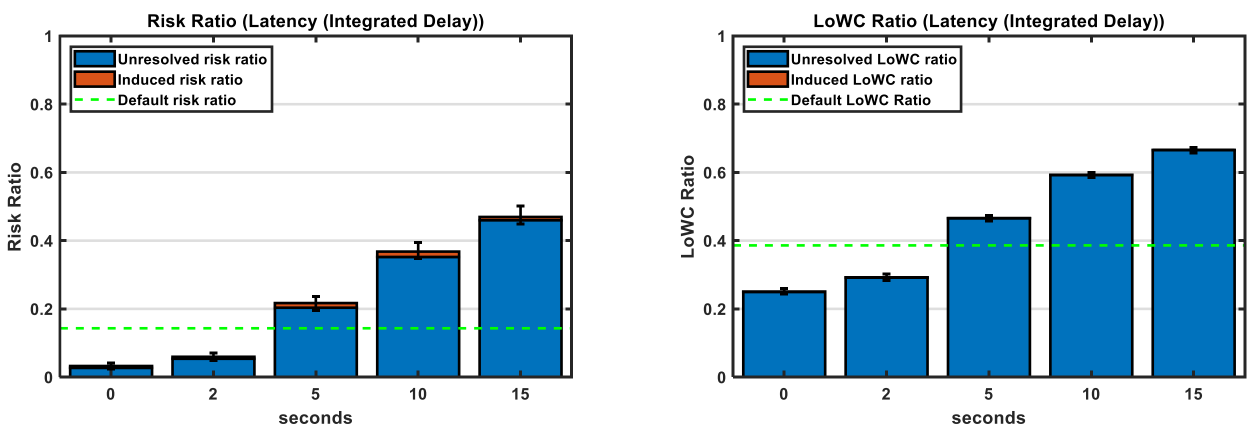

Figure 9. Integrated delay sensitivity results.

3.2.3 C2 Interruption Sensitivity Results

The interruption results were compared against a ratio threshold that is 25% larger than the default configuration; this threshold is consistent with the risk degradation for the 5 second en route interruption requirement from MITRE's Phase I analysis results. In Phase I, 5 seconds was considered to be an acceptable interruption value, and the number of NMACs for 5 seconds (875 NMACs) was approximately 25% above the number of NMACs for the baseline case (695 NMACs) [7]. Hence, 25% is a rough threshold that was used for comparison while the SRM analysis was still in progress.

Figure 10 shows the risk ratios and loss of well clear ratios for the C2 interruption sweep using Method 1 (dropping on the first alert triggering a maneuver). As expected, the risk increases as the interruption length increases. The risk ratios for interruptions up to 5 seconds are comparable to the default; however, the risk ratio starts to increase significantly after 10 seconds.

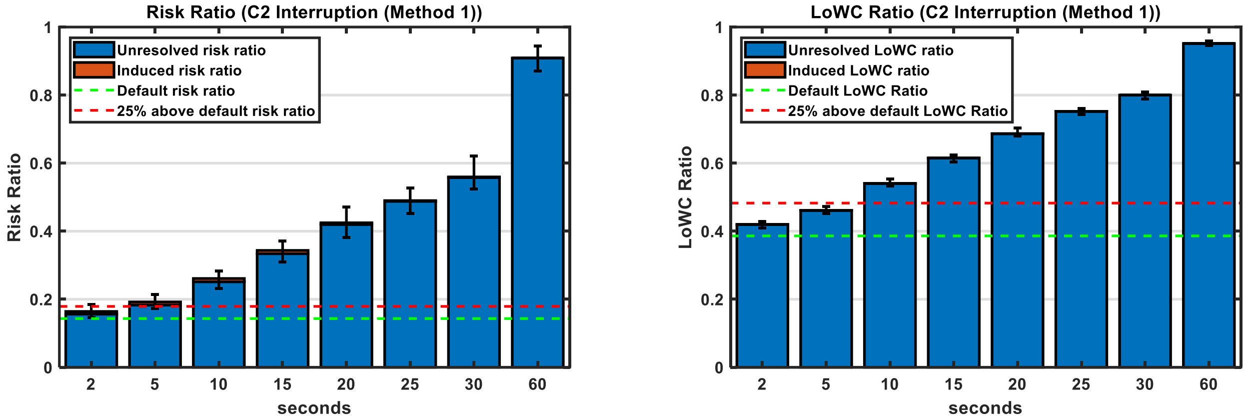

Figure 10. C2 interruption sensitivity results (Method 1).

Figure 11 shows the risk ratios and loss of well clear ratios for the C2 interruption sweep using Method 2 (dropping on the first warning alert). The results are similar to the Method 1 results because only warning alerts are issued in the DTA. However, the results are not identical because there are some encounters where the ownship starts outside the DTA and receives corrective alerts; hence, the risk ratios with Method 2 are slightly higher.

Again, the risk increases as the interruption time increases. However, Method 2 with a 3-second interruption (the current C2 MASPS requirement) is still within the "25% above default" threshold, indicating that the C2 MASPS requirement of 3 seconds is acceptable.

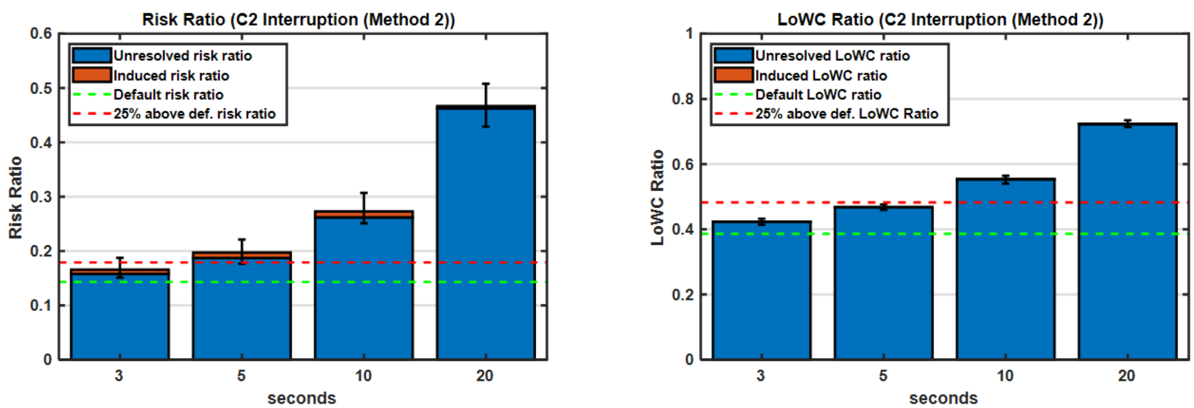

Figure 11. C2 interruption sensitivity results (Method 2).

Appendix C (Section C.1.2) shows an example encounter evaluated with a 0-second interruption vs. a 3-second interruption.

3.2.4 C2 Interruption Sampling Scheme

This section describes the sampling scheme for the C2 interruption length that was used in the final safety runs. This sampling scheme was developed in coordination with SC-228 C2 SMEs. Given results from the C2 interruption sensitivity analysis (Section 3.2), Method 2 (dropping on the first warning alert) was used to model C2 interruptions as the worst case. The assumed link availability from the C2 MASPS is 99.9%, so interruption lengths are multiplied by 1/(1-99.9/100)) = 1000 seconds to get the time between interruptions. Thus, an interruption of 3 seconds (the C2 MASPS requirement) will occur on average every 3000 seconds, so on average a C2 interruption occurs every 3000/*encounter_length* encounters. Table 31 shows the *encounter_length* for each encounter set.

Table 31. Encounter lengths.

Encounter Set	***encounter_length***
Uncorrelated	240 seconds
Correlated	120 seconds
Terminal	Varies, median = 100 seconds

For instance, for terminal encounters, a 3-second C2 interruption would occur on average once every 3000/100 = 30 encounters. However, it would not be realistic for the interruptions to occur *exactly* every 30 encounters. Instead, the number of encounters between interruptions should vary between 10 and 100 encounters and have a mean of 30 encounters. The lower bound of 10 encounters comes from the fact that an interruption of 1 sec will occur on average every 1000 seconds (or every 1000/*encounter_length* = 1000/100 = 10 encounters), and the upper bound comes from the fact that an interruption of 10 seconds will occur every 10,000 seconds (or every 10,000/*encounter_length* = 10,000/100 = 100 encounters).

The number of encounters between interruptions was sampled from the distributions shown in Table 32. The distribution is different for each encounter set to reflect the different encounter lengths in each encounter set.

Table 32. Number of encounters between interruptions.

Encounter Set	Minimum	Mean	Maximum
Uncorrelated	4	12.5	40
Correlated	8	25	80
Terminal	10	30	100

For encounters that have an interruption, the distribution in Table 33 was used to sample the length of the interruption. The same encounter has the same interruption in all scenario runs. This distribution has an expected (average) value of 3 seconds, which aligns with the C2 MASPS requirement. This distribution of C2 interruption lengths (provided by SC-228 C2 SMEs) is independent of the distribution used to model the number of encounters between interruptions—i.e., the distribution in Table 32 is a realistic and typical representation of how often C2 interruptions occur, but it was not rigorously developed based on C2 interruption distribution in Table 33.

Table 33. Distribution of C2 interruptions.

Interruption Length (sec)	Probability
1	40.49%
2	14.17%
3	9.31%
4	6.88%
5	6.07%
6	5.26%
7	4.86%
8	4.45%
9	4.45%
10	4.05%

3.3 GBSS Sensitivity Analysis

Table 34 shows the default track error parameter configuration for the GBSS sensor. For this parameter sweep, each GBSS track error parameter was adjusted to be 50%, 75%, 125%, and 150% of the values in Table 7. While sweeping over a parameter, the other parameters are held constant at their default value from Table 7. The GBSS sensitivity analysis was performed using one million MALE encounters from the en route encounter sets (correlated and uncorrelated). Note that the correlated results may be less relevant since it is unlikely that GBSS will be the sole sensor used to detect a cooperative aircraft, like those represented in the correlated encounter set. However, they are not completely irrelevant because Class 8 does not include active surveillance (only GBSS and ADS-B), so GBSS will be used to track transponder-only aircraft. In these sensitivity runs, the C2 interruption was set to a constant of 3 seconds with Method 2, which aligns with the current C2 MASPS requirement.

Table 34. GBSS parameter sweep values.

Parameter	Default Value (from Table 7) Total Error 1-σ	Values
Horizontal Position	80.91 m	50%, 75%, 125%, 150%, 200%, 300%, 400% of requirements in DO-365B
Vertical Position	68.57 m	
Horizontal Velocity	2.89 m/s	
Vertical Rate	2.76 m/s	

Appendix C (Section C.2) shows an example encounter that was run with both ADS-B and GBSS with default parameters from DO-365B (Table 7) to illustrate the effect of GBSS track error.

3.3.1 Uncorrelated Horizontal Error Sensitivity Results

Figure 12 shows the results from sweeping over horizontal position and velocity error for the uncorrelated encounters. Results for horizontal position error are shown in the top row and results for horizontal velocity error are shown in the bottom row. The risk ratio and LoWC ratio from using the default GBSS track error values from Table 7 are shown by the dotted green line. The risk ratio and LoWC ratio from setting all of the errors to zero are shown by the dotted red line.

In general, the risk ratios and LoWC ratios are not sensitive to changes in horizontal position and velocity error, though the risk ratio and LoWC ratio do start to increase as the position and velocity errors are increased to 300% and 400%. This may be because the errors are relatively small compared to the magnitude of the East and North velocities. Note: the risk ratio for 150% horizontal velocity error appears to be greater than the risk ratio for 200% horizontal velocity error, but this is likely just due to the randomness in the sensor error; there is overlap in the confidence intervals for these two cases, so the difference is not statistically significant. In addition, a large portion of the risk ratios are due to induced NMACs. The induced risk is likely due to the large vertical uncertainty in the GBSS measurements even when using the default vertical error values.

The GBSS uncorrelated LoWC ratio is higher than in the baseline results, which were around 0.1 (Section 3.1). This is because the baseline runs used ADS-B, and GBSS is noisier than ADS-B, especially vertically—the LoWC ratio when setting all GBSS errors to zero is close to the baseline LoWC ratios. Furthermore, the baseline runs assumed no C2 interruptions, whereas these results assume a 3-second C2 interruption.

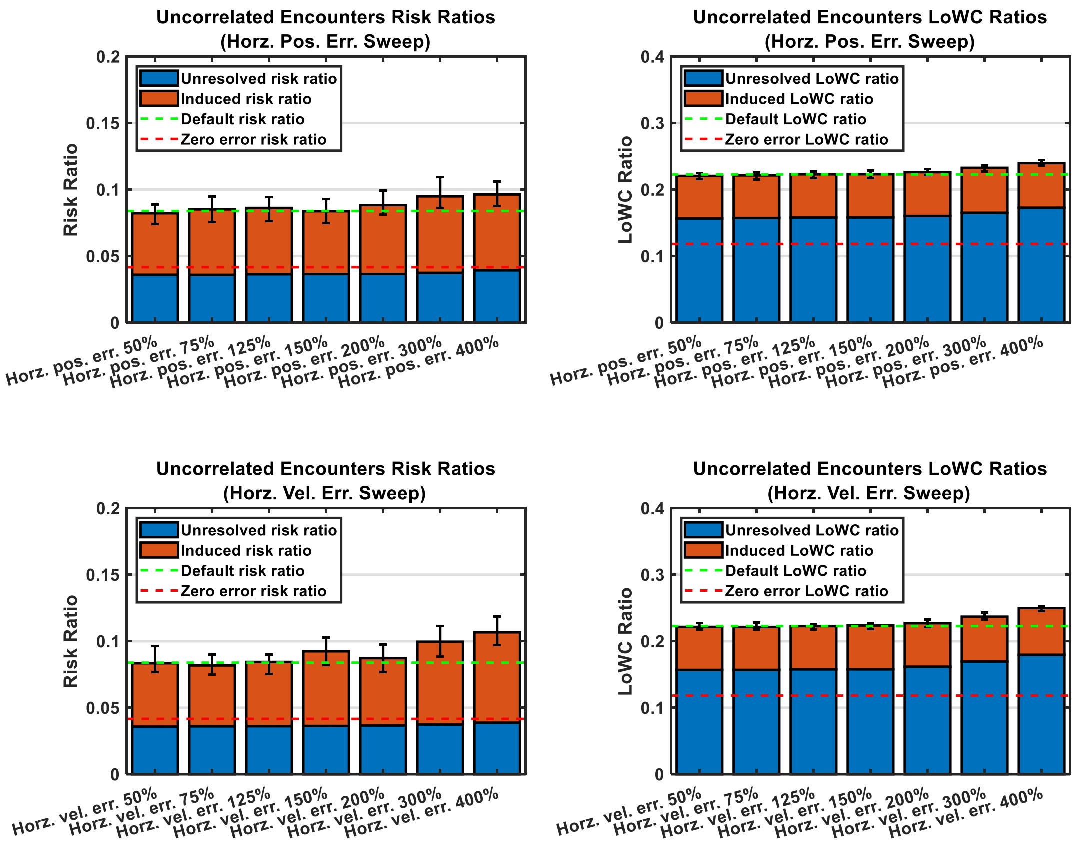

Figure 12. GBSS sensitivity: uncorrelated horizontal error results.

3.3.2 Uncorrelated Vertical Error Sensitivity Results

Figure 13 shows the results from sweeping over vertical position and velocity error for the uncorrelated encounters. Results for vertical position error are shown in the top row and results for vertical velocity error are shown in the bottom row. The risk ratio and LoWC ratio from using the default GBSS track error values from Table 7 are shown by the dotted green line. The risk ratio and LoWC ratio from setting all of the errors to zero are shown by the dotted red line.

Unlike with horizontal error, risk ratio and LoWC ratio are sensitive to vertical track errors. As the vertical error increases, the risk ratio and LoWC ratios increase, which is the expected trend. Unlike with horizontal errors, vertical errors may have a large impact on whether the DAA system thinks the intruder is climbing, descending, or flying level, which would have a significant impact on the DAA guidance.

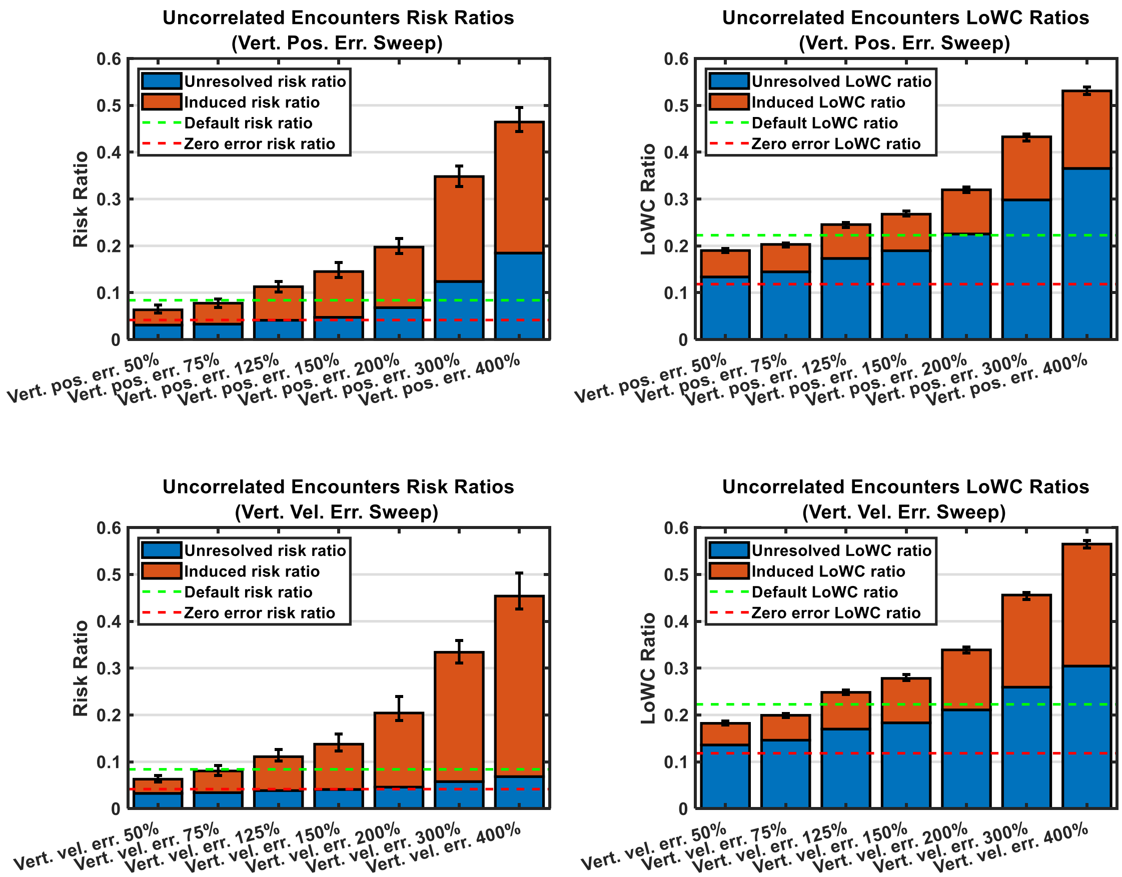

Figure 13. GBSS sensitivity: uncorrelated vertical error results.

The induced risk is particularly sensitive to increases in vertical error. A few additional runs were performed in which only horizontal maneuvers were performed when the vertical position and velocity errors were increased to 200% and 400%. (For the results in Figure 13, the pilot model was able to select from both horizontal and vertical maneuvers). The results for these additional results are shown in Figure 14. Although this change did not make much difference in the 200% results, there was a reduction in the risk ratio and loss of well clear ratios for the 400% vertical error results. This suggests that some of the risk could be mitigated by the UAS operator's executing horizontal maneuvers when using GBSS if it is known that the sensor has high vertical position and velocity uncertainty. Only performing horizontal maneuvers against noncooperative aircraft is consistent with the special cases in RTCA DO-365B for other noncooperative sensors such as ATAR, when the large vertical track uncertainties prevent effective vertical maneuvers. The 200% vertical position and velocity errors with only horizontal maneuvers result in risk ratios consistent with ATAR (scenario 53); thus, this increase in track errors could be considered acceptable in the en route environment against noncooperative aircraft.

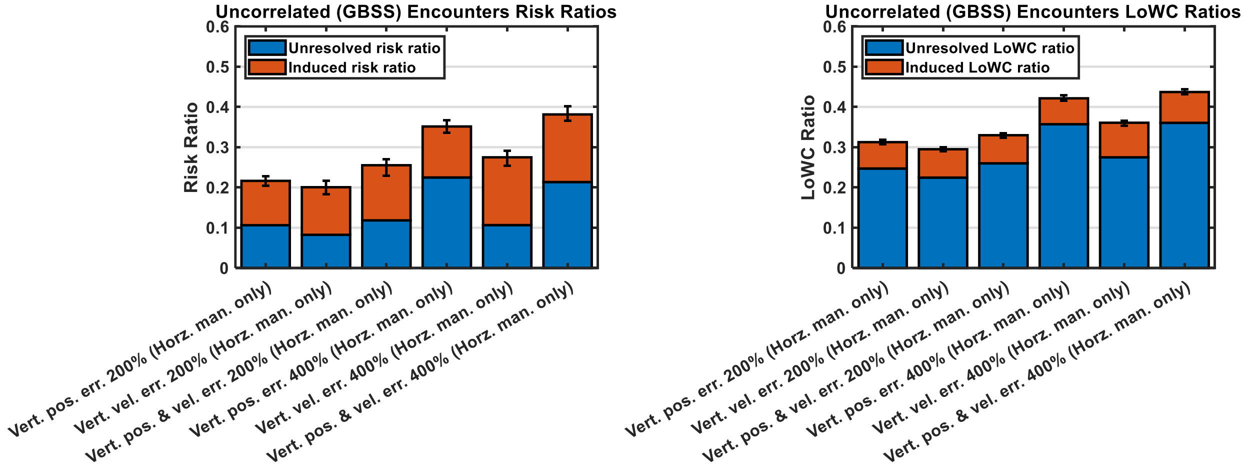

Figure 14. GBSS sensitivity: horizontal maneuvers only results.

3.3.3 Correlated Horizontal Error Sensitivity Results

Figure 15 shows the results from sweeping over horizontal position and velocity error for the correlated encounters. Results for horizontal position error are shown in the top row and results for horizontal velocity error are shown in the bottom row. The risk ratio and LoWC ratio from using the default GBSS track error values from Table 7 are shown by the dotted green line. The risk ratio and LoWC ratio from setting all of the errors to zero are shown by the dotted red line.

Similar to the uncorrelated results, the risk ratio and LoWC ratio are not sensitive to changes in horizontal position and velocity error until the position and velocity errors are increased to 300% and 400%. The correlated risk ratio is higher than the uncorrelated risk ratio; this is the same trend that was seem in the baseline results with ADS-B in Section 3.1.

Similar to the uncorrelated results, the LoWC ratio for the correlated results for GBSS is higher than in the baseline results, which were around 0.5 (Section 3.1). Once again, this is because the baseline runs used ADS-B, and GBSS is noisier than ADS-B—the LoWC ratio for the run from setting all of the errors to 0 is close to the baseline LoWC ratios. Furthermore, the baseline runs assumed no C2 interruptions, whereas these results assume a 3-second C2 interruption.

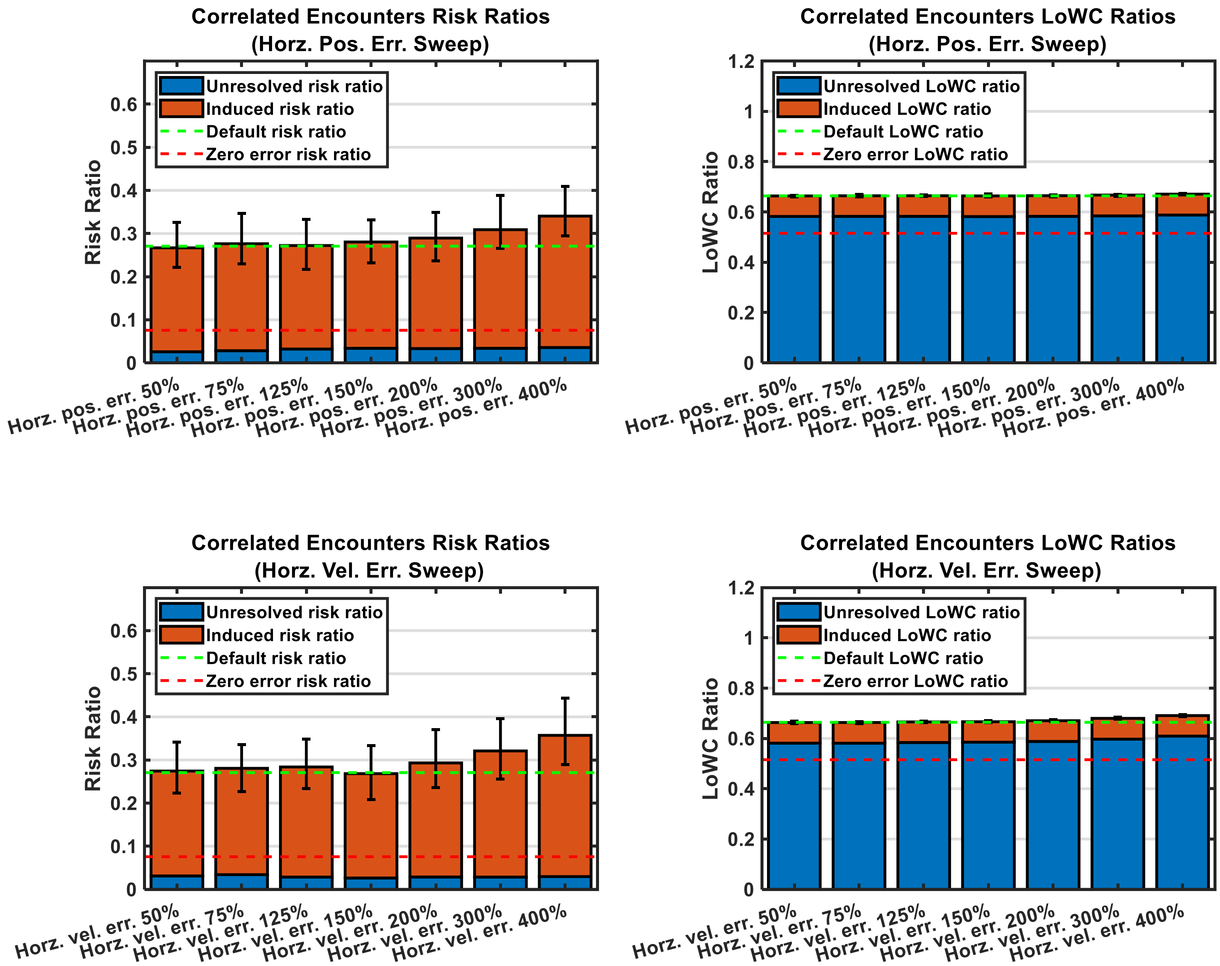

Figure 15. GBSS sensitivity: correlated horizontal error results.

3.3.4 Correlated Vertical Error Sensitivity Results

Figure 16 shows the results from sweeping over vertical position and velocity error for the uncorrelated encounters. Results for vertical position error are shown in the top row and results for vertical velocity error are shown in the bottom row. The risk ratio and LoWC ratio from using the default GBSS track error values from Table 7 are shown by the dotted green line. The risk ratio and LoWC ratio from setting all of the errors to zero are shown by the dotted red line.

As with the uncorrelated results, the correlated risk ratio and LoWC ratio are sensitive to vertical velocity error. As the vertical velocity error increases, the risk ratio and LoWC ratios increase, which is the expected trend. Setting the vertical position and velocity errors to 300% and 400% is especially detrimental for the correlated encounters, with the risk ratios going above one, indicating that the situation with the DAA system is worse than without the DAA system. However, this does not necessarily indicate that GBSS is unsuitable for DAA systems. As mentioned in Section 3.3.2, the operator's choice of maneuver direction (horizontal vs. vertical) can also impact the risk ratio. Furthermore, as mentioned at the beginning of Section 3.3, it is unlikely that GBSS will be the sole sensor used to detect a cooperative aircraft. If necessary, special cases like those for ATAR (which also may have large vertical uncertainty) could be considered. For example, §2.2.4.3.7.1 of DO-365B [1] suggests assuming an ATAR Only intruder is co-altitude when it is within 3000 ft vertically of the UAS.

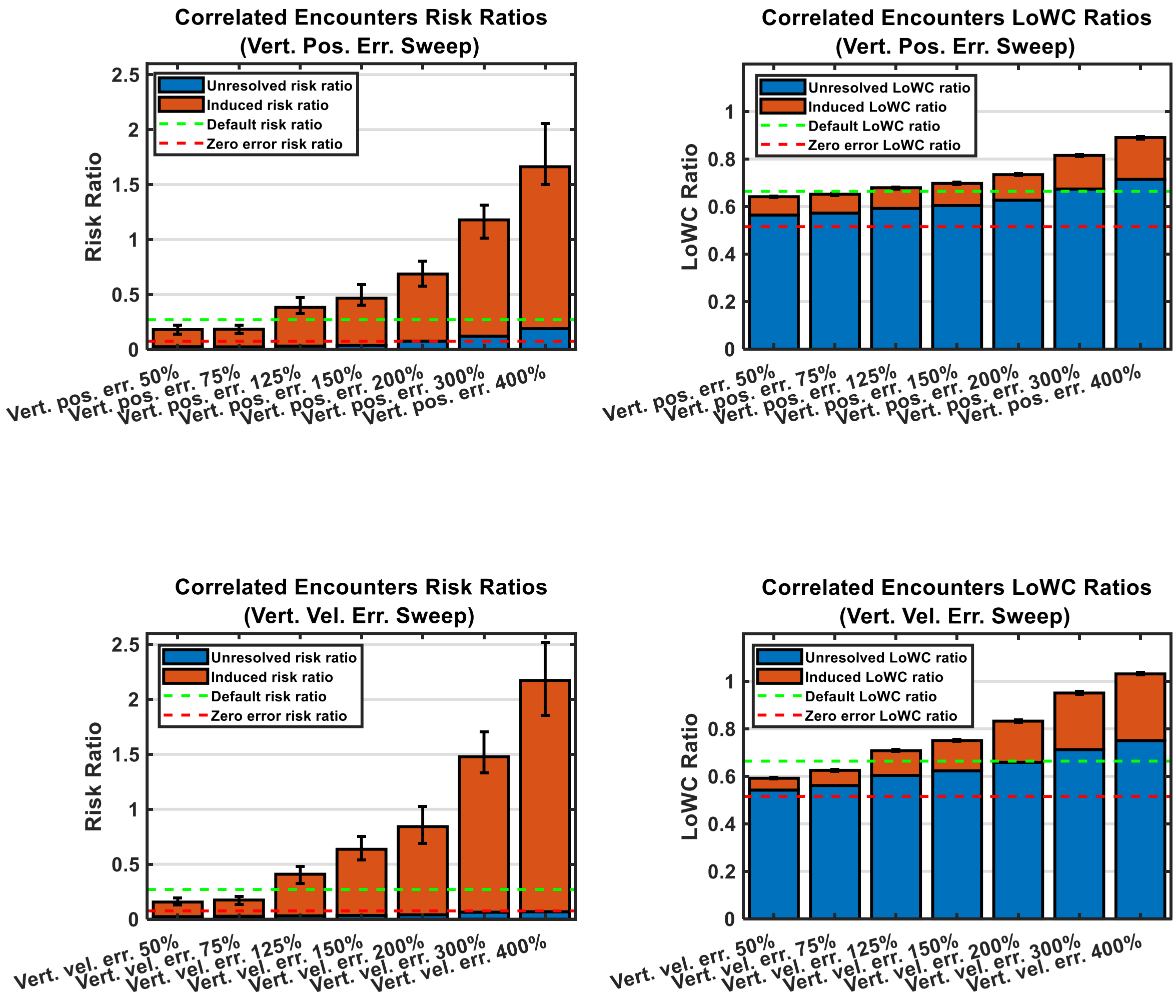

Figure 16. GBSS sensitivity: correlated vertical error results.

4 FINAL SAFETY EVALUATION

This section describes the analysis of the scenarios that were run to support the final safety evaluation. Each subsection discusses the results from running each of the scenarios. Unless otherwise indicated, the scenario runs test all 3 UAS platform types: HALE, MALE, and LEPR. Section 3.2.4 describes the C2 interruption sampling scheme that was used in the final safety evaluation scenarios. Section 3.1 describes the results of the baseline runs that were used to determine default settings for the final safety evaluation scenarios. All terminal encounters are sampled from Version 3 of the terminal encounter model.

The following subsections discuss the primary safety metrics: risk ratio and loss of well clear ratio. Additional metrics, including alert rate, SLoWC, best sensor selection frequency, and number of individual alert types, can be found in Appendix D.

The names of the scenarios in the following subsections refer to the DAA Class descriptions in Table 2. For example, Class 1+6 means that the scenarios use the DAA RWC function (i.e., DAIDALUS) only (Class 1) and it also allows the inclusion of the GBSS sensor (Class 6). In addition, because it is Class 6, an extra second of latency is simulated (the integrated delay for Class 6 is 5 seconds vs. 4 seconds for Class 1). Another important notation is “+5”, which indicates scenarios that were simulated in the terminal environment. All of the scenarios include a noncooperative sensor; “combined” denotes scenarios in which there is also one or more cooperative sensor.

Due to issues with how the integrated Phase II tracker (Version 7.5.1) processes ATAR data, the Phase I tracker was used for all final safety evaluation runs with ATAR. More information on these issues can be found in Section 5.1.4.

Note: many of the results have high induced risk and may not meet required risk ratios even using the most accurate sensors. This may not be due to the sensors themselves, but may be due to the tracker not selecting the most appropriate sensor as the best sensor—the Phase II tracker selects the best sensor solely based on horizontal position accuracy. The high induced risk could also be due to extra jitter introduced by the tracker when switching between best sensors; this issue could be explored as figure work as discussed in in Section 5.1.4.

4.1 DAA Class 1+6 (ATAR Combined)

This section discusses Scenarios 1-9. The sensors used in these scenarios are AST, ADS-B, and ATAR. ATAR A1 is used for HALE, ATAR A2 is used for MALE, and ATAR A3 is used with LEPR. These scenario runs were performed with the correlated encounters and en route DWC volume. The integrated delay is 5 seconds. The purpose of these runs was to assess en route DAA performance with DAIDALUS and ATAR.

Figure 17 shows the risk ratios and loss of well clear ratios for Scenarios 1-9. For the risk ratios, HALE performs better than MALE, which performs better than LEPR, which is expected given the maneuverability of the three platforms. Perhaps contrary to expectations, the addition of ADS-B actually increases the risk when the quantization is 100 ft (e.g., going from Scenario 1 to 2, 4 to 5, or 7 to 8). The ADS-B-only baseline runs from Section 3.1 showed that ADS-B quantization was not a factor; however, the multi-sensor track is less stable when switching between sensors than when ADS-B is used alone. In fact, the tracked vertical velocity is most jittery when ATAR, ADS-B, and AST are run together using 100 ft quantization. Appendix C (Section C.3) shows a comparison of the tracker output for an example encounter run with the configurations for Scenarios 4, 5, and 6.

On the other hand, the loss of well clear ratios show the expected trends, with ATAR + AST + ADS-B (25 ft quantization) performing better than ATAR + AST + ADS-B (100 ft quantization), both of which perform better than ATAR + AST only. This suggests the extra jitter for the ATAR + AST + ADS-B (100 ft quantization) does not have a significant impact on the DAA system's ability to avoid a LoWC, but has a significant impact on whether an NMAC is induced or not after LoWC occurs.

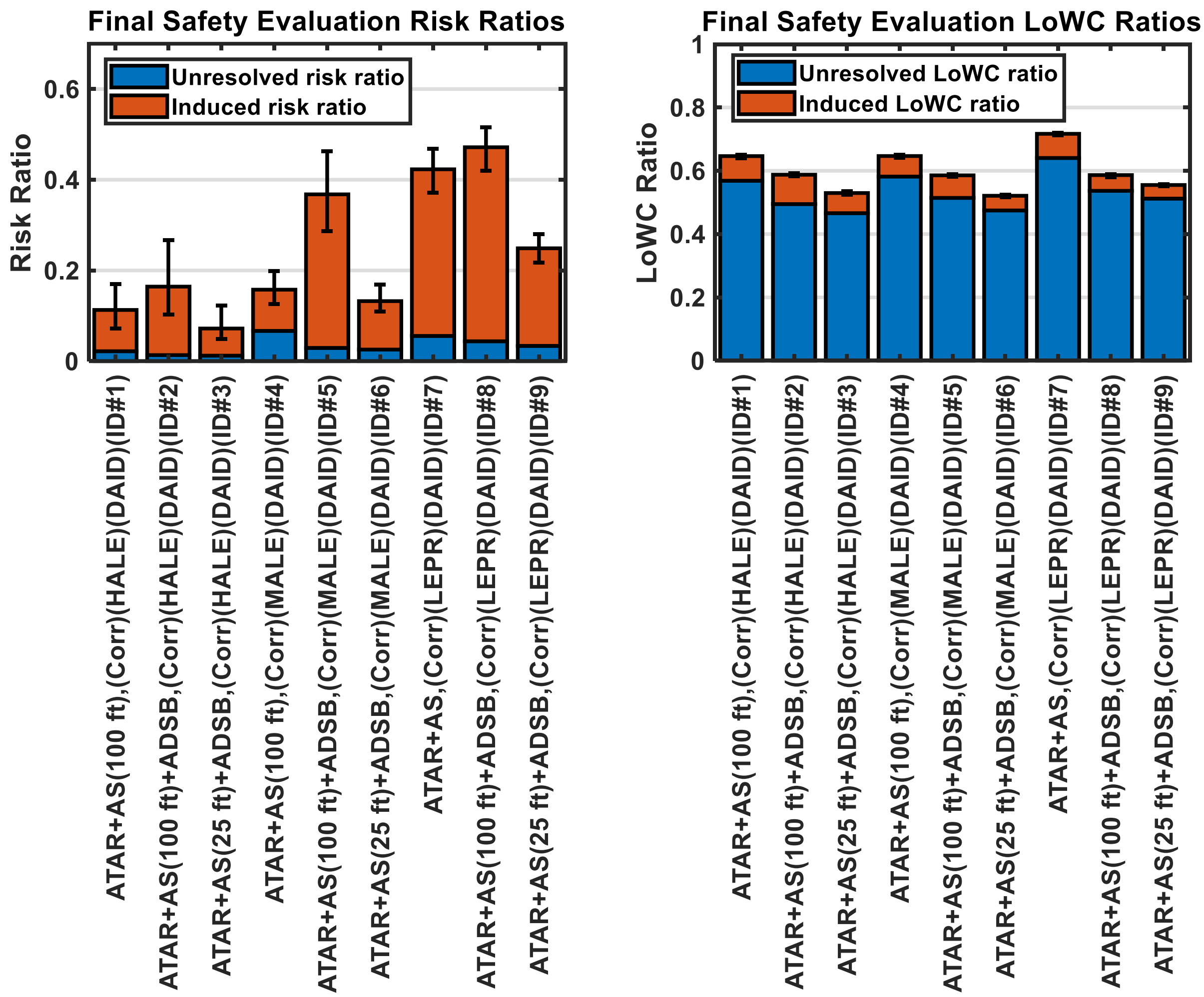

Figure 17. Final Safety Evaluation DAA Class 1+6 (ATAR Combined) results.

4.2 DAA Class 1+6 (GBSS Combined)

This section discusses Scenarios 10-18. The sensors used in these scenarios are AST, ADS-B, and GBSS. These scenario runs were performed with the correlated encounters and en route DWC volume. The integrated delay due to C2 latencies is 5 seconds. The purpose of these runs was to assess en route DAA performance with DAIDALUS and GBSS.

Figure 18 shows the risk ratios and loss of well clear ratios for Scenarios 10-18. The performance is best for HALE (followed by MALE and then LEPR): the risk ratios for HALE are around 0.1, the risk ratios for MALE are around 0.2, and the risk ratios for LEPR are near 0.4. The risk ratios for GBSS + AS only are slightly higher than the risk ratios for ATAR + AS only (Section 4.1). The majority of the risk comes from induced encounters.

Contrary to the DAA Class 1+6 ATAR Combined results (Section 4.1), the performance with ADS-B is typically better than the performance with GBSS + AST only, and when using ADS-B, the performance with 100 ft quantization is typically slightly better than performance with 25 ft quantization. Despite the large differences in the risk ratio, the LoWC ratios are largely comparable across the scenarios, though the LEPR LoWC ratios are slightly higher than those for HALE and MALE.

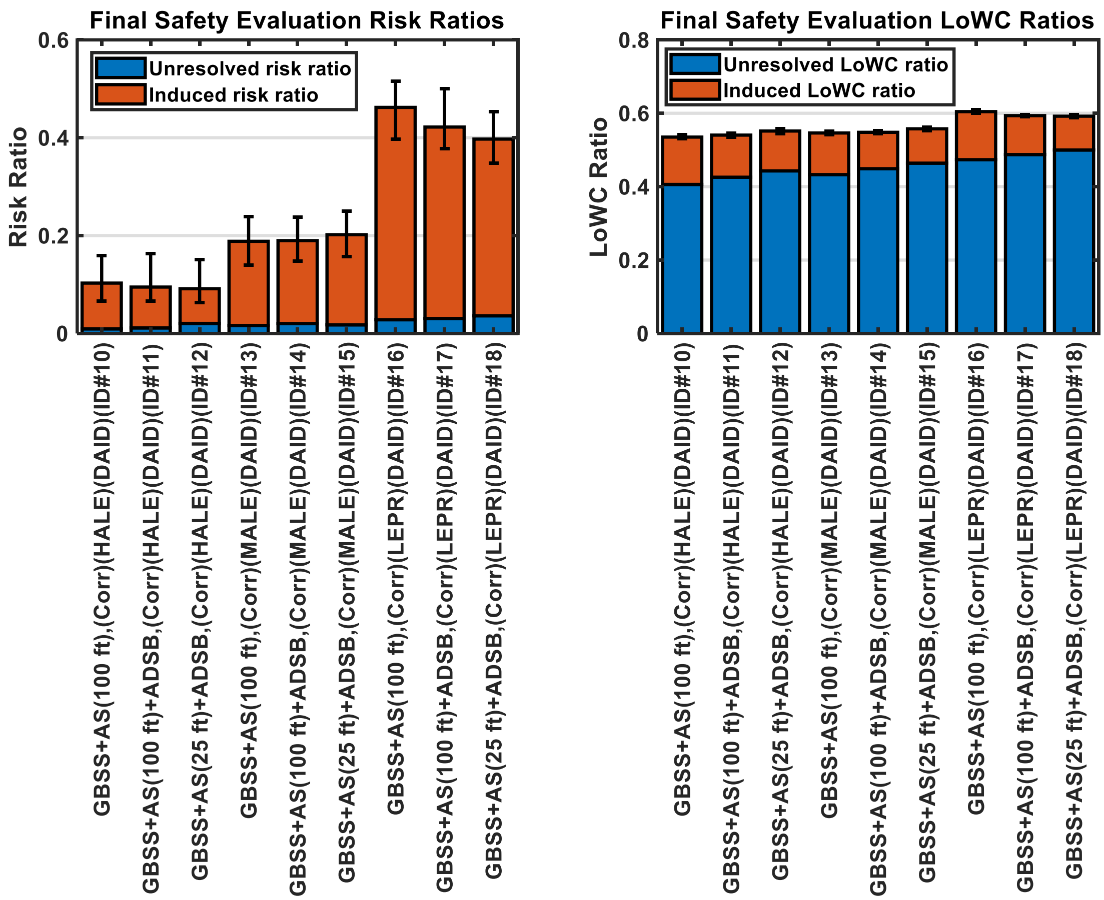

Figure 18. Final Safety Evaluation DAA Class 1+6 (GBSS Combined) results.

4.3 DAA Class 2+6 (ATAR Combined)

This section discusses Scenarios 19-24. The sensors used in these scenarios are AST, ADS-B, and ATAR. ATAR A1 is used for HALE, ATAR A2 is used for MALE, and ATAR A3 is used with LEPR. These scenario runs were performed with the correlated encounters and en route DWC volume. The integrated delay is 5 seconds. The purpose of these runs was to assess en route DAA performance with DAIDALUS with TCAS RA logic and ATAR. Note that only the DAA equipped ownship responds to TCAS RA logic in these scenarios.

Figure 19 shows the risk ratios and loss of well clear ratios for Scenarios 19-24. As expected, performance is best for HALE, followed by MALE, and then LEPR. The addition of ADS-B (Scenarios 20, 22, and 24) results in a slight reduction in the LoWC ratios compared to when ATAR and AST are used alone (Scenarios 19, 21, and 23) for each of the respective UAS platform types. However, for the risk ratios for the

ATAR+AST scenarios are within the risk ratio confidence intervals for ATAR+AST+ADS-B scenarios for each of the UAS platform types.

Compared with the results from Section 4.1, the HALE and MALE performance is generally improved when using TCAS RA logic in addition to DAIDALUS, especially for the runs with ADS-B. However, the addition of TCAS RAs has degraded the performance for LEPR; this may be because TCAS RAs are vertical maneuvers and LEPR has the worst maximum climb rate of the three platforms (500 feet per minute).

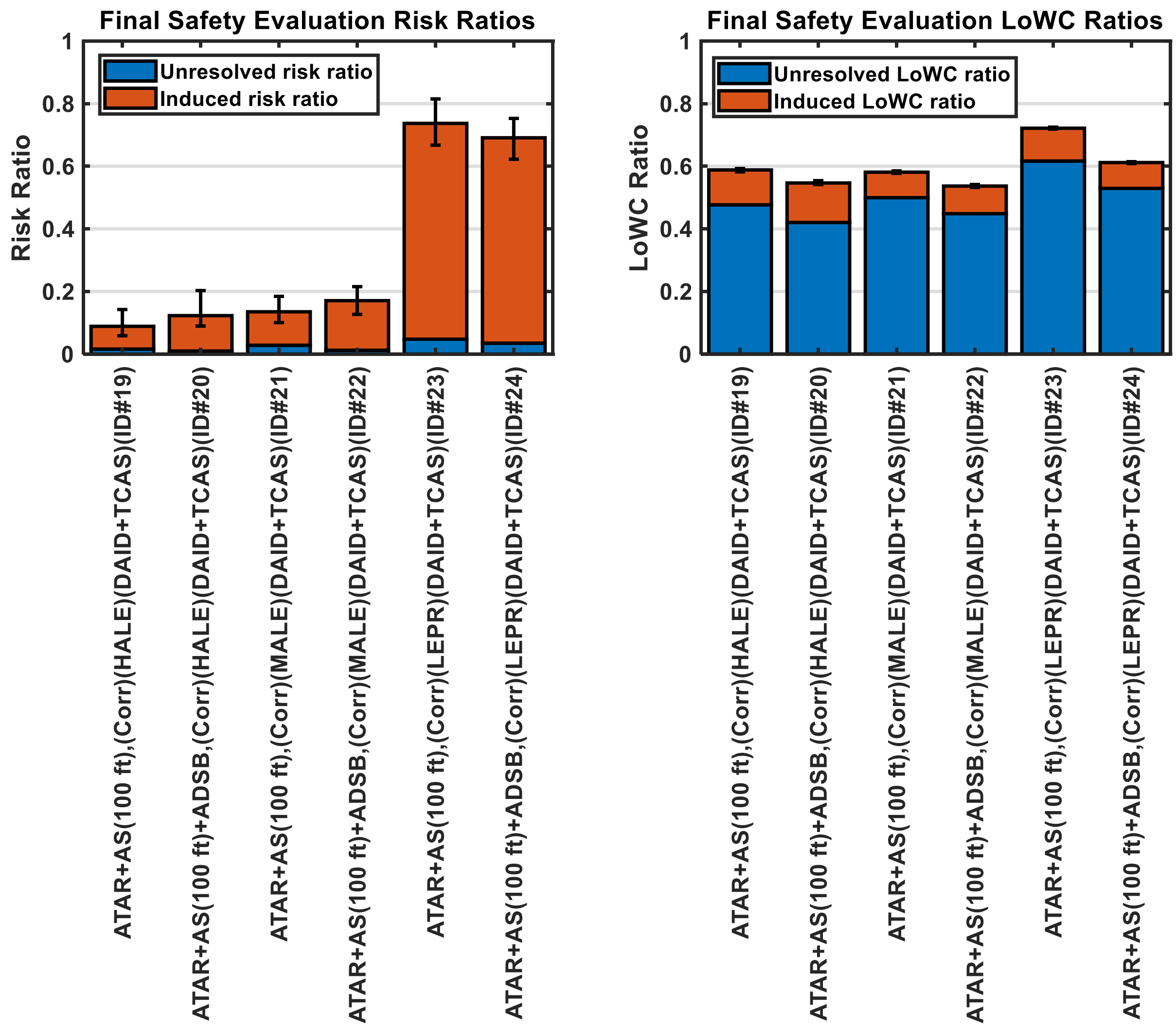

Figure 19. Final Safety Evaluation DAA Class 2+6 (ATAR Combined) results.

4.4 DAA Class 2+6 (GBSS Combined)

This section discusses Scenarios 25-30. The sensors used in these scenarios are AST, ADS-B, and GBSS. These scenario runs were performed with the correlated encounters and en route DWC volume. The integrated delay is 5 seconds. The purpose of these runs was to assess en route DAA performance with DAIDALUS with TCAS RA logic and GBSS. Note that only the ownship responds to TCAS RA logic in these scenarios.

Figure 20 shows the risk ratios and loss of well clear ratios for Scenarios 25-30. The performance from using only GBSS and AST (Scenarios 25, 27, and 29) is only slightly improved with the addition of ADS-B (Scenarios 26, 28, and 30). The performance for LEPR is much worse that the performance for HALE and MALE. Compared to DAA Class 1+6 (GBSS Combined) (Section 4.2), the addition of TCAS RAs has improved performance for HALE and MALE. However, similar to DAA Class 2+6 (ATAR Combined) Section 4.3, the addition of TCAS RAs has degraded the performance for LEPR.

The performance is similar to the results from DAA Class 2+6 (ATAR Combined (Section 4.3)); however, the LoWC ratios are generally slightly lower.

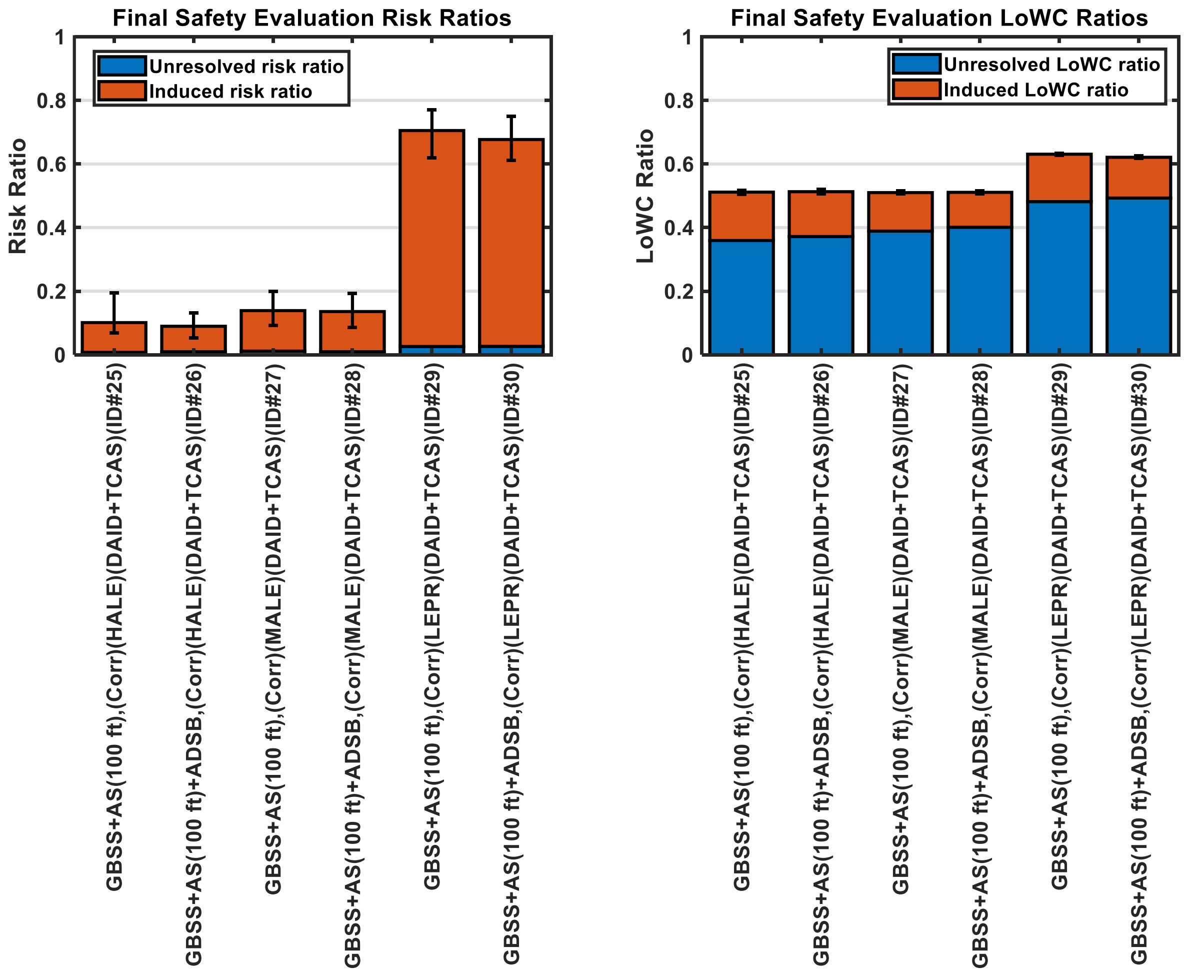

Figure 20. Final Safety Evaluation DAA Class 2+6 (GBSS Combined) results.

4.5 DAA Class 8 (GBSS Combined)

This section discusses Scenarios 31-33. The sensors used in these scenarios are ADS-B and GBSS. These scenario runs were performed with the correlated encounters and en route DWC volume. The integrated delay is 3 seconds. The purpose of these runs was to assess en route DAA performance with DAIDALUS, when the only sensors are ADS-B and GBSS. The ADS-B quantization in these runs is 25 ft.

Figure 21 shows the risk ratios and loss of well clear ratios for Scenarios 31-33. On the whole, the HALE and MALE performance from running with only ADS-B and GBSS is slightly better than running with

ADS-B, GBSS, and AST (Scenarios 12, and 15 from Section 4.2), whereas the LEPR performance is slightly worse than Scenario 18 from Section 4.2.

Two additional LEPR scenarios were run to understand the high risk ratio for Scenario 33: one which used ADS-B only and one where only horizontal maneuvers were executed; all other configuration parameters were the same as in Scenario 33. In both of these additional scenarios, the risk ratio was reduced considerably. This suggests preferring the use of ADS-B or performing horizontal only maneuvers could be mitigations for operating LEPR UAS.

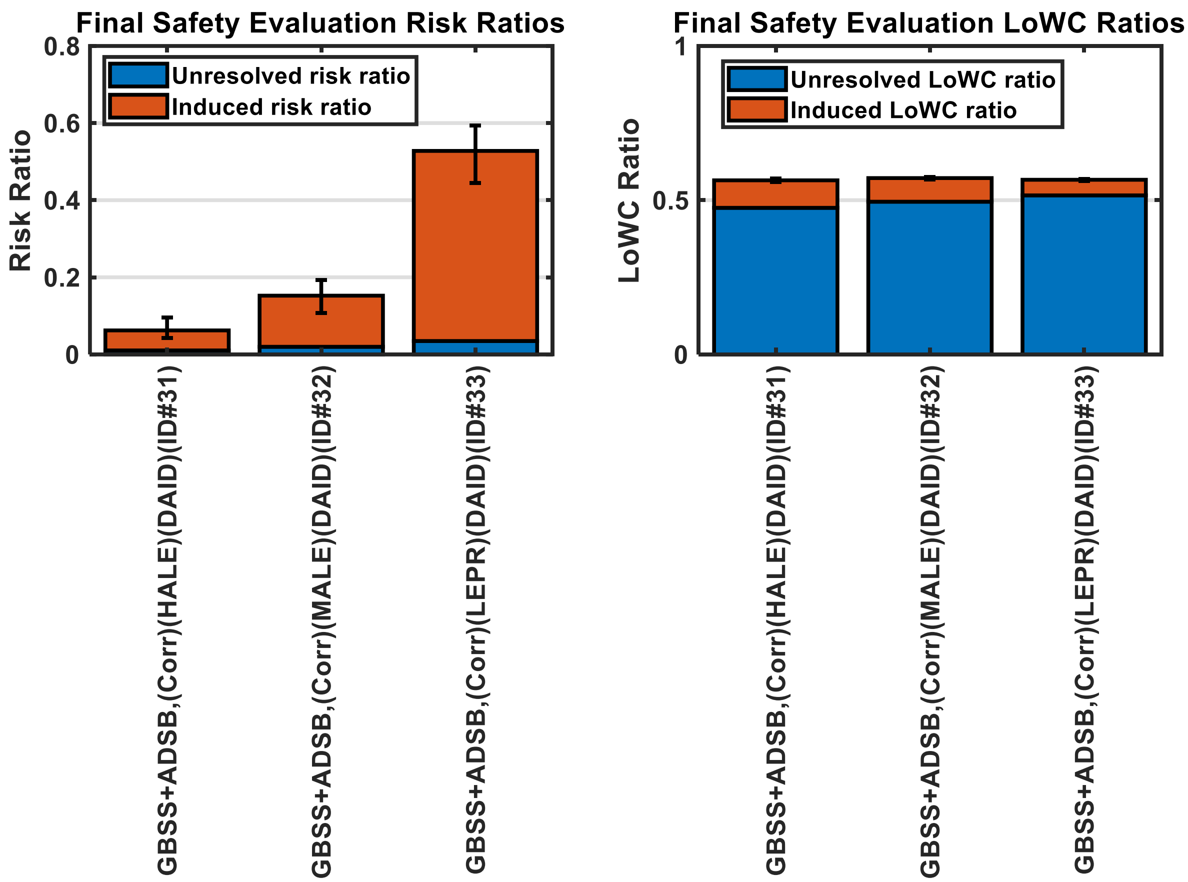

Figure 21. Final Safety Evaluation DAA Class 8 (GBSS Combined) results.

4.6 DAA Class 1+6+5 (GBSS Combined Terminal)

This section discusses Scenarios 34-42. The sensors used in these scenarios are AST, ADS-B, and GBSS. These scenario runs were performed with the terminal encounters and terminal DWC volume. The integrated delay is 5 seconds. The purpose of these runs was to assess terminal DAA performance with DAIDALUS and GBSS. These scenarios are similar to the scenarios in Section 4.2 except in the terminal environment instead of en route.

Figure 22 shows the risk ratios and loss of well clear ratios for Scenarios 34-42. The performance from using GBSS as the noncooperative sensor in the terminal environment with AST and ADS-B is quite good. The risk ratios for HALE and MALE are typically below 0.1, and even for LEPR, the highest risk ratio is less than 0.25. As expected, performance is best for HALE, followed by MALE, and then LEPR. This performance degradation based on platform maneuverability can be seen in both the risk ratios and the LoWC ratios. Interestingly, the risk and LoWC ratios are slightly higher when ADS-B is used, which is different from the trends that were seen for the correlated encounters in Section 4.2 and Section 4.4. This could be due to a known issue in Version 7.5.1 of the Phase II tracker, where the track measurements are significantly noisier that the actual sensor measurements when the tracker switches between best sensor sources. However, the terminal encounters in general are also more difficult to mitigate than the correlated encounters because the two aircraft are closer together and the ownship's maneuverability is hampered (i.e., limited to vertical only maneuvers in the DTA).

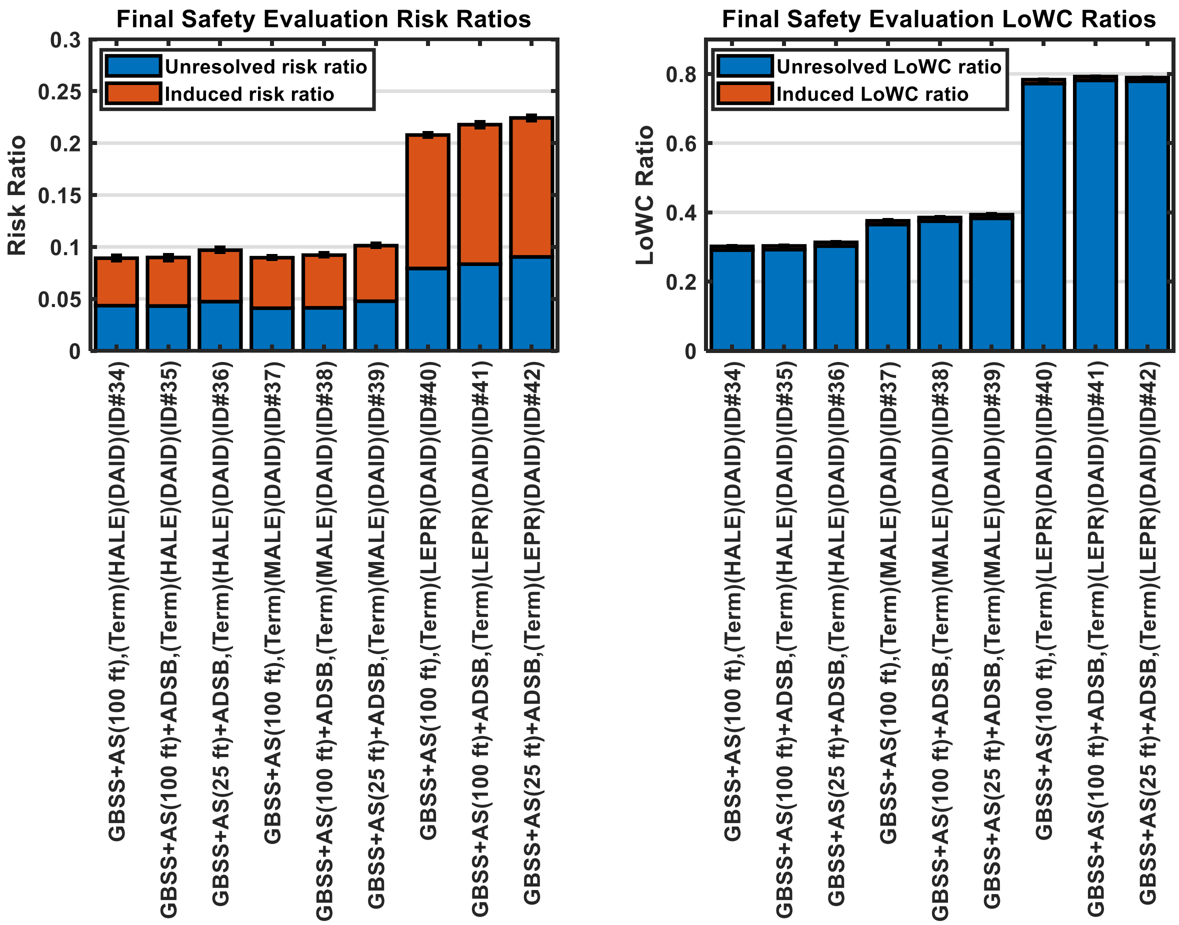

Figure 22. Final Safety Evaluation DAA Class 1+6+5 (GBSS Combined Terminal) results.

4.7 DAA Class 8+5 (GBSS Combined Terminal)

This section discusses Scenarios 43-45. The sensors used in these scenarios are ADS-B and GBSS. These scenario runs were performed with the terminal encounters and terminal DWC volume. The integrated delay is 3 seconds. The purpose of these runs was to assess en route DAA performance with DAIDALUS, when the only sensors are ADS-B and GBSS. These scenarios are similar to the scenarios in Section 4.5 except in the terminal environment instead of en route.

Figure 23 shows the risk ratios and loss of well clear ratios for Scenarios 43-45. These results are slightly better than the results from when AST is included (DAA Class 1+6+5 (GBSS Combined Terminal), Section

4.6). The risk ratios and LoWC ratios for HALE, MALE, and LEPR are slightly less than the corresponding risk ratios for GBSS with Active (25ft) and ADS-B from Section 4.6. The integrated delay is also slightly shorter in these runs (3 seconds vs. 5 seconds).

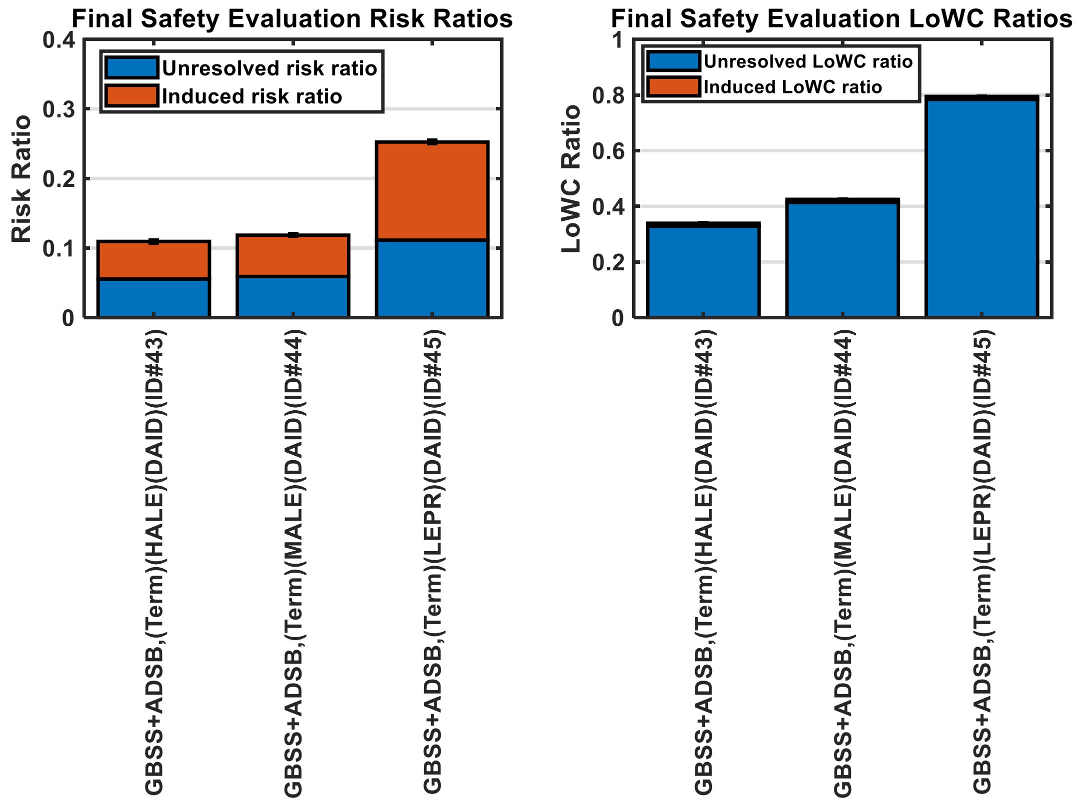

Figure 23. Final Safety Evaluation DAA Class 8+5 (GBSS Combined Terminal) results.

4.8 DAA Class 1+6 (GBSS and ATAR Correlated with Noncooperative DWC)

This section discusses Scenarios 46-51. Only one noncooperative sensor is used in each scenario—either ATAR or GBSS depending on the run. ATAR A1 is used for HALE, ATAR A2 is used for MALE, and ATAR A3 is used with LEPR. These scenario runs were performed with the correlated encounters and noncooperative DWC volume. Although correlated encounters are typically run with the en route DWC, the purpose of these scenarios is to draw out the difference between correlated and uncorrelated encounters when using a noncooperative DWC. For these runs, only encounters with ownship altitudes up to FL100 are included in the analysis; encounters are filtered based on initial altitude. The DAA algorithm used in DAIDALUS. The integrated delay is 5 seconds.

Figure 24 shows the risk ratios and loss of well clear ratios for Scenarios 46-51. The risk ratios and LoWC ratios are lower for GBSS than for ATAR, which is expected since GBSS measurements are significantly less noisy than ATAR measurements and there are no FOR limitations for the GBSS (unlike for ATAR). Furthermore, performance degrades as platform maneuverability degrades (HALE is better than MALE, which is better than LEPR).

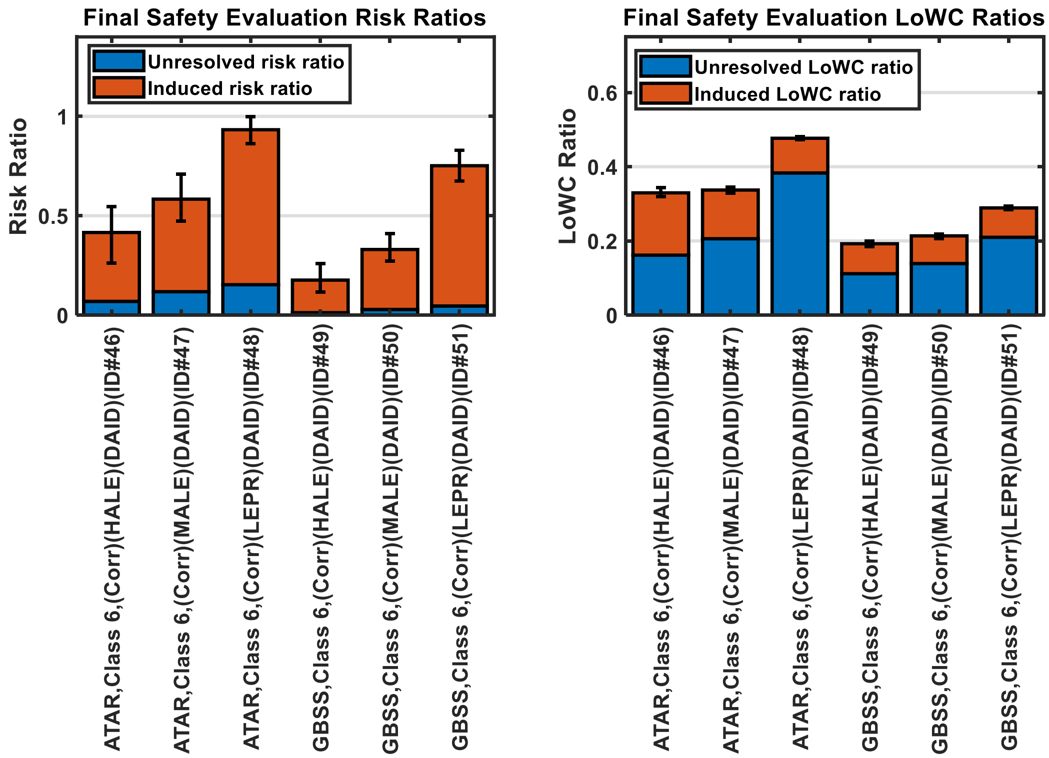

Figure 24. Final Safety Evaluation DAA Class 1+6 (GBSS and ATAR Correlated with noncooperative DWC) results.

4.9 DAA Class 1+6 (GBSS and ATAR Noncooperative)

This section discusses Scenarios 52-57. Only one noncooperative sensor is used in these scenarios—either ATAR or GBSS depending on the run. ATAR A1 is used for HALE, ATAR A2 is used for MALE, and ATAR A3 is used with LEPR. These scenario runs were performed with the uncorrelated encounters and noncooperative DWC volume. For these runs, only encounters with ownship altitudes up to FL100 are included in the analysis; encounters are filtered based on initial altitude. The DAA algorithm used in DAIDALUS. These scenarios are similar to the scenarios in Section 4.8 except they use uncorrelated encounters instead of correlated. The integrated delay is 5 seconds.

Figure 25 shows the risk ratios and loss of well clear ratios for Scenarios 46-51. The trends are similar to those in Section 4.8 in that the GBSS results are better than the ATAR results, and HALE performs better than MALE, which performs better than LEPR. However, the results using noncooperative sensors and noncooperative DWC are reasonably safe for uncorrelated encounters (the use case for which they were designed), with LoWC ratios well below 0.5 in most cases.

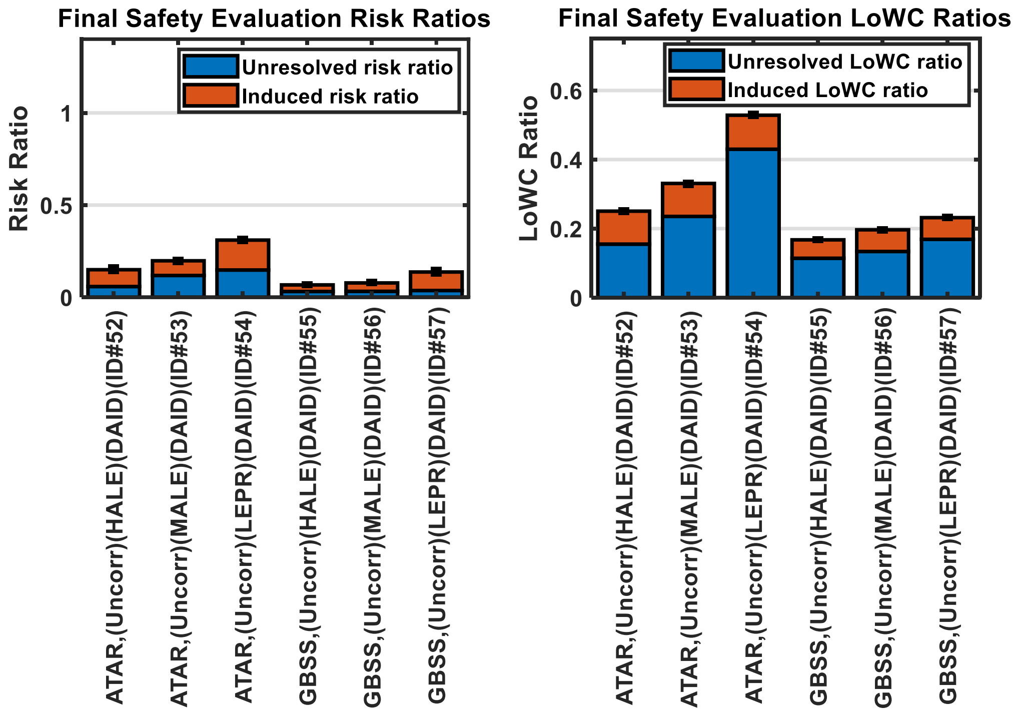

Figure 25. Final Safety Evaluation DAA Class 1+6 (GBSS and ATAR noncooperative) results.

Even though the same noncooperative DWC volume was used for both these scenarios and the scenarios in Section 4.8, the risk ratios are much lower than the correlated encounter set results in Section 4.8. This is likely because the noncooperative DWC is not suitable for the faster closing speeds in the correlated encounters. When using the smaller noncooperative DWC volume, DAIDALUS does not alert in time to avoid an NMAC with faster intruders. When used alone without ADS-B and/or AST, the noisier noncooperative sensors (ATAR and GBSS) are also less suited to detecting these faster intruders in time, and the measurement error has a larger impact as alerting range increases.

4.10 DAA Class 8 (GBSS Correlated with Noncooperative DWC)

This section discusses Scenarios 58-60. The sensor used in these scenarios was GBSS. Similar to the scenarios in Section 4.8, these scenario runs were performed with the correlated encounters and noncooperative DWC volume. The difference is that in these runs, the integrated delay is 3 seconds. For these runs, only encounters with ownship altitudes up to FL100 are included in the analysis; encounters are filtered based on initial altitude. The DAA algorithm used in DAIDALUS.

Figure 26 shows the risk ratios and loss of well clear ratios for Scenarios 58-60. As expected, the results are lower than the corresponding GBSS results from Section 4.8, which had a slightly longer integrated delay of 5 seconds.

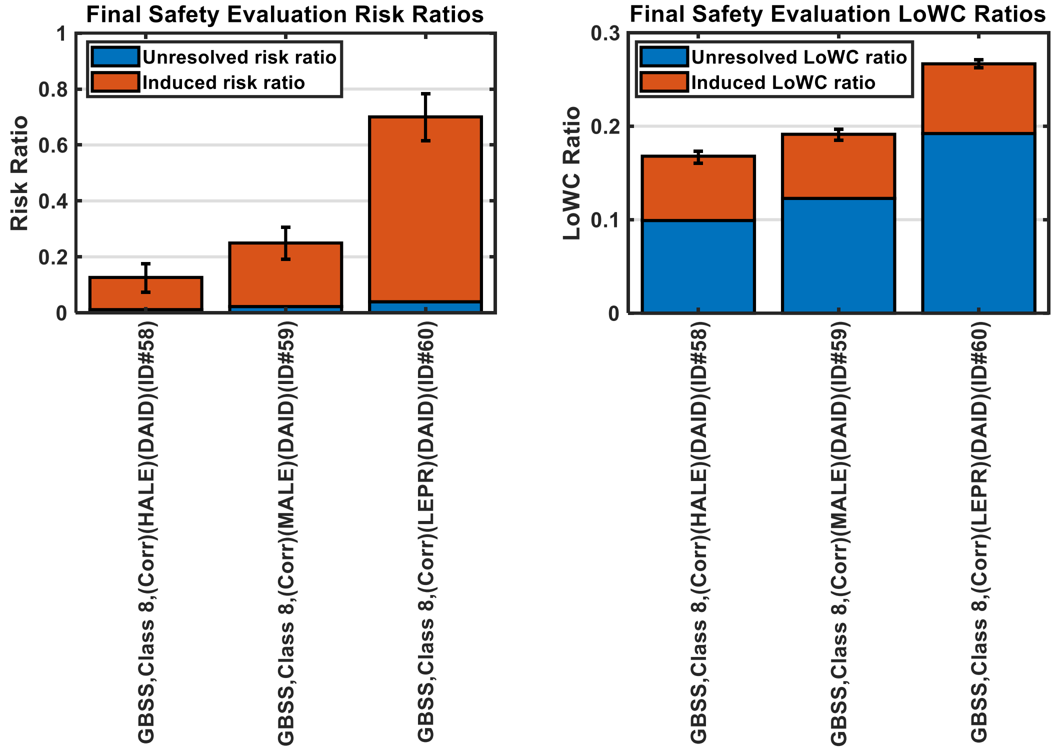

Figure 26. Final Safety Evaluation DAA Class 8 (GBSS Correlated with noncooperative DWC) results.

4.11 DAA Class 1+6+5 (GBSS Only Terminal)

This section discusses Scenarios 61-63. The sensor used in these scenarios was GBSS. These scenario runs were performed with the terminal encounters and terminal DWC volume. The purpose of these runs was to assess terminal DAA performance with DAIDALUS, when the only sensor is GBSS and the integrated delay is 5 seconds.

Figure 27 shows the risk ratios and loss of well clear ratios for Scenarios 61-63. As expected, these results using only GBSS are higher than the corresponding results with GBSS + AS (25ft) + ADS-B from Section 4.6.

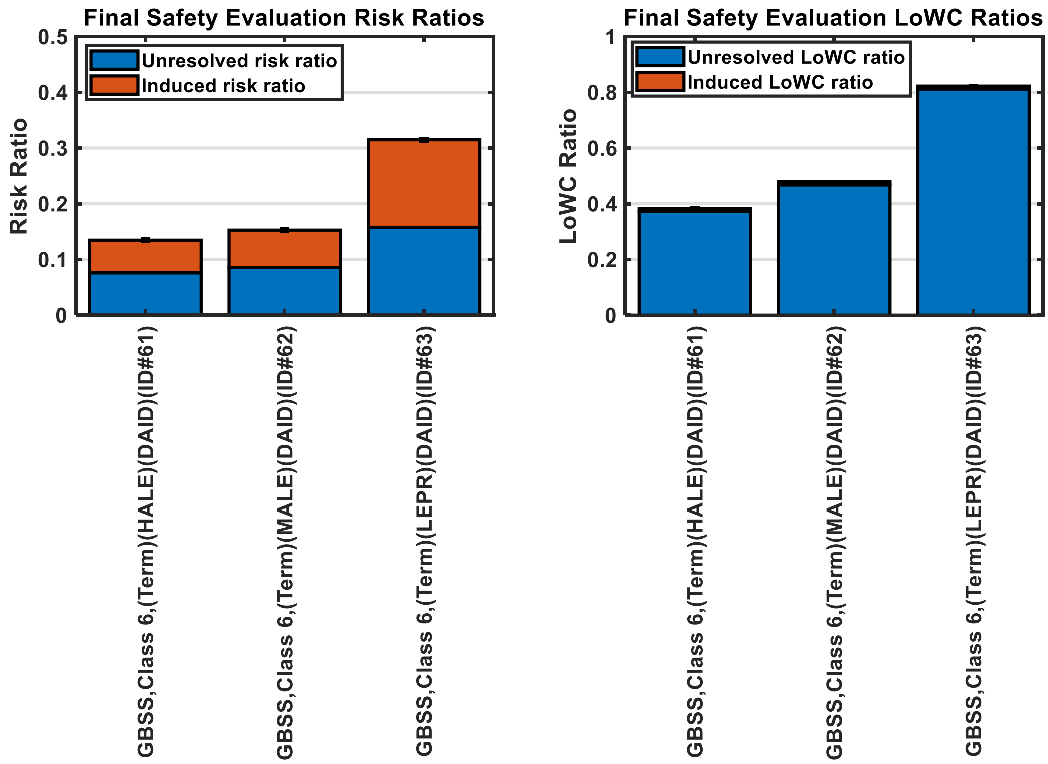

Figure 27. Final Safety Evaluation DAA Class 1+6+5 (GBSS Only Terminal) results.

4.12 DAA Class 8+5 (GBSS Only Terminal)

This section discusses Scenarios 64-66. The sensor used in these scenarios was GBSS. Similar to the scenarios in Section 4.11, these scenario runs were performed with the terminal encounters and terminal DWC volume. The difference is that in these runs, the integrated delay is 3 seconds. The purpose of these runs was to assess terminal DAA performance with DAIDALUS, when the only sensor is GBSS.

Figure 28 shows the risk ratios and loss of well clear ratios for Scenarios 64-66. As expected, the results are slightly lower than the results from Section 4.11, which had a slightly longer integrated delay of 5 seconds.

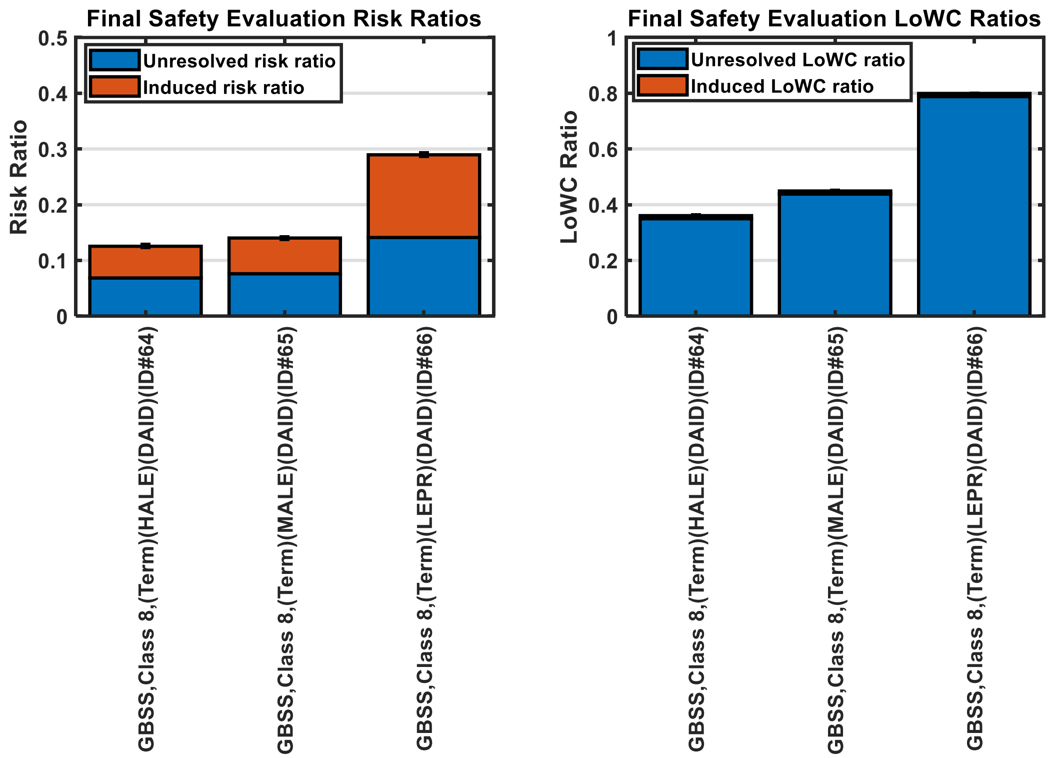

Figure 28. Final Safety Evaluation DAA Class 8+5 (GBSS Only Terminal) results.

4.13 Secondary Runs

This section describes the results from secondary final safety scenarios runs; these runs are not required for the final safety evaluation but are beneficial. Due to time and resources constraints, only Scenarios 73-75 (DAA Class 1+6 EO/IR Noncooperative) were evaluated; however, the other scenarios can be performed as future work as discussed in Section 5.

4.13.1 DAA Class 1+6 (EO/IR Noncooperative)

This section discusses Scenarios 73-75. The sensor used in these scenarios was EO/IR; thus, these runs were performed using Version 8.0 of the Phase II tracker—the only version that includes EO/IR. These scenario runs were performed with the terminal encounters and terminal DWC volume. The integrated delay is 3 seconds. The purpose of these runs was to assess en route DAA performance against noncooperative intruders using DAIDALUS and EO/IR as the only sensor. These results only include encounters with ownship altitudes up to 1200 ft.

Figure 29 shows the risk ratios and loss of well clear ratios for Scenarios 73-75. Contrary to the trends seen in the primary final safety evaluation runs (Sections 4.1-4.12), HALE performs worse than MALE, which performs worse than LEPR. This is because unlike the other sensors, EO/IR sensor noise is dependent on range and range rate. Because HALE encounters have the highest range rates, they also have the most noise. This noise results in a large number of encounters that have saturated DAIDALUS guidance. Furthermore, these results only include encounters with ownship altitudes up to 1200 ft; this threshold was specified by MITRE to align with ASTM DAA performance standards for smaller UAS flying in "lower risk" airspace, which is typically defined as below 1200 ft AGL in Class G and E airspace [16]. At lower altitudes, there are fewer options for the aircraft to maneuver—e.g., some of the descend guidance options (issued in 500 ft intervals) may not be available when the ownship is so close to the ground. Thus, the HALE's larger vertical rate is less advantageous at these altitudes.

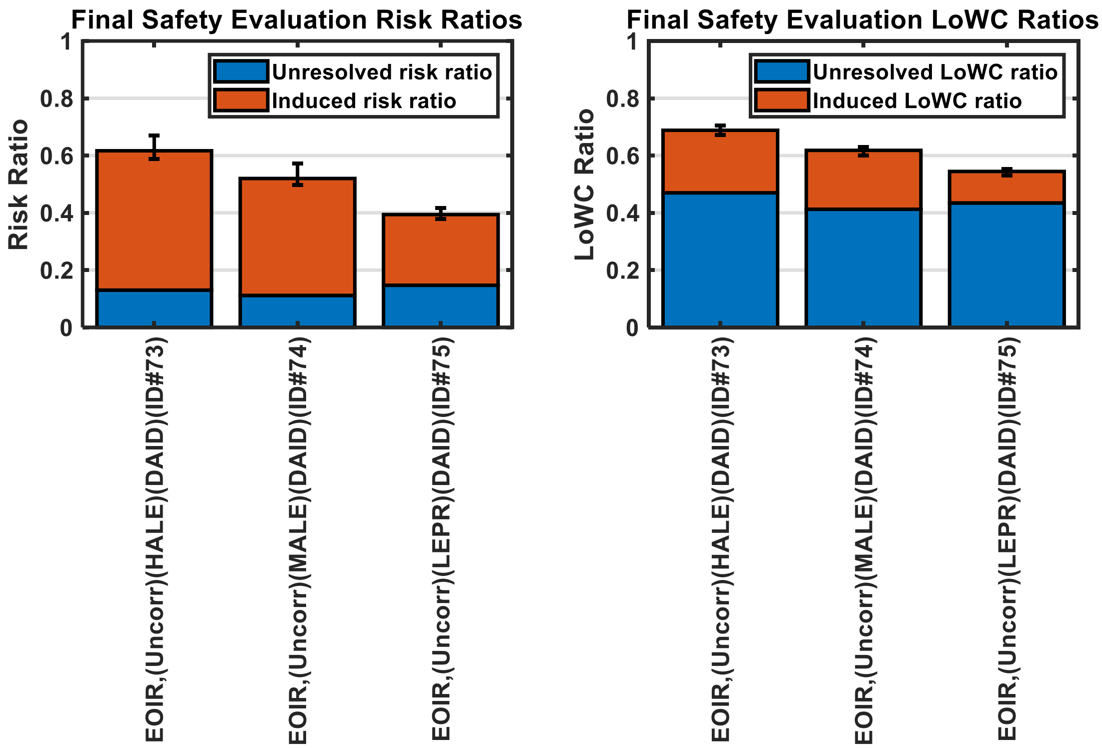

Figure 29. Final Safety Evaluation DAA Class 1+6 (EO/IR Noncooperative) results (up to 1200 ft).

Figure 30 shows the risk ratios and loss of well clear ratios for Scenarios 73-75 for encounters at all altitudes with encounters that have both saturated vertical guidance and saturated horizontal guidance filtered out. With this filtering applied, the trend in the risk ratio matches what was seen in the primary scenarios, with HALE performing best, followed by MALE, followed by LEPR. This confirms that the poor HALE performance was caused by saturated guidance due to noisier EO/IR errors, which were caused by faster range rates. Including all altitudes also aids in very slightly reducing the risk ratio, confirming that HALE performs slightly worse at lower altitudes due to having fewer DAIDALUS maneuver options. (Although MALE and LEPR have similarly constrained maneuver options, HALE is most affected by the loss of these additional maneuver options because it has the highest vertical rates and is best able to take advantage of vertical maneuvers.)

In Section 4.9, the uncorrelated encounters were simulated with the ATAR and GBSS noncooperative sensors. The EO/IR risk ratios in Figure 30 are in the same range as the ones simulated with GBSS in Section 4.9, and are lower than the ones that were simulated with ATAR. However, the LoWC ratios in Figure 30 are generally higher than the ones in Section 4.9 for both GBSS and ATAR.

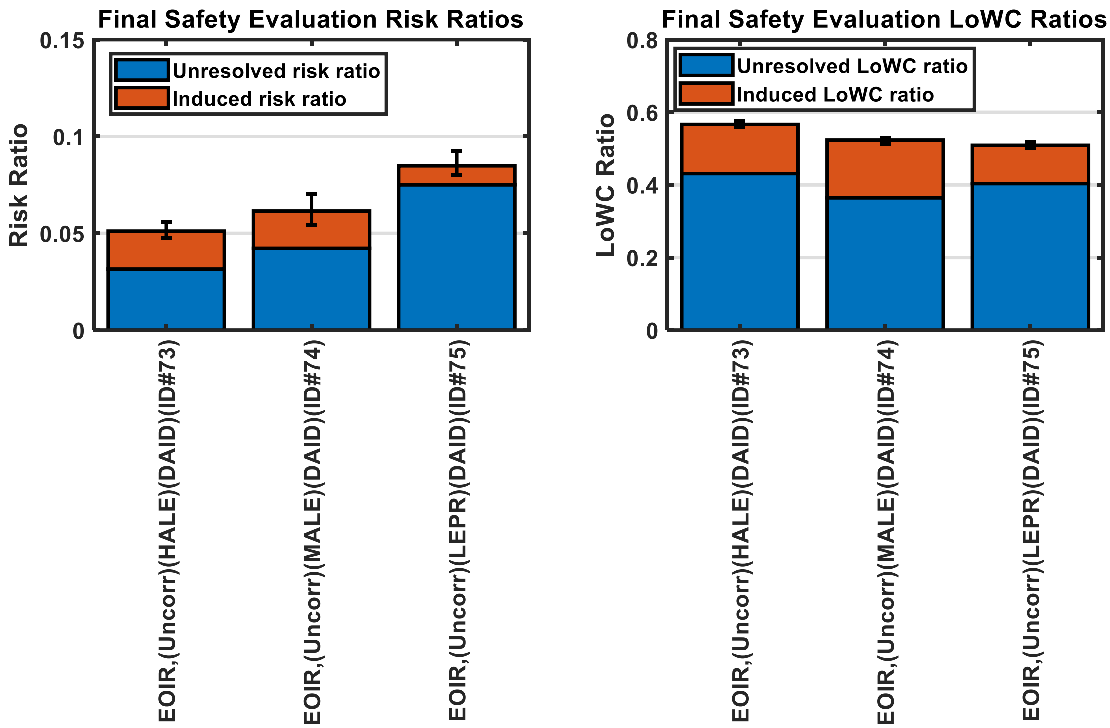

Figure 30. Final Safety Evaluation DAA Class 1+6 (EO/IR Noncooperative) results (all altitudes with saturation filtering).

5 FUTURE WORK

Due to time and resource constraints, secondary scenarios 67-72 and 76-78 of the final safety evaluation were not performed as part of this SRMD analysis. However, these scenarios (discussed below) may be performed as future work. In addition, the issues with ATAR in the Version 7.5.1 tracker should be addressed. Finally, additional analysis could be performed to fully understand the impact of the DAIDALUS SUM algorithm.

5.1.1 UAS 2+6 (TCAS RA Logic Enabled on Intruder)

Scenarios 67-72 are similar to the ones in Section 4.3 and Section 4.4 in that the sensors used would be AST, ADS-B, and either ATAR or GBSS. These scenario runs would be performed with the correlated encounters and en route DWC volume; and the integrated delay would be 5 seconds. The difference between these scenarios and the ones in Section 4.3 and Section 4.4 is that the intruder would respond to TCAS RA logic. The purpose of these runs would be to assess en route DAA performance with DAIDALUS with TCAS RA logic and GBSS/ATAR. However, note that DAIDALUS v.2.0.2 does not fully implement requirements for modification of DAA guidance based on intruder TCAS/ACAS X RA capability and information. Thus, scenarios run with DAIDALUS and intruder TCAS RAs would not be consistent with the requirements. Future runs that evaluate intruder TCAS RAs should be performed with an updated version of DAIDALUS that does consider these requirements.

5.1.2 DAA Class 1/2+6 in Class A Airspace (TCAS RA Logic on Intruder)

Scenarios 76-77 uses AST, ADS-B, and ATAR A1. These scenario runs would be performed with the correlated Class A encounters (i.e., encounters with altitude from FL180 to FL600), the en route DWC volume, and HALE UAS platform. The integrated delay would be 5 seconds. In both of these scenarios, the intruder would respond to TCAS RA logic. The purpose of these runs would be to assess en route DAA performance with DAIDALUS and ATAR in Class A airspace. However, note the caveat in Section 5.1.1 regarding simulating intruder TCAS RAs with DAIDALUS v.2.0.2.

5.1.3 DAA Class 3 (ACAS Xu and TCAS RA Logic on Intruder)

Scenario 78 is a secondary scenario where the DAA logic is ACAS Xu. The sensors used in this scenario would be AST, ATAR B, and ADS-B. This scenario would be performed with correlated encounters, the en route DWC volume, and HALE UAS platform. The integrated delay would be 4 seconds, and the intruder would respond to TCAS RA logic. The purpose of this scenario would be to compare the performance with ACAS Xu to the performance with DAIDALUS. (The corresponding scenario with DAIDALUS is Scenario 67 from Section 5.1.1.) In order to perform this scenario, ACAS Xu would need to be integrated into the DEGAS simulation.

5.1.4 Tracker Issues

Due to issues with how the integrated Phase II tracker (Version 7.5.1) processes ATAR data, the Phase I tracker was used for all final safety evaluation runs with ATAR. One issue is that when ATAR is used in a multi-sensor setup, the track is more inaccurate than the sensor data alone, which is unexpected behavior since the tracker is expected to perform smoothing. Another issue is that the tracker has a tendency to continue to select ATAR as the best sensor source even when the ATAR does not produce valid data (e.g., when the intruder is outside the field of regard). When this happens, DAIDALUS can issue guidance based on coasted tracks, which can lead to unexpected behavior and NMACs. Future work would involve further investigation into these issues, debugging, and potential coordination with ARCON who created the tracker.

In addition, the Phase I tracker exhibited some oddities in processing multi-sensor data. For Final Safety Evaluation Scenarios 1-9, the tracker estimated rates were worse for ATAR+AST+ADS-B (100 ft altitude quantization) than for ATAR+AST only. The altitude quantization (100 ft vs. 25 ft) also had a larger impact in the ATAR+AST+ADS-B results compared to when ADS-B was run by itself. This increase in jitter when ADS-B is run with multiple sensors is another issue that should be explored as future work.

Despite these issues, the data generated in this report can be trusted for a safety assessment because the issues with the Phase II tracker were mitigated by using the Phase I tracker; additionally, the increase in jitter when ADS-B is run with multiple sensors when using the Phase I tracker is unexpected, but not unrealistic for a worst-case assessment. However, if changes are made to the trackers in the future, a small set of final safety evaluation scenarios could be rerun to confirm that the difference in the results is slight.

5.1.5 DAIDALUS SUM

Some of the scenarios in the final safety evaluation had high ratios. In addition to the reasons discussed in Section 4, another reason for these high risk ratios could be that the FAA Tracker's vertical state error estimate is lower than what is expected in the DAIDALUS SUM algorithm. Future work could involve tuning the parameters in SUM to see if that makes a difference on the results. In addition, the baseline results in Section 3.1 were performed using ADS-B only, and show little difference between scenarios run with and without SUM. Future work could involve rerunning the baseline results with ATAR only or GBSS only to determine if SUM or no SUM works better for noncooperative intruders detected by these noncooperative sensors.

6 SUMMARY

Three main analyses were performed to support the FAA's detect-and-avoid (DAA) Safety Risk Management Document (SRMD) and Technical Standard Order (TSO) applicable to RTCA SC-228 Phase 2 (DO-365B): an integrated delay and C2 interruption sensitivity analysis in the terminal environment, a Ground Based Surveillance System (GBSS) sensor accuracy sensitivity analysis in the en route environment, and a comprehensive final safety analysis to provide data for the SRMD and TSO. The C2 sensitivity analysis affirmed that the 3-second C2 interruption requirement in the C2 MASPS is acceptable for the DAA function. The GBSS sensitivity analysis indicated that the accuracy requirements in DO-365B result in reasonable risk ratios. Lastly, the final safety runs provided key DAA performance information that will feed into the final safety evaluation to support the TSO and SRM. The results from the final safety evaluation generally matched expectations. For example, the HALE platform generally achieved the lowest risk ratios, followed by the MALE platform, which is then followed by the LEPR platform. For the correlated encounters, the GBSS and ATAR noncooperative sensors achieved similar performance. In the future, additional safety analysis runs could be performed to analyze the impact of having the intruder respond the TCAS RAs. In addition, issues that were identified with the tracker's multi-sensor performance should be investigated.

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APPENDIX A FINAL SAFETY ANALYSIS RUN MATRIX SCENARIOS

Table 35 of this appendix documents the complete set of scenarios that were evaluated to support the final safety evaluation. Note that all primary runs were executed, and the results are discussed in Section 4. Of the secondary runs, only Scenarios 73-75 were executed. These scenarios used EO/IR as the noncooperative sensor, and the results are discussed in Section 4.13. The other secondary scenarios may be executed as future work as discussed in Section 5.

The following assumptions were made when developing the scenarios in Table 35:

1. Runs with Class 7 are eliminated because Class 6 is more stressing from a latency perspective (Class 7 only requires two C2 exchanges whereas Class 6 requires three).
2. Runs with only Class 1 or only Class 2 are eliminated because these are a subset of Class 1+6 and 2+6. (From a simulation point of view, Class 6 functionally just allows the inclusion of the GBSS sensor).
3. ATAR is not used with Class 5, 6, 7, and 8. (Noncooperative sensor is GBSS or EO/IR only. ATAR is assumed inoperative at low terminal altitudes.)
4. Some Class 8 (Correlated Model, En route DWC) simulations are not needed as they are subsets of Class 1+6 For example, a Class 8 UAS equipped with GBSS and ADS-B operating in the en route environment with DAIDALUS is technically also Class 1+6.
5. Some Class 8+5 (Terminal Model, Terminal DWC) simulations are not needed as they are subsets of Class 1+6+5.
6. Class 2+6+5 is not needed as TCAS is disabled by either altitude inhibit or terminal area inhibit (i.e., the system reverts to Class 1+6+5, per DO-365B Section 2.2.4.1).
7. Class 8 has GBSS and ADS-B only, no AST (per Table 2-1 in DO-365B)
8. Class 3 is limited to HALE.
9. Class A is limited to HALE
10. ATAR A1 is equipped on HALE aircraft, ATAR A2 is equipped on MALE aircraft, and ATAR A3 is equipped on LEPR aircraft.
11. All sensor fail (nil) simulation runs are not counted here as these are baseline unmitigated simulations.
12. It is assumed that there is only one noncooperative sensor (ATAR, GBSS, EO/IR, etc.) working at a time as this is the most stressing case.
13. ATAR is assumed to be inoperative below 2000 ft AGL (it will ultimately depend on the specific radar).
14. Since the difference between ADS-B Mode C (100) and ADS-B Mode S (25) results is negligible (see Section 3.1), Mode S (25) is assumed for runs where the intruder is equipped with ADS-B, unless the transponder is otherwise specified (e.g., by the active surveillance).

The following legend corresponds to the priority of each of the scenarios in Table 35:

	Required		Secondary (Nice to Have)

Table 35. Scenarios (Run Matrix).

				DAA Logic Ownship	DAA Logic Intruder	UA Platform	Surveillance				WC Criteria (DWC)	Encounter Model	
Scenario Name (Section #)	Simulation ID	DAA Class	C2 Exchanges (Latency)	>RWC >TCAS >ACAS	>None >TCAS	>HALE >MALE >LEPR	UAS Active Sensors	UA Noncooperative Sensor	Intruder Sensors	Sensors Providing Information to Tracker	>Terminal >Noncooperative >En route	>Correlated >Uncorrelated >Terminal	Altitude Band
DAA Class 1+6 ATAR Combined (Section 4.1)	1	Class 1+6	3 (5 sec)	RWC	None	HALE	AST + ADS-B	ATAR A1	AST (100 ft)	ATAR A1 + AST (100 ft)	En route	Correlated	1,200 ft AGL to FL180
	2	Class 1+6	3 (5 sec)	RWC	None	HALE	AST + ADS-B	ATAR A1	AST (100 ft) + ADS-B	ATAR A1 + AST (100 ft) + ADS-B	En route	Correlated	1,200 ft AGL to FL180
	3	Class 1+6	3 (5 sec)	RWC	None	HALE	AST + ADS-B	ATAR A1	AST (25 ft) + ADS-B	ATAR A1 + AST (25 ft) + ADS-B	En route	Correlated	1,200 ft AGL to FL180
	4	Class 1+6	3 (5 sec)	RWC	None	MALE	AST + ADS-B	ATAR A2	AST (100 ft)	ATAR A2 + AST (100 ft)	En route	Correlated	1,200 ft AGL to FL180
	5	Class 1+6	3 (5 sec)	RWC	None	MALE	AST + ADS-B	ATAR A2	AST (100 ft) + ADS-B	ATAR A2 + AST (100 ft) + ADS-B	En route	Correlated	1,200 ft AGL to FL180
	6	Class 1+6	3 (5 sec)	RWC	None	MALE	AST + ADS-B	ATAR A2	AST (25 ft) + ADS-B	ATAR A2 + AST (25 ft) + ADS-B	En route	Correlated	1,200 ft AGL to FL180
	7	Class 1+6	3 (5 sec)	RWC	None	LEPR	AST + ADS-B	ATAR A3	AST (100 ft)	ATAR A3 + AST (100 ft)	En route	Correlated	1,200 ft AGL to FL180
	8	Class 1+6	3 (5 sec)	RWC	None	LEPR	AST + ADS-B	ATAR A3	AST (100 ft) + ADS-B	ATAR A3 + AST (100 ft) + ADS-B	En route	Correlated	1,200 ft AGL to FL180
	9	Class 1+6	3 (5 sec)	RWC	None	LEPR	AST + ADS-B	ATAR A3	AST (25 ft) + ADS-B	ATAR A3 + AST (25 ft) + ADS-B	En route	Correlated	1,200 ft AGL to FL180
DAA Class 1+6 GBSS Combined (Section 4.2)	10	Class 1+6	3 (5 sec)	RWC	None	HALE	AST + ADS-B	GBSS	AST (100 ft)	GBSS + AST (100 ft)	En route	Correlated	1,200 ft AGL to FL180
	11	Class 1+6	3 (5 sec)	RWC	None	HALE	AST + ADS-B	GBSS	AST (100 ft) + ADS-B	GBSS + AST (100 ft) + ADS-B	En route	Correlated	1,200 ft AGL to FL180
	12	Class 1+6	3 (5 sec)	RWC	None	HALE	AST + ADS-B	GBSS	AST (25 ft) + ADS-B	GBSS + AST (25 ft) + ADS-B	En route	Correlated	1,200 ft AGL to FL180
	13	Class 1+6	3 (5 sec)	RWC	None	MALE	AST + ADS-B	GBSS	AST (100 ft)	GBSS + AST (100 ft)	En route	Correlated	1,200 ft AGL to FL180
	14	Class 1+6	3 (5 sec)	RWC	None	MALE	AST + ADS-B	GBSS	AST (100 ft) + ADS-B	GBSS + AST (100 ft) + ADS-B	En route	Correlated	1,200 ft AGL to FL180
	15	Class 1+6	3 (5 sec)	RWC	None	MALE	AST + ADS-B	GBSS	AST (25 ft) + ADS-B	GBSS + AST (25 ft) + ADS-B	En route	Correlated	1,200 ft AGL to FL180
	16	Class 1+6	3 (5 sec)	RWC	None	LEPR	AST + ADS-B	GBSS	AST (100 ft)	GBSS + AST (100 ft)	En route	Correlated	1,200 ft AGL to FL180
	17	Class 1+6	3 (5 sec)	RWC	None	LEPR	AST + ADS-B	GBSS	AST (100 ft) + ADS-B	GBSS + AST (100 ft) + ADS-B	En route	Correlated	1,200 ft AGL to FL180
	18	Class 1+6	3 (5 sec)	RWC	None	LEPR	AST + ADS-B	GBSS	AST (25 ft) + ADS-B	GBSS + AST (25 ft) + ADS-B	En route	Correlated	1,200 ft AGL to FL180

				DAA Logic Ownship	DAA Logic Intruder	UA Platform	Surveillance				WC Criteria (DWC)	Encounter Model	
Scenario Name (Section #)	Simulation ID	DAA Class	C2 Exchanges (Latency)	>RWC >TCAS >ACAS	>None >TCAS	>HALE >MALE >LEPR	UAS Active Sensors	UA Noncooperative Sensor	Intruder Sensors	Sensors Providing Information to Tracker	>Terminal >Noncooperative >En route	>Correlated >Uncorrelated >Terminal	Altitude Band
DAA Class 2+6 ATAR Combined (Section 4.3)	19	Class 2+6	3 (5 sec)	RWC/ TCAS	None	HALE	AST + ADS-B + TCAS	ATAR A1	AST (100 ft)	ATAR A1 + AST (100 ft)	En route	Correlated	1,200 ft AGL to FL180
	20	Class 2+6	3 (5 sec)	RWC/ TCAS	None	HALE	AST + ADS-B + TCAS	ATAR A1	AST (100 ft) + ADS-B	ATAR A1 + AST (100 ft) + ADS-B	En route	Correlated	1,200 ft AGL to FL180
	21	Class 2+6	3 (5 sec)	RWC/ TCAS	None	MALE	AST + ADS-B + TCAS	ATAR A2	AST (100 ft)	ATAR A2 + AST (100 ft)	En route	Correlated	1,200 ft AGL to FL180
	22	Class 2+6	3 (5 sec)	RWC/ TCAS	None	MALE	AST + ADS-B + TCAS	ATAR A2	AST (100 ft) + ADS-B	ATAR A2 + AST (100 ft) + ADS-B	En route	Correlated	1,200 ft AGL to FL180
	23	Class 2+6	3 (5 sec)	RWC/ TCAS	None	LEPR	AST + ADS-B + TCAS	ATAR A3	AST (100 ft)	ATAR A3 + AST (100 ft)	En route	Correlated	1,200 ft AGL to FL180
	24	Class 2+6	3 (5 sec)	RWC/ TCAS	None	LEPR	AST + ADS-B + TCAS	ATAR A3	AST (100 ft) + ADS-B	ATAR A3 + AST (100 ft) + ADS-B	En route	Correlated	1,200 ft AGL to FL180
DAA Class 2+6 GBSS Combined (Section 4.4)	25	Class 2+6	3 (5 sec)	RWC/ TCAS	None	HALE	AST + ADS-B + TCAS	GBSS	AST (100 ft)	GBSS + AST (100 ft)	En route	Correlated	1,200 ft AGL to FL180
	26	Class 2+6	3 (5 sec)	RWC/ TCAS	None	HALE	AST + ADS-B + TCAS	GBSS	AST (100 ft) + ADS-B	GBSS + AST (100 ft) + ADS-B	En route	Correlated	1,200 ft AGL to FL180
	27	Class 2+6	3 (5 sec)	RWC/ TCAS	None	MALE	AST + ADS-B + TCAS	GBSS	AST (100 ft)	GBSS + AST (100 ft)	En route	Correlated	1,200 ft AGL to FL180
	28	Class 2+6	3 (5 sec)	RWC/ TCAS	None	MALE	AST + ADS-B + TCAS	GBSS	AST (100 ft) + ADS-B	GBSS + AST (100 ft) + ADS-B	En route	Correlated	1,200 ft AGL to FL180
	29	Class 2+6	3 (5 sec)	RWC/ TCAS	None	LEPR	AST + ADS-B + TCAS	GBSS	AST (100 ft)	GBSS + AST (100 ft)	En route	Correlated	1,200 ft AGL to FL180
	30	Class 2+6	3 (5 sec)	RWC/ TCAS	None	LEPR	AST + ADS-B + TCAS	GBSS	AST (100 ft) + ADS-B	GBSS + AST (100 ft) + ADS-B	En route	Correlated	1,200 ft AGL to FL180
DAA Class 8 GBSS Combined (Section 4.5)	31	Class 8	1 (3 sec)	RWC	None	HALE	ADS-B	GBSS	ADS-B	GBSS + ADS-B	En route	Correlated	1,200 ft AGL to FL180
	32	Class 8	1 (3 sec)	RWC	None	MALE	ADS-B	GBSS	ADS-B	GBSS + ADS-B	En route	Correlated	1,200 ft AGL to FL180
	33	Class 8	1 (3 sec)	RWC	None	LEPR	ADS-B	GBSS	ADS-B	GBSS + ADS-B	En route	Correlated	1,200 ft AGL to FL180
DAA Class 1+6+5 GBSS Combined Terminal (Section 4.6)	34	Class 1+6+5	3 (5 sec)	RWC	None	HALE	AST + ADS-B	GBSS	AST (100 ft)	GBSS + AST (100 ft)	Terminal	Terminal	SFC to 5000 ft AGL
	35	Class 1+6+5	3 (5 sec)	RWC	None	HALE	AST + ADS-B	GBSS	AST (100 ft) + ADS-B	GBSS + AST (100 ft) + ADS-B	Terminal	Terminal	SFC to 5000 ft AGL
	36	Class 1+6+5	3 (5 sec)	RWC	None	HALE	AST + ADS-B	GBSS	AST (100 ft)	GBSS + AST (25 ft) + ADS-B	Terminal	Terminal	SFC to 5000 ft AGL
	37	Class 1+6+5	3 (5 sec)	RWC	None	MALE	AST + ADS-B	GBSS	AST (100 ft)	GBSS + AST (100 ft)	Terminal	Terminal	SFC to 5000 ft AGL

				DAA Logic Ownship	DAA Logic Intruder	UA Platform	Surveillance				WC Criteria (DWC)	Encounter Model	
Scenario Name (Section #)	**Simulation ID**	**DAA Class**	**C2 Exchanges (Latency)**	**>RWC >TCAS >ACAS**	**>None >TCAS**	**>HALE >MALE >LEPR**	**UAS Active Sensors**	**UA Noncooperative Sensor**	**Intruder Sensors**	**Sensors Providing Information to Tracker**	**>Terminal >Noncooperative >En route**	**>Correlated >Uncorrelated >Terminal**	**Altitude Band**
	38	Class 1+6+5	3 (5 sec)	RWC	None	MALE	AST + ADS-B	GBSS	AST (100 ft) + ADS-B	GBSS + AST (100 ft) + ADS-B	Terminal	Terminal	SFC to 5000 ft AGL
	39	Class 1+6+5	3 (5 sec)	RWC	None	MALE	AST + ADS-B	GBSS	AST (100 ft)	GBSS + AST (25 ft) + ADS-B	Terminal	Terminal	SFC to 5000 ft AGL
	40	Class 1+6+5	3 (5 sec)	RWC	None	LEPR	AST + ADS-B	GBSS	AST (100 ft)	GBSS + AST (100 ft)	Terminal	Terminal	SFC to 5000 ft AGL
	41	Class 1+6+5	3 (5 sec)	RWC	None	LEPR	AST + ADS-B	GBSS	AST (100 ft) + ADS-B	GBSS + AST (100 ft) + ADS-B	Terminal	Terminal	SFC to 5000 ft AGL
	42	Class 1+6+5	3 (5 sec)	RWC	None	LEPR	AST + ADS-B	GBSS	AST (100 ft)	GBSS + AST (25 ft) + ADS-B	Terminal	Terminal	SFC to 5000 ft AGL
Class 8+5 GBSS Combined Terminal (Section 4.7)	43	Class 8+5	1 (3 sec)	RWC	None	HALE	ADS-B	GBSS	ADS-B	GBSS + ADS-B	Terminal	Terminal	SFC to 5000 ft AGL
	44	Class 8+5	1 (3 sec)	RWC	None	MALE	ADS-B	GBSS	ADS-B	GBSS + ADS-B	Terminal	Terminal	SFC to 5000 ft AGL
	45	Class 8+5	1 (3 sec)	RWC	None	LEPR	ADS-B	GBSS	ADS-B	GBSS + ADS-B	Terminal	Terminal	SFC to 5000 ft AGL
DAA Class 1+6 GBSS and ATAR Correlated with **Noncoop DWC** (Section 4.8)	46	Class 1+6	3 (5 sec)	RWC	None	HALE	AST + ADS-B	ATAR A1	None	ATAR A1	Noncooperative	Correlated	SFC to 10000 ft AGL
	47	Class 1+6	3 (5 sec)	RWC	None	MALE	AST + ADS-B	ATAR A2	None	ATAR A2	Noncooperative	Correlated	SFC to 10000 ft AGL
	48	Class 1+6	3 (5 sec)	RWC	None	LEPR	AST + ADS-B	ATAR A3	None	ATAR A3	Noncooperative	Correlated	SFC to 10000 ft AGL
	49	Class 1+6	3 (5 sec)	RWC	None	HALE	AST + ADS-B	GBSS	None	GBSS	Noncooperative	Correlated	SFC to 10000 ft AGL
	50	Class 1+6	3 (5 sec)	RWC	None	MALE	AST + ADS-B	GBSS	None	GBSS	Noncooperative	Correlated	SFC to 10000 ft AGL
	51	Class 1+6	3 (5 sec)	RWC	None	LEPR	AST + ADS-B	GBSS	None	GBSS	Noncooperative	Correlated	SFC to 10000 ft AGL
DAA Class 1+6 GBSS and ATAR Noncoop (Section 4.9)	52	Class 1+6	3 (5 sec)	RWC	None	HALE	AST + ADS-B	ATAR A1	None	ATAR A1	Noncooperative	Uncorrelated	SFC to 10000 ft AGL
	53	Class 1+6	3 (5 sec)	RWC	None	MALE	AST + ADS-B	ATAR A2	None	ATAR A2	Noncooperative	Uncorrelated	SFC to 10000 ft AGL
	54	Class 1+6	3 (5 sec)	RWC	None	LEPR	AST + ADS-B	ATAR A3	None	ATAR A3	Noncooperative	Uncorrelated	SFC to 10000 ft AGL
	55	Class 1+6	3 (5 sec)	RWC	None	HALE	AST + ADS-B	GBSS	None	GBSS	Noncooperative	Uncorrelated	SFC to 10000 ft AGL

				DAA Logic Ownship	DAA Logic Intruder	UA Platform	Surveillance				WC Criteria (DWC)	Encounter Model	
Scenario Name (Section #)	**Simulation ID**	**DAA Class**	**C2 Exchanges (Latency)**	**>RWC >TCAS >ACAS**	**>None >TCAS**	**>HALE >MALE >LEPR**	**UAS Active Sensors**	**UA Noncooperative Sensor**	**Intruder Sensors**	**Sensors Providing Information to Tracker**	**>Terminal >Noncooperative >En route**	**>Correlated >Uncorrelated >Terminal**	**Altitude Band**
	56	Class 1+6	3 (5 sec)	RWC	None	MALE	AST + ADS-B	GBSS	None	GBSS	Noncooperative	Uncorrelated	SFC to 10000 ft AGL
	57	Class 1+6	3 (5 sec)	RWC	None	LEPR	AST + ADS-B	GBSS	None	GBSS	Noncooperative	Uncorrelated	SFC to 10000 ft AGL
DAA Class 8 Correlated with **Noncoop DWC** (Section 4.10)	58	Class 8	1 (3 sec)	RWC	None	HALE	ADS-B	GBSS	None	GBSS	Noncooperative	Correlated	SFC to 10000 ft AGL
	59	Class 8	1 (3 sec)	RWC	None	MALE	ADS-B	GBSS	None	GBSS	Noncooperative	Correlated	SFC to 10000 ft AGL
	60	Class 8	1 (3 sec)	RWC	None	LEPR	ADS-B	GBSS	None	GBSS	Noncooperative	Correlated	SFC to 10000 ft AGL
DAA Class 1+6+5 GBSS Only Terminal (Section 4.11)	61	Class 1+6+5	3 (5 sec)	RWC	None	HALE	AST + ADS-B	GBSS	None	GBSS	Terminal	Terminal	SFC to 5000 ft AGL
	62	Class 1+6+5	3 (5 sec)	RWC	None	MALE	AST + ADS-B	GBSS	None	GBSS	Terminal	Terminal	SFC to 5000 ft AGL
	63	Class 1+6+5	3 (5 sec)	RWC	None	LEPR	AST + ADS-B	GBSS	None	GBSS	Terminal	Terminal	SFC to 5000 ft AGL
DAA Class 8+5 GBSS Only Terminal (Section 4.12)	64	Class 8+5	1 (3 sec)	RWC	None	HALE	ADS-B	GBSS	None	GBSS	Terminal	Terminal	SFC to 5000 ft AGL
	65	Class 8+5	1 (3 sec)	RWC	None	MALE	ADS-B	GBSS	None	GBSS	Terminal	Terminal	SFC to 5000 ft AGL
	66	Class 8+5	1 (3 sec)	RWC	None	LEPR	ADS-B	GBSS	None	GBSS	Terminal	Terminal	SFC to 5000 ft AGL
DAA Class 2+6 TCAS RA Logic Enabled on Intruder (Section 5.1.1)	67	Class 2+6	3 (5 sec)	RWC/ TCAS	TCAS	HALE	AST + ADS-B + TCAS	ATAR A1	AST (25 ft) + ADS-B + TCAS	ATAR A1 + AST (25 ft) + ADS-B	En route	Correlated	1,200 ft AGL to FL180
	68	Class 2+6	3 (5 sec)	RWC/ TCAS	TCAS	MALE	AST + ADS-B + TCAS	ATAR A2	AST (25 ft) + ADS-B + TCAS	ATAR A2 + AST (25 ft) + ADS-B	En route	Correlated	1,200 ft AGL to FL180
	69	Class 2+6	3 (5 sec)	RWC/ TCAS	TCAS	LEPR	AST + ADS-B + TCAS	ATAR A3	AST (25 ft) + ADS-B + TCAS	ATAR A3 + AST (25 ft) + ADS-B	En route	Correlated	1,200 ft AGL to FL180
	70	Class 2+6	3 (5 sec)	RWC/ TCAS	TCAS	HALE	AST + ADS-B + TCAS	GBSS	AST (25 ft) + ADS-B + TCAS	GBSS + AST (25 ft) + ADS-B	En route	Correlated	1,200 ft AGL to FL180

				DAA Logic Ownship	DAA Logic Intruder	UA Platform	Surveillance				WC Criteria (DWC)	Encounter Model	
Scenario Name (Section #)	**Simulation ID**	**DAA Class**	**C2 Exchanges (Latency)**	**>RWC >TCAS >ACAS**	**>None >TCAS**	**>HALE >MALE >LEPR**	**UAS Active Sensors**	**UA Noncooperative Sensor**	**Intruder Sensors**	**Sensors Providing Information to Tracker**	**>Terminal >Noncooperative >En route**	**>Correlated >Uncorrelated >Terminal**	**Altitude Band**
	71	Class 2+6	3 (5 sec)	RWC/ TCAS	TCAS	MALE	AST + ADS-B + TCAS	GBSS	AST (25 ft) + ADS-B + TCAS	GBSS + AST (25 ft) + ADS-B	En route	Correlated	1,200 ft AGL to FL180
	72	Class 2+6	3 (5 sec)	RWC/ TCAS	TCAS	LEPR	AST + ADS-B + TCAS	GBSS	AST (25 ft) + ADS-B + TCAS	GBSS + AST (25 ft) + ADS-B	En route	Correlated	1,200 ft AGL to FL180
DAA Class 1+6 EO/IR Noncoop (Section 4.13.1)	73	Class 1+6	3 (5 sec)	RWC	None	HALE	AST + ADS-B	EO/IR	None	EO/IR	Noncooperative	Uncorrelated	SFC to 1,200 ft AGL
	74	Class 1+6	3 (5 sec)	RWC	None	MALE	AST + ADS-B	EO/IR	None	EO/IR	Noncooperative	Uncorrelated	SFC to 1,200 ft AGL
	75	Class 1+6	3 (5 sec)	RWC	None	LEPR	AST + ADS-B	EO/IR	None	EO/IR	Noncooperative	Uncorrelated	SFC to 1,200 ft AGL
DAA Class 1/2+6 in Class A Airspace (TCAS Logic on Intruder) (Section 5.1.2)	76	Class 1+6	3 (5 sec)	RWC	TCAS	HALE	AST + ADS-B	ATAR A1	AST (100 ft) + ADS-B + TCAS	ATAR A1 + AST (100 ft) + ADS-B	En route	Correlated	FL180 to FL600
	77	Class 2+6	3 (5 sec)	RWC/ TCAS	TCAS	HALE	AST + ADS-B + TCAS	ATAR A1	AST (25 ft) + ADS-B + TCAS	ATAR A1 + AST (25 ft) + ADS-B	En route	Correlated	FL180 to FL600
DAA Class 3 ATAR (TCAS Logic on Intruder) (Section 5.1.3)	78	Class 3	2 (4 sec)	ACAS	TCAS	HALE	AST + ADS-B	ATAR B	AST (25 ft) + ADS-B + TCAS	ATAR B + AST (25 ft) + ADS-B	En route	Correlated	1,200 ft AGL to FL180

APPENDIX B DEGAS CHANGE LOG

This appendix describes the changes made to DEGAS for the SRMD analysis and includes end-to-end integration test results in Section B.9, which demonstrate that the newly added capabilities function as expected.

B.1 New Encounter Sets

New encounter sets representing HALE, MALE, and LEPR platforms were generated using the correlated, uncorrelated, and terminal encounter models. These encounter sets were verified by plotting distributions of key features including ownship/intruder altitude, speed, vertical rate, and ensuring that the distributions were within the desired min/max limits for each platform.

B.2 DAIDALUS v.2.0.2 with DTA Logic

The publicly released version of DEGAS interfaces with DAIDALUS v.2.0.1. For this study, DAIDALUS v.2.0.2 was integrated into DEGAS. A major difference in v.2.0.2 of DAIDALUS is the addition of terminal area (DTA) logic. Only warning guidance is issued when the intruder is within the DTA. In accordance with DO-365 (Section 2.2.4.4.2), when the ownship is landing, the DTA logic does not issue horizontal recovery guidance. The default alerting parameters provided on GitHub are used in the analysis: https://github.com/nasa/daidalus/blob/master/Configurations/DO_365B_SUM.conf. The DTA radius and height are set to 4.2 NM and 2000 ft, respectively. For this simulation, intruder-centric alerting was used—i.e., the DTA logic is triggered by the intruder being in the DTA cylinder.

Another difference is the inclusion of Sensor Uncertainty Mitigation (SUM). This functionality was enabled in all of the final safety simulations.

B.3 Terminal Area Pilot Model

The Lincoln Laboratory pilot model used in Phase I was designed for en route operations. This model was updated for the Phase II analysis to respond to warning or recovery guidance received from DAIDALUS when in the DTA. (Preventive and corrective guidance is not provided in the DTA). These changes were vetted by SC-228 human factors SMEs.

The terminal area pilot model follows vertical bands guidance. When landing, DAIDALUS produces guidance that allows the pilot to continue to descend or perform a missed approach maneuver. When taking off, DAIDALUS produces guidance that allows the pilot to level off or continue to descend. Note that

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optionally, horizontal guidance may be used with caution during takeoffs (Section 2.2.4.4.2 of DO-365B); however, horizontal maneuvers are not modeled in this analysis.

The terminal area pilot model implements the following assumptions:

- If warning or recovery guidance is received from the DAA system in the DTA while the ownship is landing or taking off, then the pilot model follows vertical guidance to climb or descend to a sampled altitude that is conflict free.
- When there are options to either climb or descend, the pilot model selects a climb.
- If guidance is saturated, the pilot model levels off. (Aggregate metrics from the runs in Section 4 indicate that saturated guidance occurs 4% of the time in terminal encounters where there is an alert and the ownship does not start in an NMAC or LoWC).
- Vertical maneuvers are sampled from the same altitude distribution (a Gamma distribution) regardless of the ownship's current altitude. This altitude distribution is the same one that was used in the Phase I (en route) model.
- In the DTA, no horizontal maneuvers are selected by the pilot model. However, if a nominal horizontal maneuver is being performed as the ownship enters the DTA, and a warning alert occurs, then the ownship continues the nominal horizontal maneuver.
- When a vertical maneuver is issued, the ownship climbs or descends at the maximum vertical rate for the platform type (i.e., HALE/MALE/LEPR).
- All timing parameters except for the initial delay are the same as in the en route pilot model. The initial delay is shorter (2 sec mean for terminal vs. 5 sec mean for en route). This is based on NASA TOPS2 results [4] that showed maneuver timing in response to DTA warning alerts is shorter than for en route.

B.4 Phase II FAA Tech Center Tracker

The FAA Tech Center tracker version released in November 2016 was used in the Phase I analysis. For the Phase II analysis, tracker Version 7.5.1 was integrated into DEGAS. Major differences include best-source selection now being based solely on horizontal error (selects ATAR/GBSS more often than ADS-B now), and the inclusion of GBSS.

Version 8.0 of the Phase II tracker was also integrated into DEGAS. The difference between Version 8.0 and Version 7.5.1 of the Phase II tracker is the inclusion of the EO/IR sensor. This tracker was used for a few secondary final safety runs described in Section 4.13. Version 7.5.1 of the Phase II tracker was used in all other Phase II analyses apart from the exceptions discussed below.

The Phase I tracker was used to generate the C2 sensitivity results (Section 3.2), as well as the final safety runs that used ATAR (Sections 4.1, 4.3, 4.8, and 4.9). Note that only ADS-B was used for the integrated delay and C2 interruption sensitivity analysis, and ADS-B performance is consistent between the Phase I tracker and Phase II tracker (Version 7.5.1). The Phase I tracker was used for the final safety runs that used ATAR due to issues with how the Phase II tracker handles ATAR data; these issues are documented in in Section 5.1.4.

B.5 GBSS Model

A GBSS model that follows the parameters described in Table 6 and Table 7 was added to DEGAS. This model was based on the existing SC-228 ADS-B model and was unit tested to ensure the error distributions match expectations.

B.6 TCAS RA Integration

DEGAS was updated to include TCAS RA logic. (This model has been used and tested extensively in the past as part of CASSATT, from which DEGAS was developed). If both RAs and DAIDALUS guidance are issued, the pilot model follows RAs. In accordance with DO-365B requirement (663), RAs are not issued within the DTA.

B.7 Latency/C2 Interruptions Model

The latency and C2 interruptions model described in Section 2.1.2.4 was added to DEGAS. This model was tested by running several encounters through the simulation and ensuring the time between model components (as described in Section 3.1.2.4) matched the desired interruption and delays.

B.8 EOIR/ATAR Model Declaration Range Update

The field of regard in the ATAR model was updated to account for Radar Declaration Range (RDR) and its corresponding correction factors (as described in Table P-15 of DO-365B). Likewise, the requirements for EO/IR Declaration Range and the corresponding correction factors (described in Table B-5 and Table B-6 of DO-387) were added to the EO/IR model. Unit tests for the ATAR model and EO/IR model were updated to verify that these parameters were properly implemented (e.g., by testing that intruders with different speeds and relative bearings were not detected until they were within the factor-corrected declaration ranges).

B.9 End-to-End Integration Test Results

The SRMD effort required a new simulation with many components integrated, including C2 latency and interruptions; DAIDALUS DTA logic; pilot model terminal maneuvers; TCAS RAs; and the Phase II FAA Tech Center Tracker. These new components are documented in Sections B.1-B.6. To determine if the components were integrated correctly, end-to-end encounter simulations were run and the results were analyzed. For these tests, HALE terminal encounters were used, and RAs are enabled for testing purposes even though they are normally disabled when the ownship is in in the DTA. These tests were performed using Version 7.5.1 of the FAA Tracker. Two integration test examples using ADS-B and AST are shown here. However, the ATAR and GBSS sensors were also tested and verified.

The first example uses the AST sensor in an encounter where the ownship is taking off and the intruder is transiting (en route), as shown in Figure 31. The tracker output of the intruder's position is shown in Figure 32, and the DAIDALUS guidance for this encounter is shown in Figure 33.

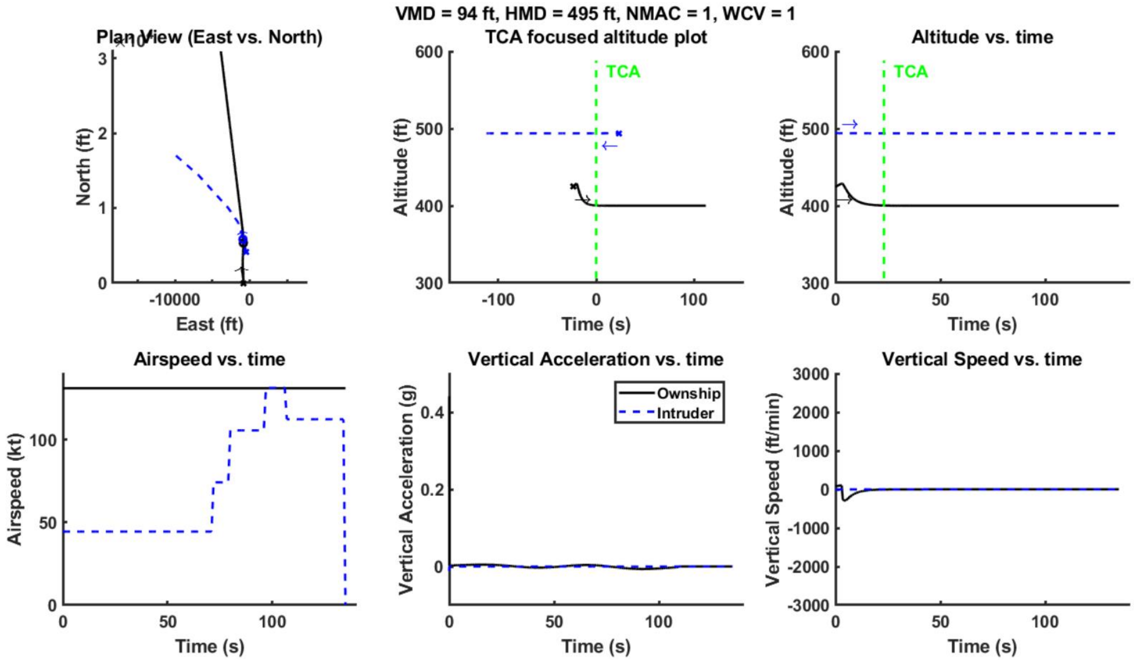

Figure 31. AST integration test encounter

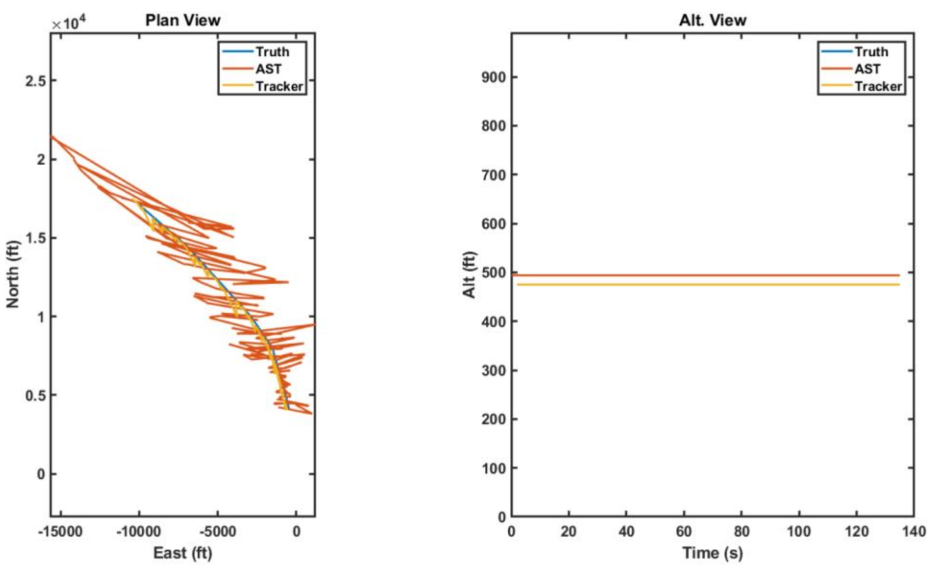

Figure 32. AST integration test encounter tracker output.

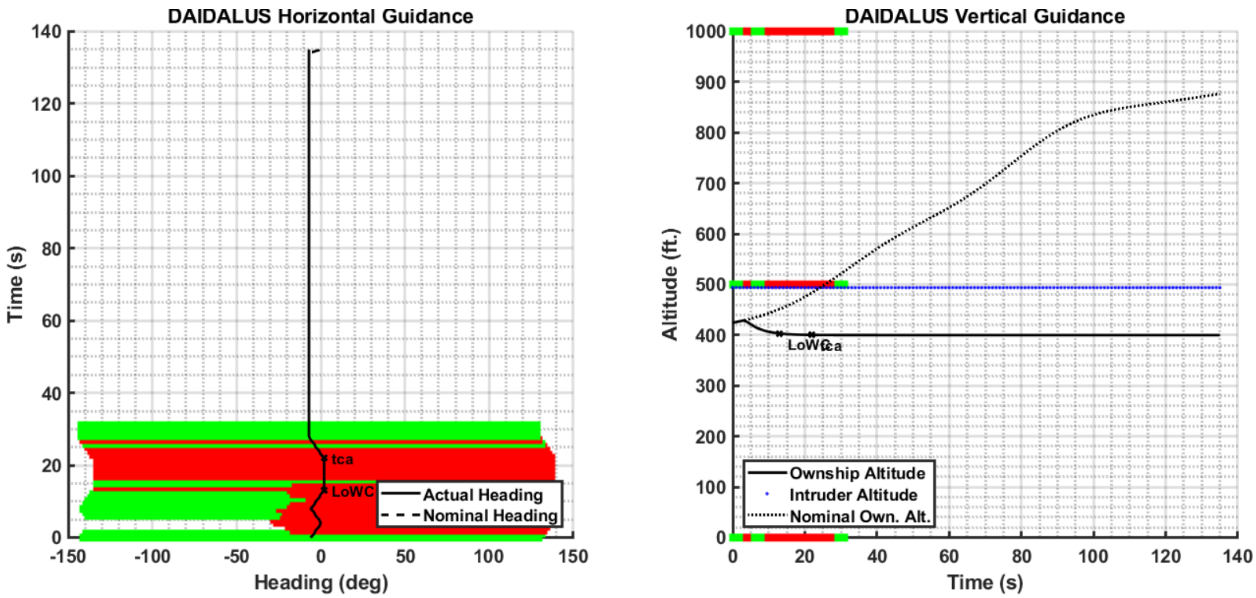

Figure 33. AST integration test encounter DAIDALUS guidance.

In this encounter, the ownship starts inside of the DTA and in an alerted state. A vertical maneuver is issued at time 1 second. From time 1-3 and 5-8, all of the altitudes have recovery bands, and thus, the pilot model issues a command to 400 ft. The pilot model issues commands to level off to the nearest 100 ft increment if it is in the middle of maneuvering vertically and all of the guidance bands are of the same level. From time 9-28, the vertical bands are saturated and no maneuver is issued. This encounter results in both an NMAC and a LoWC.

In this example, the pilot model responds as expected to the guidance and the FAA tracker is able to output an intruder track that is close to the truth. These results suggest the DEGAS simulation is working as intended.

The second example uses the ADS-B sensor in an encounter where the ownship and intruder are both landing, as shown in Figure 34. The tracker output of the intruder's position is shown in Figure 35, and the DAIDALUS guidance for this encounter is shown in Figure 36.

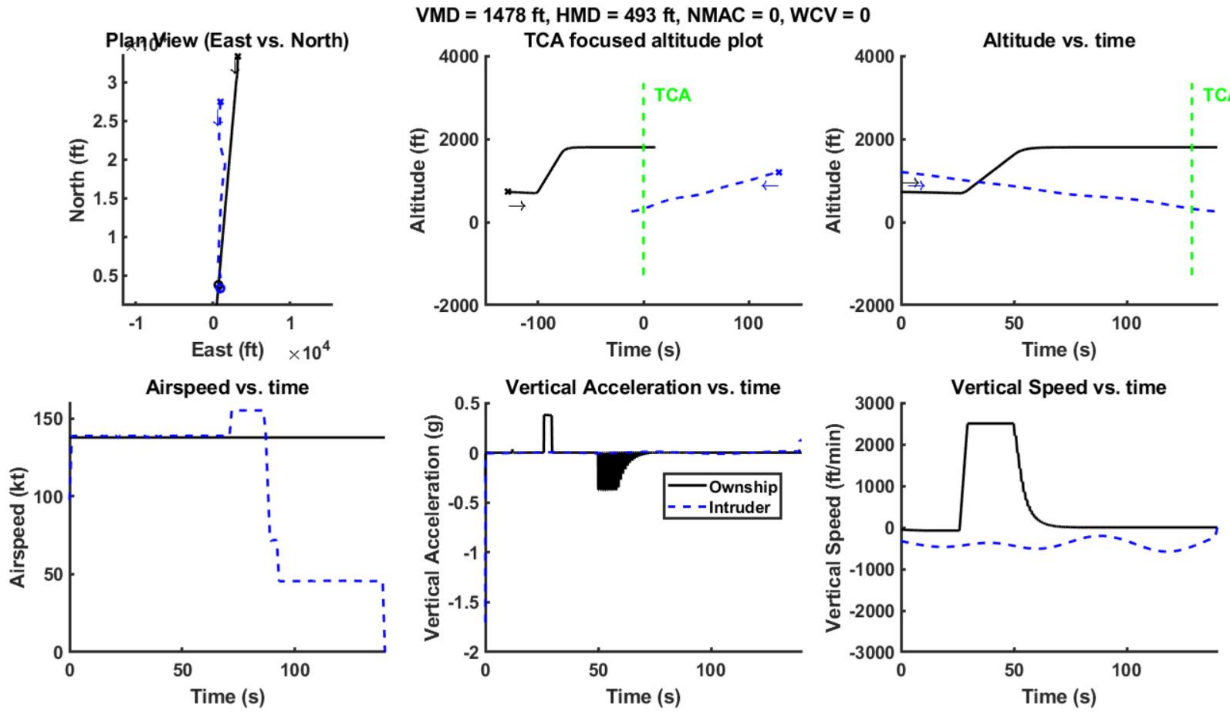

Figure 34. ADS-B example.

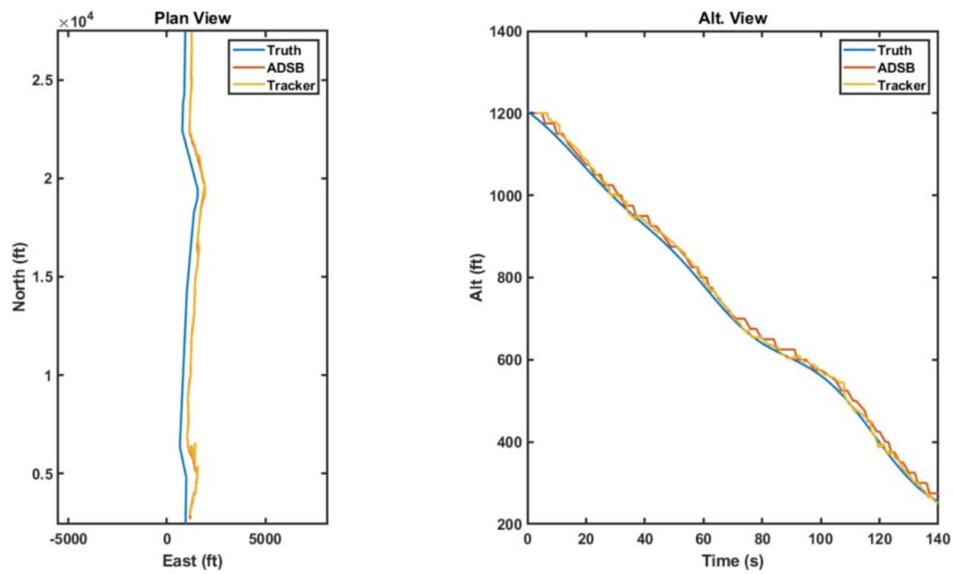

Figure 35. ADS-B example tracker output.

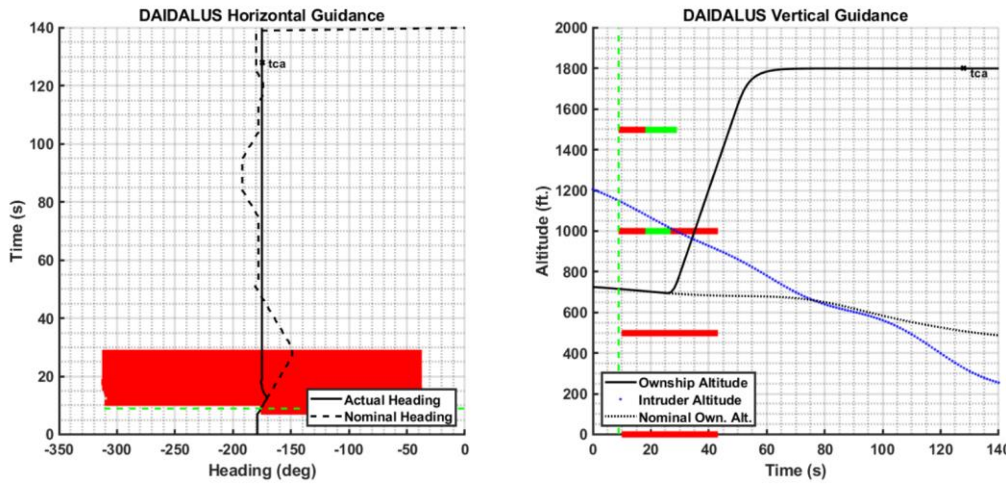

Figure 36. ADS-B example DAIDALUS guidance.

In this encounter, the ownship starts outside of the DTA. The green dashed line in Figure 36 indicates the time when the ownship enters the DTA. The ownship makes an initial horizontal maneuver at time 7; the ownship is outside the DTA at this time, so horizontal maneuvers are allowed. The ownship later makes a vertical maneuver to 1800 ft at time 23 in accordance with the recovery guidance that is issued at that time. In this encounter, no NMAC or LoWC occurs. In this example, the pilot model responds as expected to the guidance and the FAA tracker outputs an intruder track that is close to the truth. These results suggest the DEGAS simulation is working as intended.

All of the integration test results indicate that the new and updated model components work as expected.

APPENDIX C EXAMPLE ENCOUNTERS

This appendix includes a few example encounters from the integrated delay and C2 interruption sensitivity analysis (Section 3.2), and the GBSS tracker error sensitivity analysis (Section 3.3). These examples provide further insight into the types of encounters used in the analysis.

C.1 Integrated Delay and C2 Interruption Example Encounters

This section discusses two example MALE terminal encounters with nominal NMACs from the integrated delay and C2 interruption sensitivity analysis. These encounters illustrate situations in which the C2 interruption and integrated delays lead to unresolved NMACs. The first example has an integrated delay of 4 seconds and a 0-second interruption (i.e., the default configuration in the parameter sweep). The second example compares a single encounter evaluated with a 0-second interruption vs. a 3-second interruption, with the integrated delay held at 4 seconds in both cases. Method 2 (i.e., dropping on the first warning alert) is used for the interruptions.

C.1.1 Integrated Delay and C2 Interruption Example Encounter #1

In this first example, the ownship is taking off and the intruder is landing. The integrated delay is 4 seconds and there are no interruptions. Figure 37 shows an overview of the encounter, and Figure 38 shows the resulting DAIDALUS guidance for this encounter.

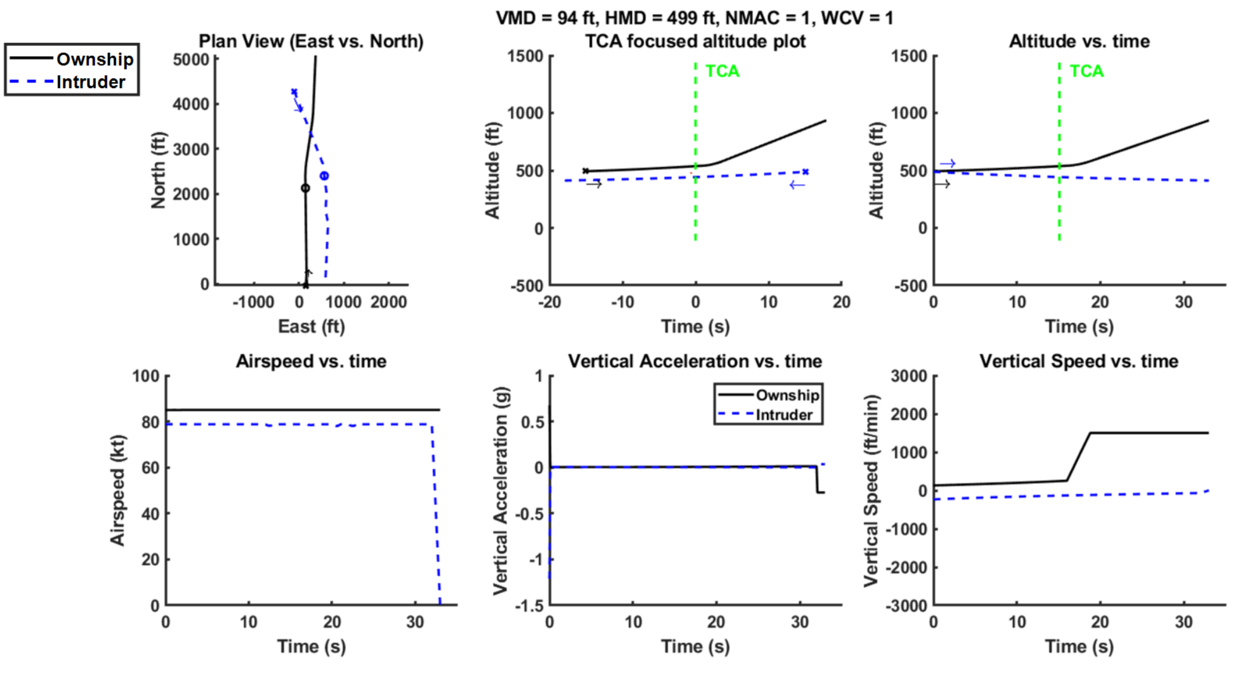

Figure 37. MALE encounter example #1 (4-second delay and 0-second interruption (default configuration)).

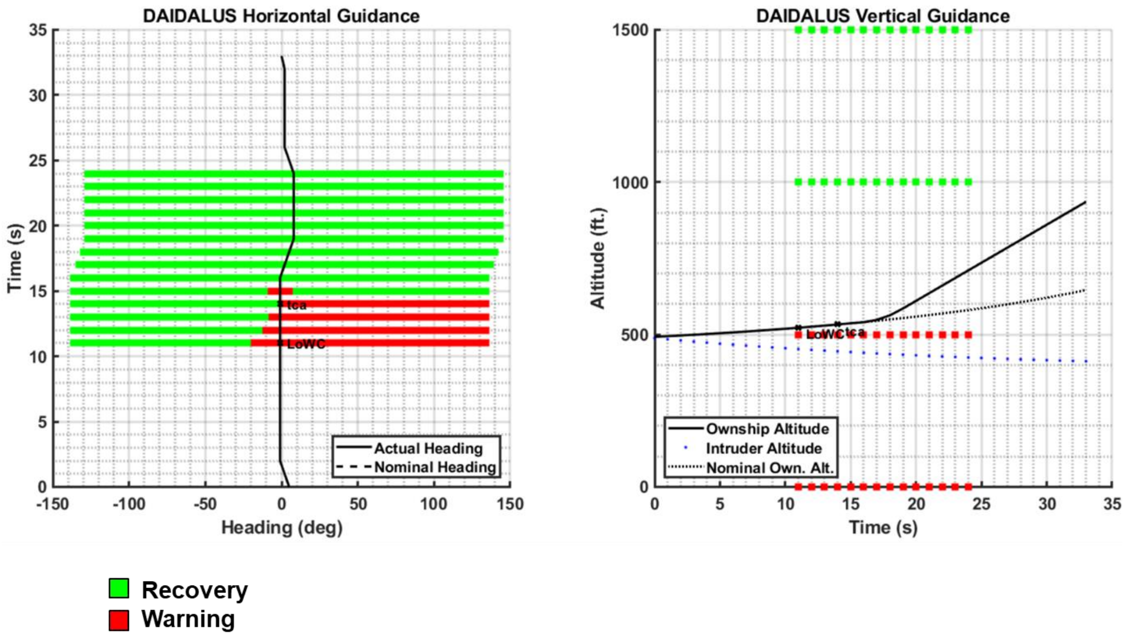

Figure 38. DAIDALUS guidance for MALE example encounter #1 (default configuration).

In this encounter, the intruder track is established at time 7, but with the 4-second integrated delay, a warning alert is not received until time 11. Unfortunately, the time of closest approach is at 15.1 seconds, and the ownship maneuvers after TCA due to pilot model delays. Because the two aircraft start so close to each other, even a 4-second integrated delay can have an impact.

C.1.2 Integrated Delay and C2 Interruption Example Encounter #2

In this second example, the ownship is taking off and the intruder is landing. The integrated delay is 4 seconds and there are no interruptions. Figure 39 shows an overview of the encounter, and Figure 40 shows the resulting DAIDALUS guidance for this encounter.

Because there are no interruptions, the ownship maneuvers as soon as it can, given the integrated delay and the pilot models delays. The pilot model samples an appropriate altitude and the ownship maneuvers to the altitude at the maximum vertical rate for the MALE platform (1500 ft per minute). Even so, the encounter narrowly avoids the NMAC threshold, with an HMD of 494 ft and a VMD of 103 ft. This indicates that having any sort of interruption would lead to an NMAC.

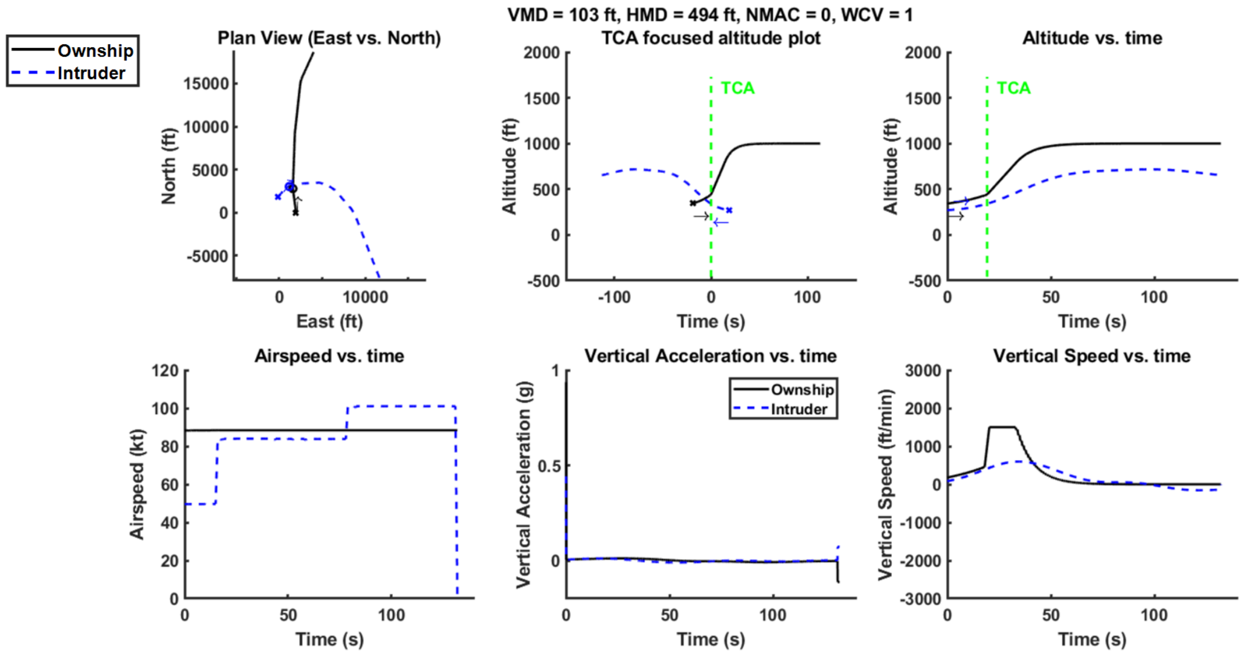

Figure 39. MALE example encounter #2 (4-second delay and 0-second interruption (default configuration)).

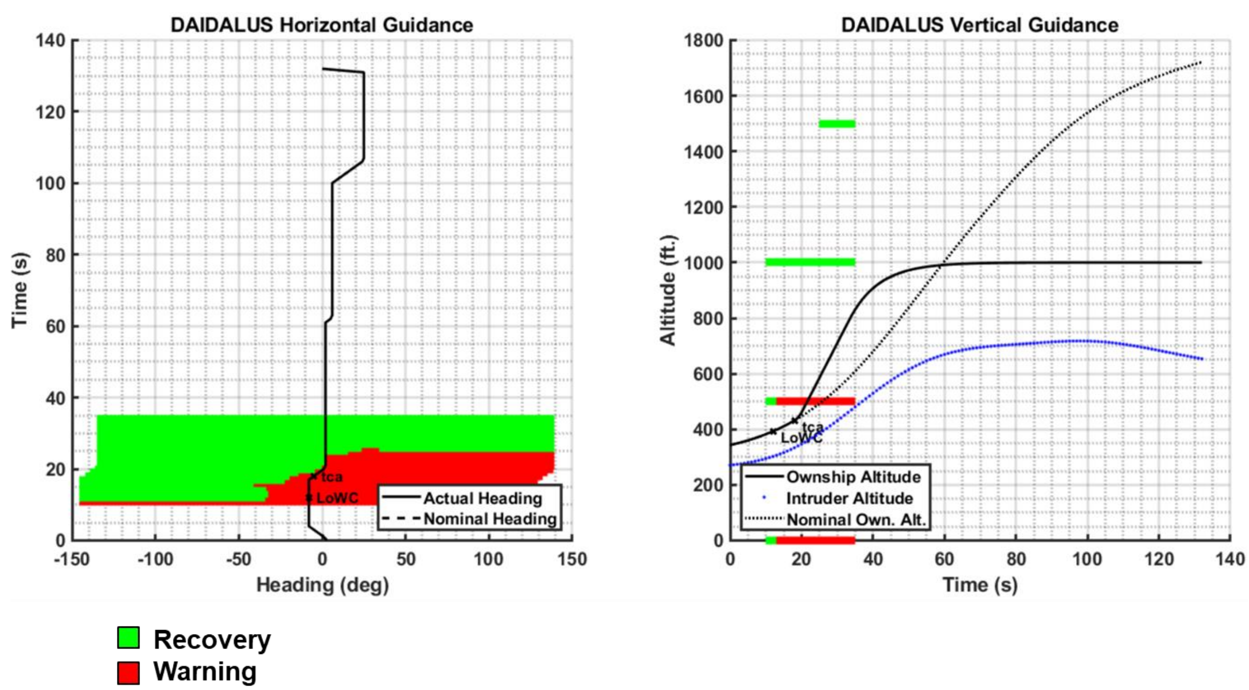

Figure 40. DAIDALUS guidance for MALE example encounter #2 (default configuration).

Figure 41 and Figure 42 show the encounter overview and DAIDALUS guidance, respectively, for the same encounter except with a 3-second interruption (Method 2). The integrated delay is still 4 seconds.

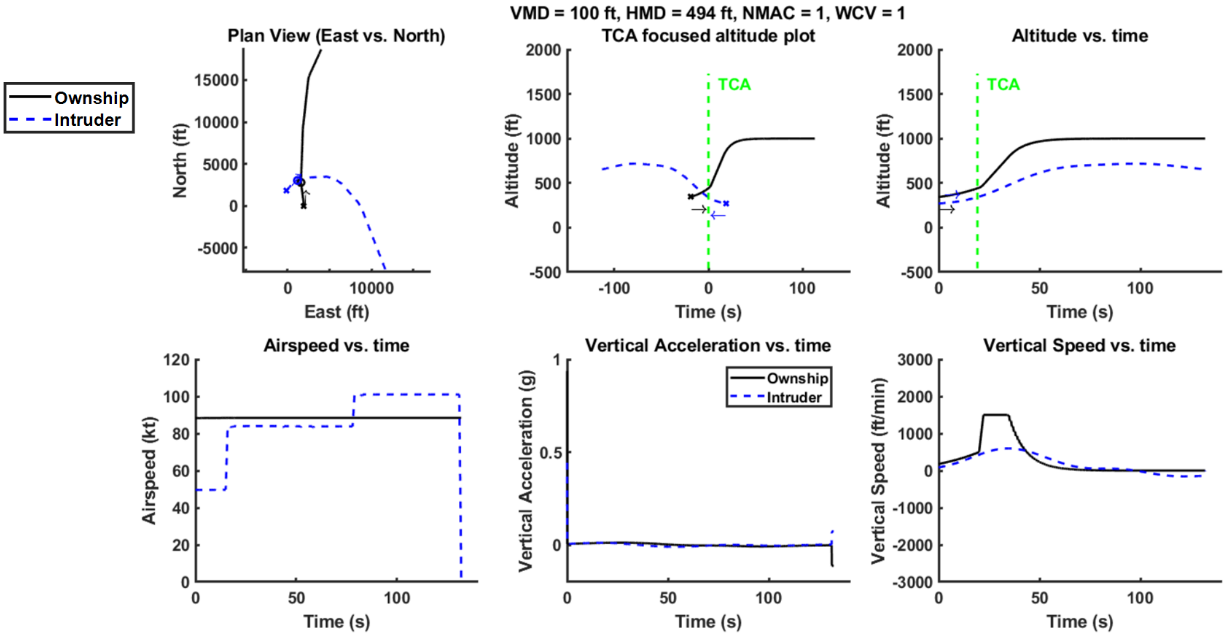

Figure 41. MALE example encounter #2 (4-second delay and 3-second interruption).

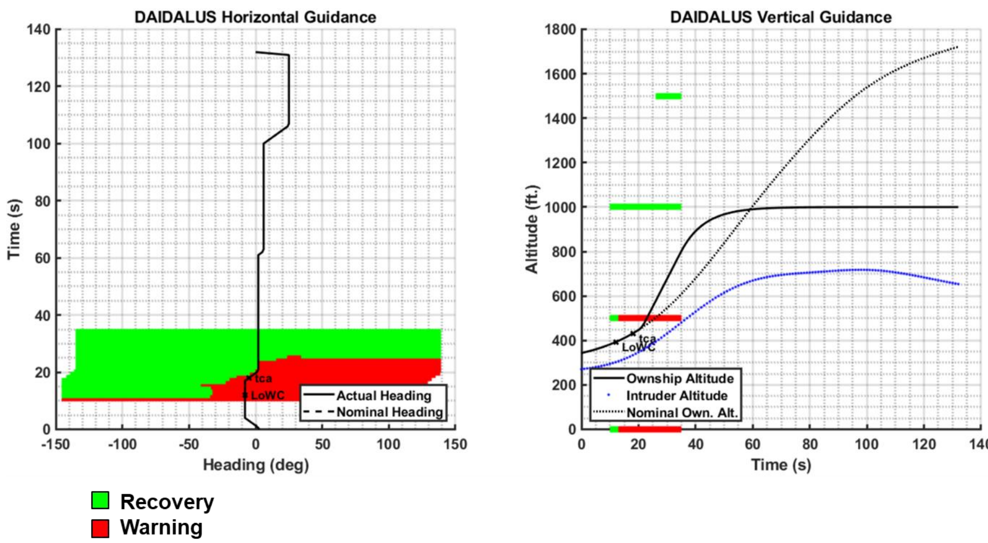

Figure 42. DAIDALUS guidance for MALE example encounter #2 (4-second delay and 3-second interruption).

At the first warning alert, there is a 3 second interruption. Again, the pilot model samples an altitude and the ownship climbs to that altitude at the maximum vertical rate. However, because of the interruption, the ownship does not maneuver quite soon enough and thus, the encounter enters the NMAC threshold. Thus, in this case, the longer C2 interruption leads to an NMAC in this encounter.

The C2 sensitivity analysis assesses different delay and interruption lengths and evaluates how these different values affect the safety in the encounter set, consistent with these examples.

C.2 GBSS Sensitivity Example Encounter

This section discusses an example encounter from the GBSS tracker error sensitivity analysis. Figure 43 shows the DAIDALUS guidance for an example correlated encounter that was run with both ADS-B and GBSS with default parameters from DO-365B (Table 7). The vertical guidance is markedly different, whereas the horizontal guidance is similar up until the point where the ownship maneuvers in the ADS-B case and there is a loss of well clear in the GBSS case. However, both horizontal and vertical guidance are issued earlier when ADS-B is used. Figure 44 shows the sensor noise for East/North velocity and vertical rate that is associated with this encounter. The GBSS sensor and tracker estimates are markedly noisier than the ADS-B estimates.

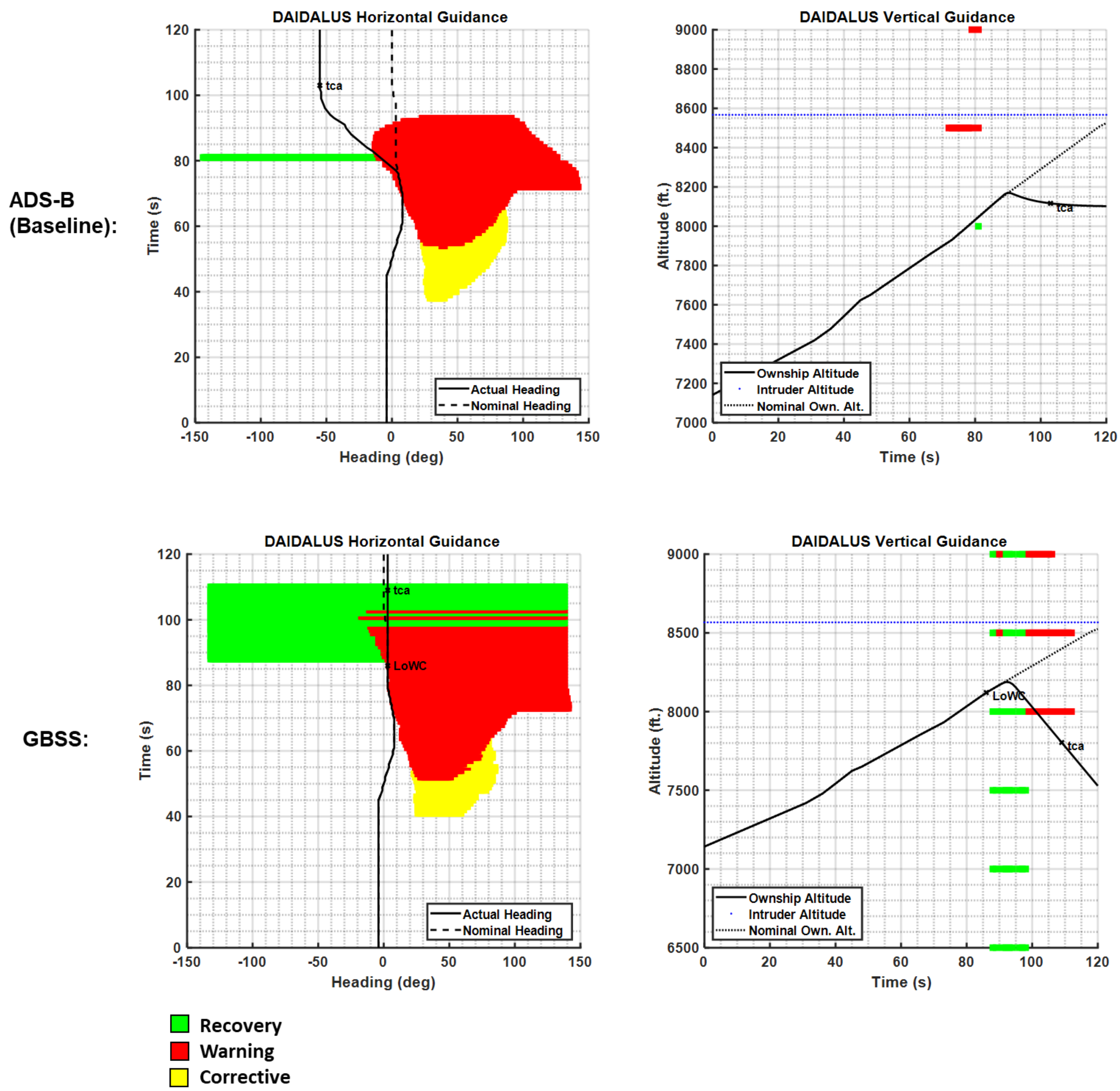

Figure 43. DAIDALUS guidance for an example encounter run with ADS-B and GBSS.

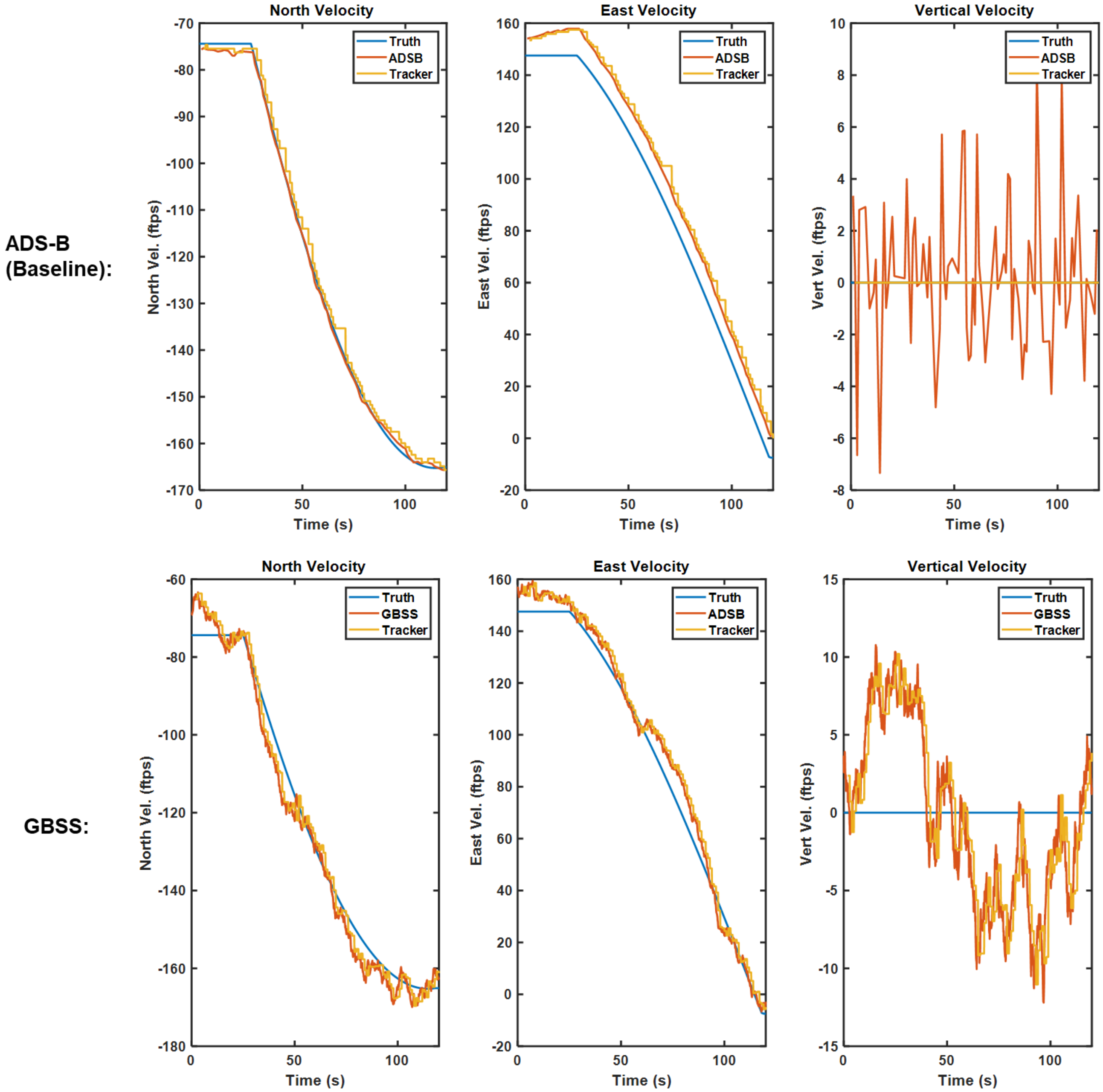

Figure 44. Sensor noise for an example encounter run with ADS-B and GBSS.

C.3 Final Safety Evaluation Scenario 4, 5, 6 Comparison

Counterintuitively, the results from Section 4.1 (Final Safety Evaluation DAA Class 1+6 (ATAR Combined)) showed that the performance of ATAR+AST+ADS-B with 100 ft quantization was worse than the performance of ATAR+AST alone. This section compares results for an example encounter run with the configurations for Scenarios 4, 5, and 6. Scenario 4 is ATAR and AST only. Scenario 5 is ATAR+AST+ADS-B with 100 ft altitude quantization. Scenario 6 is ATAR+AST+ADS-B with 25 ft altitude quantization. All of these scenarios simulate a MALE UAS.

Figure 45, Figure 46, and Figure 47 show the encounter overview, DAIDALUS guidance, and tracker intruder rate estimates, respectively, for an example encounter for Scenario 4 (ATAR and AST only). Figure 48, Figure 49, and Figure 50 show the same information for the same encounter for Scenario 5 (ATAR+AST+ADS-B with 100 ft quantization), and Figure 51, Figure 52, and Figure 53 show the same information for the same encounter for Scenario 6 (ATAR+AST+ADS-B with 25 ft quantization). For this encounter, an NMAC only occurs for the Scenario 5 configuration. Among the three scenarios, the vertical rates are clearly highest for Scenario 5. The additional jitter that occurs for multi-sensor runs with ATAR, AST, and ADS-B with 100 ft quantization is an issue that could be investigated in collaboration with the FAA Tech Center as future work (see Section 5.1.4).

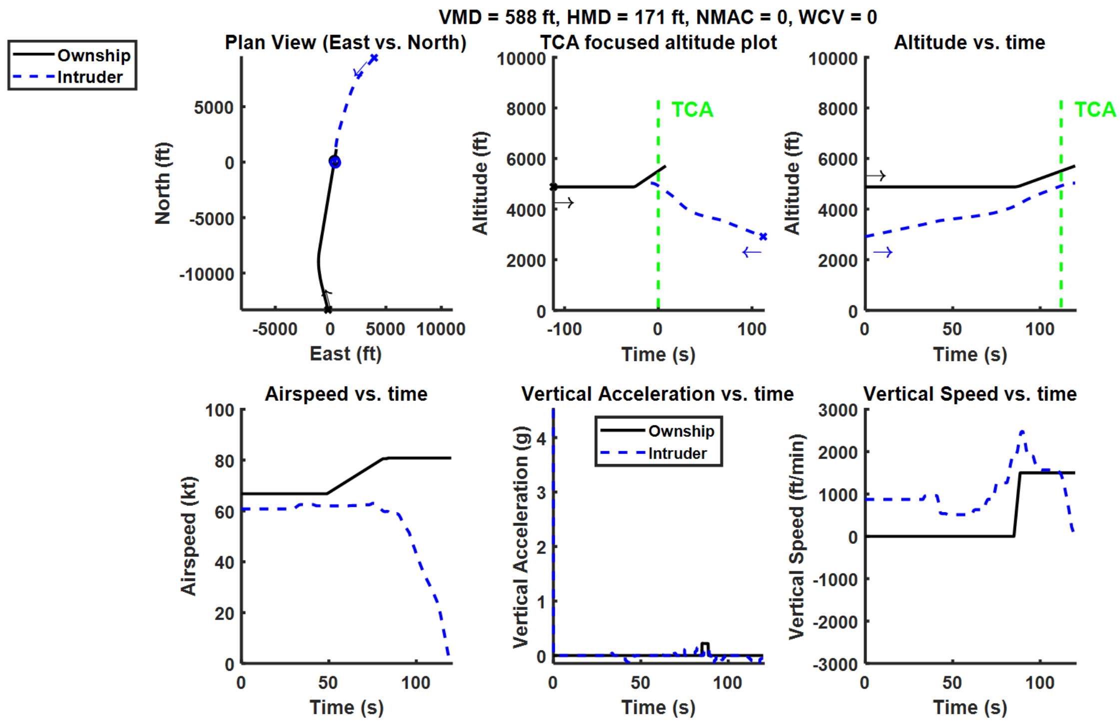

Figure 45. Final Safety Evaluation Scenario 4 example encounter.

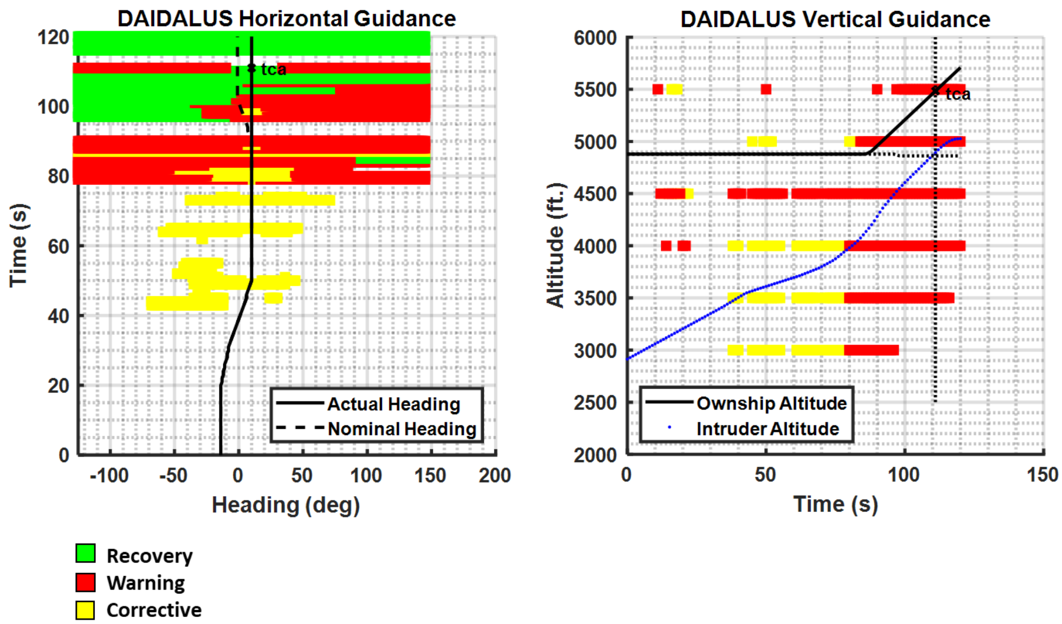

Figure 46. DAIDALUS guidance for Final Safety Evaluation Scenario 4 example encounter.

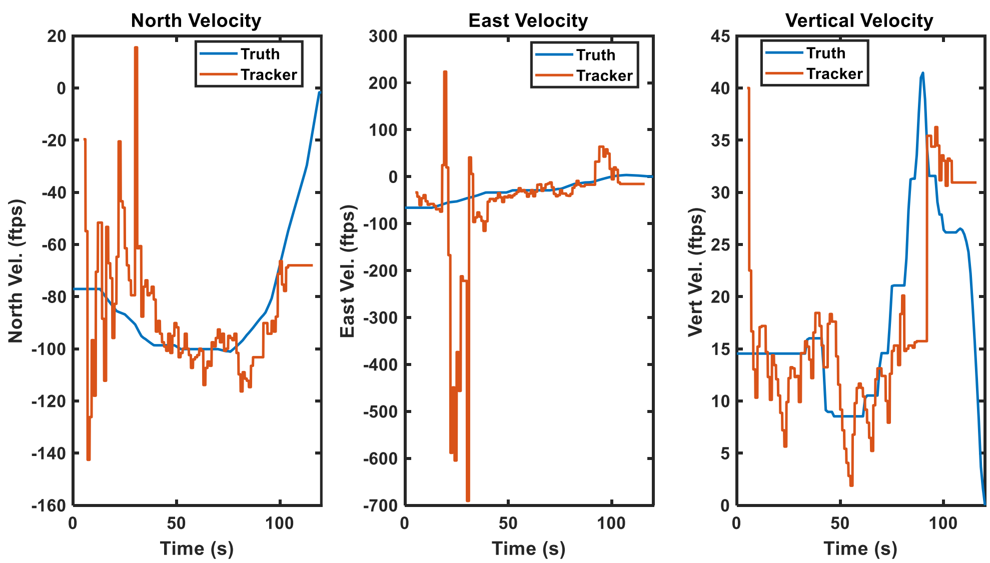

Figure 47. Tracker output for Final Safety Evaluation Scenario 4 example encounter.

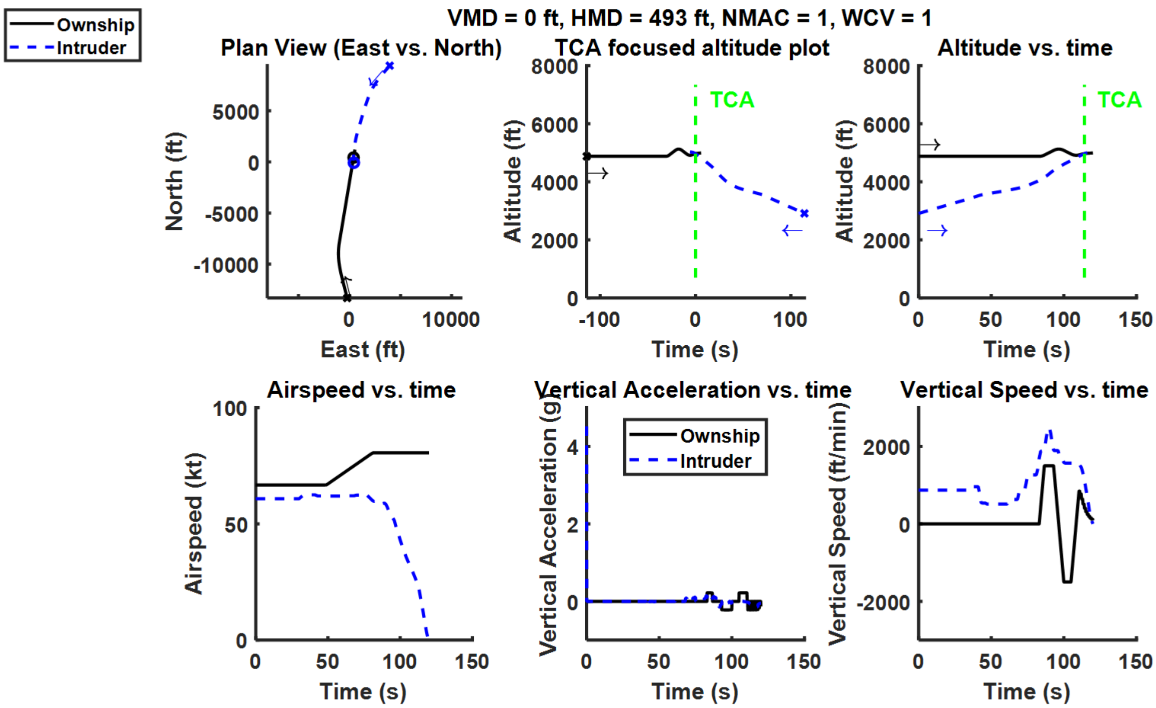

Figure 48. Final Safety Evaluation Scenario 5 example encounter.

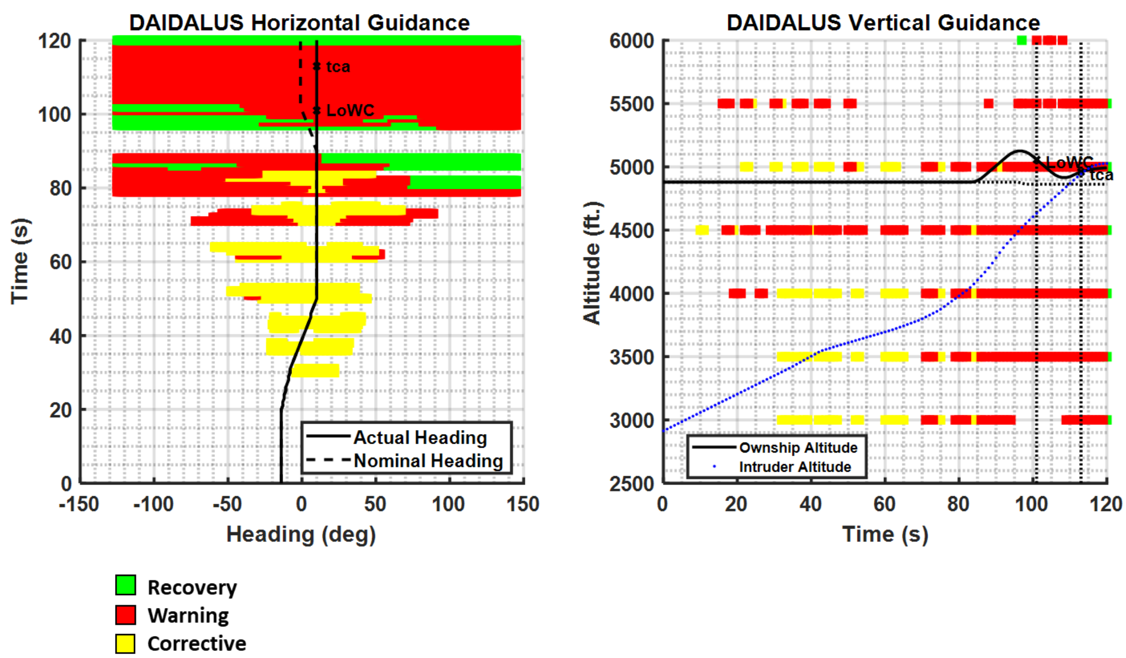

Figure 49. DAIDALUS guidance for Final Safety Evaluation Scenario 5 example encounter.

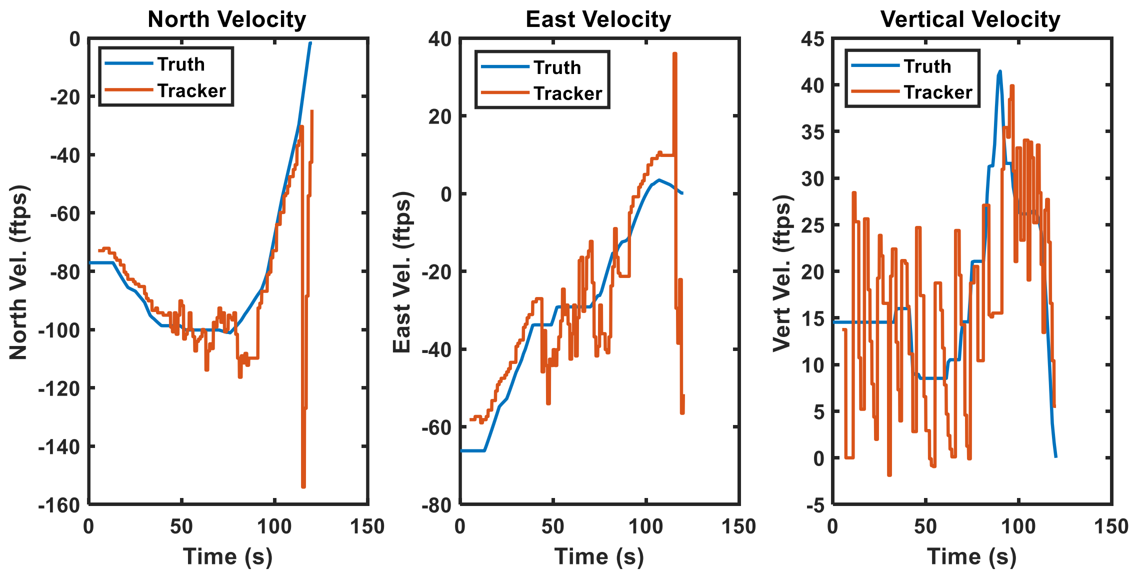

Figure 50. Tracker output for Final Safety Evaluation Scenario 4 example encounter

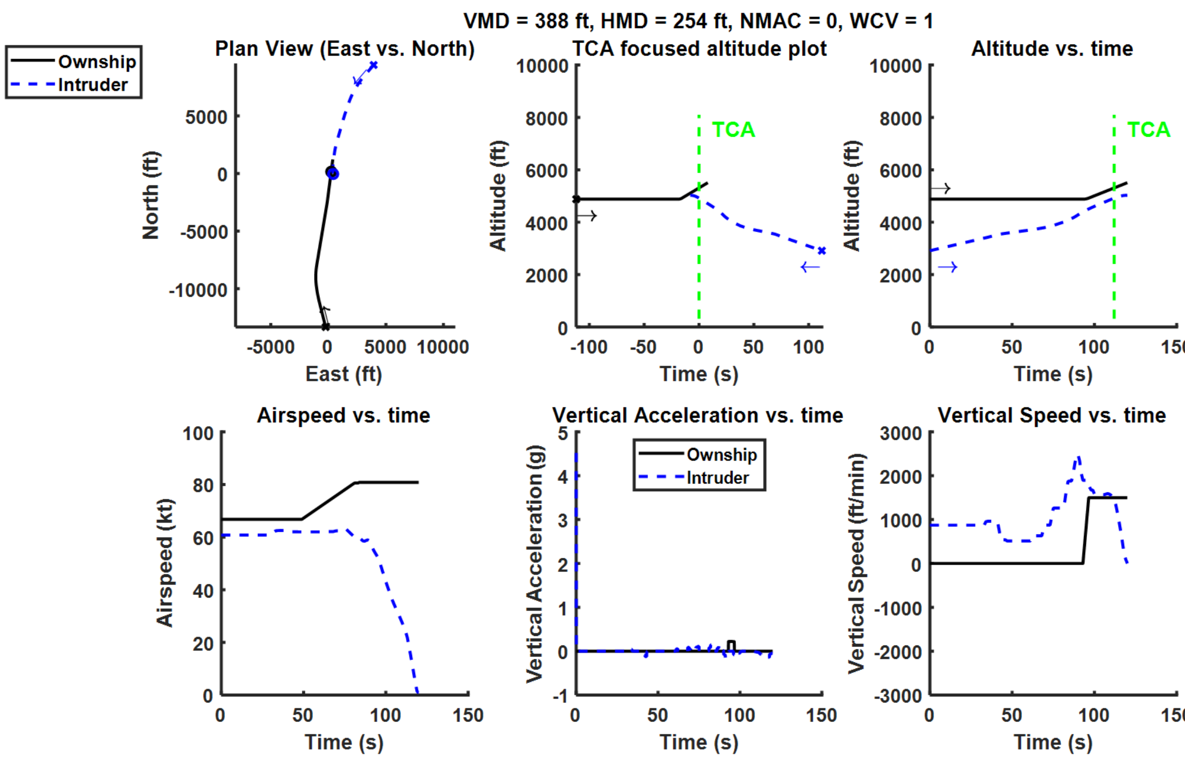

Figure 51. Final Safety Evaluation Scenario 6 example encounter.

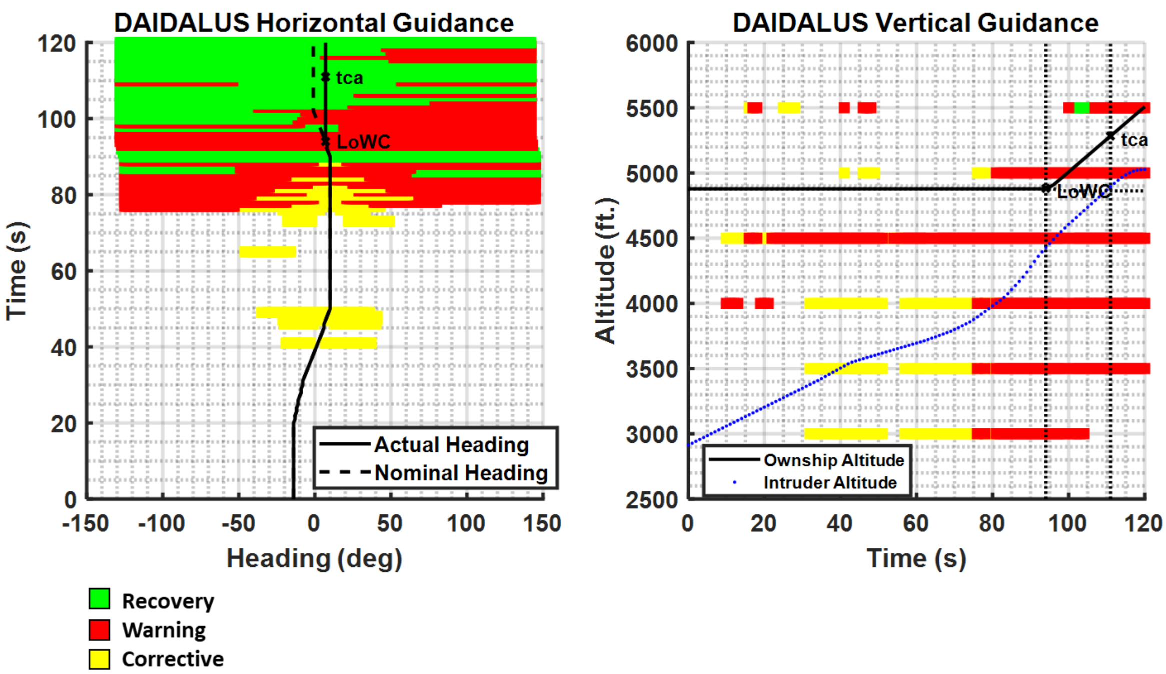

Figure 52. DAIDALUS guidance for Final Safety Evaluation Scenario 6 example encounter.

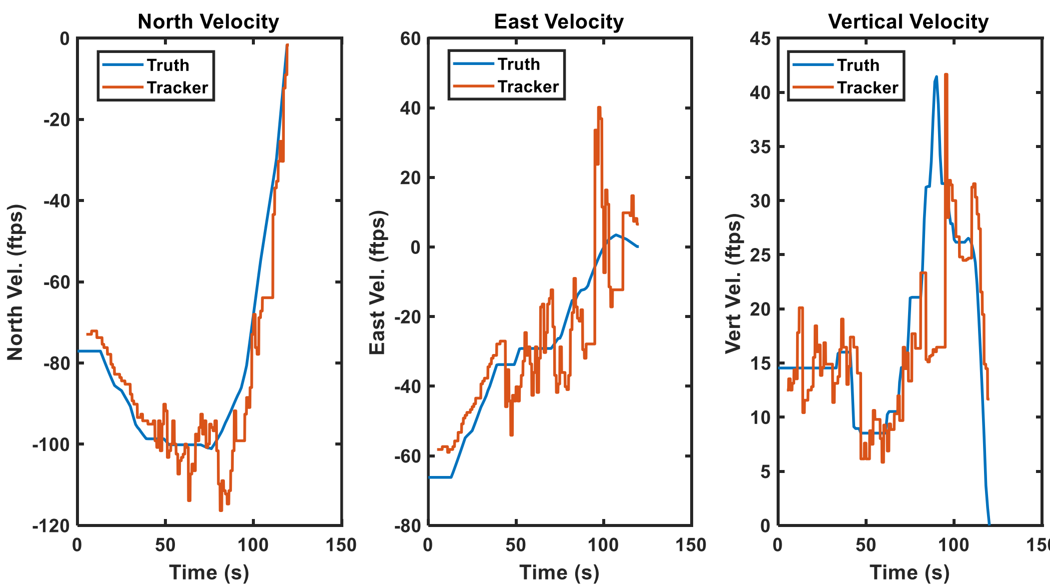

Figure 53. Tracker output for Final Safety Evaluation Scenario 6 example encounter.

APPENDIX D RESULTS METRICS

This appendix provides the numerical values of the metrics (risk ratios, loss of well clear ratios, etc.) that were shown in figures throughout Section 4. These metrics can be extracted for use in other analyses, including MITRE's fault trees. The safety metrics also include 95% confidence intervals (CI).

Table 36 shows the metrics for the baseline results discussed in Section 3.1 (Figure 5-Figure 7).

Table 36. Baseline run metrics.

		Risk Ratio			Loss of Well Clear Ratio		
	Scenario	**Unresolved**	**Induced**	**Total [lower CI, upper CI]**	**Unresolved**	**Induced**	**Total [lower CI, upper CI]**
Correlated SUM Comparison	No SUM, 4 second integrated delay	0.0209	0.0718	0.0927 [0.0723, 0.1405]	0.4427	0.0427	0.4855 [0.4805, 0.4889]
	SUM, 4 second integrated delay	0.0212	0.0643	0.0855 [0.0672, 0.1212]	0.4527	0.0416	0.4943 [0.4897, 0.4983]
	No SUM, 5 second integrated delay	0.0226	0.0837	0.1063 [0.0801, 0.1418]	0.4636	0.0449	0.5085 [0.5057, 0.5124]
	SUM, 5 second integrated delay	0.0227	0.0813	0.1040 [0.0830, 0.1329]	0.4745	0.0442	0.5187 [0.5134, 0.5222]
Correlated ADS-B Quantization Comparison	100 ft quantization, 4 second integrated delay	0.0216	0.0613	0.0829 [0.0591, 0.1037]	0.4554	0.0430	0.4983 [0.4937, 0.5017]
	25 ft quantization, 4 second integrated delay	0.0212	0.0643	0.0855 [0.0662, 0.1226]	0.4527	0.0416	0.4943 [0.4897, 0.4970]
	100 ft quantization, 5 second integrated delay	0.0228	0.0763	0.0990 [0.0769, 0.1406]	0.4769	0.0455	0.5224 [0.5187, 0.5263]
	25 ft quantization, 5 second integrated delay	0.0227	0.0813	0.1040 [0.0795, 0.1253]	0.4745	0.0442	0.5187 [0.5152, 0.5231]
Uncorrelated SUM Comparison	No SUM, 4 second integrated delay	0.0261	0.0132	0.0393 [0.0346, 0.0443]	0.0765	0.037	0.1134 [0.1107, 0.1177]
	SUM, 4 second integrated delay	0.0263	0.0133	0.0396 [0.0359, 0.0473]	0.0779	0.0357	0.1136 [0.1103, 0.1187]
	No SUM, 5 second integrated delay	0.0273	0.013	0.0403 [0.0372, 0.0443]	0.0842	0.0412	0.1254 [0.1219, 0.1306]
	SUM, 5 second integrated delay	0.0276	0.0133	0.0409 [0.0376, 0.0448]	0.0852	0.0403	0.1255 [0.1222, 0.1286]

Uncorrelated ADS-B Quantization Comparison	100 ft quantization, 4 second integrated delay	0.0265	0.0117	0.0382 [0.0361, 0.0431]	0.0786	0.0362	0.1148 [0.1117, 0.1181]
	25 ft quantization, 4 second integrated delay	0.0263	0.0133	0.0396 [0.0352, 0.045]	0.0779	0.0357	0.1136 [0.1082, 0.1168]
	100 ft quantization, 5 second integrated delay	0.0279	0.0178	0.0457 [0.0405, 0.0536]	0.0868	0.0397	0.1265 [0.1218, 0.1295]
	25 ft quantization, 5 second integrated delay	0.0276	0.0133	0.0409 [0.0379, 0.044]	0.0852	0.0403	0.1255 [0.122, 0.1293]

Table 37 shows the metrics for the C2 sensitivity results discussed in Section 3.2 (Figure 9-Figure 11).

Table 37. C2 sensitivity analysis metrics.

		Risk Ratio			**Loss of Well Clear Ratio**		
	Scenario	**Unresolved**	**Induced**	**Total [lower CI, upper CI]**	**Unresolved**	**Induced**	**Total [lower CI, upper CI]**
Default Configuration	4 second integrated delay, 0 second interruption	0.1247	0.0088	0.1335 [0.1153, 0.1497]	0.3802	0.0009	0.3811 [0.3722, 0.3901]
Integrated Delay	0 second integrated delay	0.0272	0.0053	0.0325 [0.0235, 0.0397]	0.2492	0.001	0.2503 [0.2436, 0.2596]
	2 second integrated delay	0.0497	0.0051	0.0548 [0.0446, 0.0719]	0.2901	0.0008	0.2909 [0.2834, 0.2968]
	5 second integrated delay	0.1923	0.012	0.2043 [0.1767, 0.221]	0.4577	0.0007	0.4583 [0.4512, 0.4668]
	10 second integrated delay	0.3363	0.0155	0.3518 [0.3333, 0.3746]	0.5832	0.0006	0.5838 [0.5766, 0.5942]
	15 second integrated delay	0.4422	0.01	0.4522 [0.4278, 0.4918]	0.657	0.0005	0.6575 [0.6495, 0.667]
C2 Interruption (Method 1)	2 second interruption	0.1457	0.0078	0.1535 [0.1374, 0.1757]	0.414	0.0009	0.4149 [0.4071, 0.4243]
	5 second interruption	0.1709	0.0091	0.18 [0.1593, 0.2013]	0.4558	0.0004	0.4562 [0.4485, 0.4648
	10 second interruption	0.2357	0.0099	0.2456 [0.2208, 0.2763]	0.5347	0.0006	0.5353 [0.5218, 0.5448

	15 second interruption	0.3157	0.01	0.3257 [0.2905, 0.3545]	0.6098	0.0008	0.6106 [0.5974, 0.6187]
	20 second interruption	0.4	0.0054	0.4054 [0.3598, 0.4327]	0.6818	0.0006	0.6824 [0.6715, 0.6922]
	25 second interruption	0.4675	0.0021	0.4696 [0.4392, 0.5213]	0.7483	0.0002	0.7485 [0.7388, 0.7576]
	30 second interruption	0.5376	0.0023	0.5399 [0.4867, 0.5862]	0.7967	0	0.7967 [0.7884, 0.8095]
	60 second interruption	0.9023	0	0.9023 [0.8496, 0.9258]	0.9511	0	0.9511 [0.9463, 0.9569]
C2 Interruption (Method 2)	3 second interruption	0.1472	0.0079	0.1551 [0.1315, 0.1749]	0.4179	0.0006	0.4185 [0.4072, 0.4262]
	5 second interruption	0.1747	0.0101	0.1848 [0.1594, 0.205]	0.4624	0.0005	0.4629 [0.4544, 0.4721]
	10 second interruption	0.246	0.0113	0.2573 [0.2331, 0.2831]	0.5482	0.0007	0.5489 [0.5406, 0.56]
	20 second interruption	0.4427	0.004	0.4466 [0.4088, 0.4806]	0.7184	0.0006	0.719 [0.7081, 0.7288]

Table 38 shows the metrics for the uncorrelated GBSS sensitivity results discussed in Section 3.3 (Figure 12-Figure 14). Table 39 shows the metrics for the correlated GBSS sensitivity analysis results discussed in Section 3.3 (Figure 15-Figure 16).

Table 38. GBSS uncorrelated track error sensitivity analysis metrics.

		Risk Ratio			**Loss of Well Clear Ratio**		
	Scenario	**Unresolved**	**Induced**	**Total [lower CI, upper CI]**	**Unresolved**	**Induced**	**Total [lower CI, upper CI]**
Default Configuration	Total Error 1-σ (from DO-365B) Horizontal Position: 80.91 m Vertical Position: 68.57 m Horizontal Velocity: 2.89 m/s Vertical Rate: 2.76 m/s	0.0362	0.0477	0.0839 [0.0758, 0.0916]	0.1575	0.0652	0.2227 [0.2178, 0.2271]
Zero Errors	Horizontal Position: 0 m Vertical Position: 0 m Horizontal Velocity: 0 m/s Vertical Rate: 0 m/s	0.0286	0.0131	0.0416 [0.0384, 0.0493]	0.0853	0.0329	0.1182 [0.1154, 0.1231]

Horizontal Position Error	50% of default	0.036	0.0462	0.0822 [0.0752, 0.0916]	0.1566	0.0639	0.2205 [0.2173, 0.2285]
	75% of default	0.0359	0.0492	0.0851 [0.0781, 0.0915]	0.1573	0.064	0.2213 [0.2174, 0.2263]
	125% of default	0.0364	0.0498	0.0862 [0.0782, 0.0948]	0.158	0.0649	0.2229 [0.2181, 0.2291]
	150% of default	0.0365	0.0472	0.0837 [0.0767, 0.0944]	0.1582	0.0648	0.223 [0.2172, 0.2284]
	200% of default	0.0365	0.0518	0.0883 [0.0786, 0.099]	0.1603	0.0659	0.2261 [0.2202, 0.2318]
	300% of default	0.0374	0.0575	0.0949 [0.0866, 0.1068]	0.1651	0.0675	0.2326 [0.2281, 0.2385]
	400% of default	0.0394	0.0569	0.0963 [0.0865, 0.109]	0.1727	0.0671	0.2398 [0.2356, 0.2463]
Horizontal Velocity Error	50% of default	0.0358	0.0476	0.0834 [0.0757, 0.0913]	0.1568	0.0646	0.2214 [0.2175, 0.227]
	75% of default	0.0361	0.0457	0.0818 [0.0756, 0.0914]	0.1568	0.0645	0.2214 [0.2166, 0.226]
	125% of default	0.0362	0.0483	0.0844 [0.0766, 0.0952]	0.1578	0.0648	0.2227 [0.2186, 0.228]
	150% of default	0.0363	0.0561	0.0924 [0.0819, 0.1029]	0.1579	0.0658	0.2236 [0.2184, 0.2277]
	200% of default	0.0367	0.0506	0.0873 [0.0768, 0.0973]	0.1617	0.0654	0.2271 [0.2210, 0.2325]
	300% of default	0.0374	0.0622	0.0996 [0.0885, 0.1116]	0.1695	0.0673	0.2368 [0.2326, 0.2432]
	400% of default	0.0388	0.0679	0.1067 [0.0973, 0.1185]	0.1796	0.0703	0.2499 [0.2453, 0.2531]
Vertical Position Error	50% of default	0.0309	0.0325	0.0634 [0.0563, 0.0733]	0.1337	0.0563	0.1900 [0.1856, 0.1948]
	75% of default	0.0329	0.0446	0.0775 [0.0683, 0.0864]	0.1446	0.0585	0.2031 [0.1972, 0.2065]
	125% of default	0.0411	0.0717	0.1128 [0.1016, 0.1237]	0.1732	0.0723	0.2454 [0.2392, 0.2501]
	150% of default	0.0474	0.0977	0.1451 [0.1325, 0.1641]	0.1896	0.0780	0.2676 [0.2636, 0.2741]

	200% of default	0.0681	0.1293	0.1973 [0.1833, 0.2154]	0.2255	0.0942	0.3197 [0.3141, 0.3258]
	300% of default	0.1239	0.2241	0.3480 [0.3265, 0.3703]	0.2981	0.1347	0.4328 [0.4241, 0.4386]
	400% of default	0.1846	0.2798	0.4644 [0.4443, 0.4952]	0.3653	0.1655	0.5309 [0.5236, 0.5389]
Vertical Velocity Error	50% of default	0.0326	0.0303	0.0629 [0.0568, 0.0707]	0.1360	0.0461	0.1822 [0.1784, 0.1876]
	75% of default	0.0341	0.0463	0.0804 [0.0712, 0.0916]	0.1461	0.0531	0.1992 [0.1944, 0.2033]
	125% of default	0.0386	0.0724	0.1109 [0.1012, 0.1259]	0.1699	0.0783	0.2483 [0.2437, 0.2534]
	150% of default	0.0409	0.0967	0.1376 [0.1229, 0.1592]	0.1833	0.0949	0.2781 [0.2737, 0.2864]
	200% of default	0.0460	0.1582	0.2042 [0.1882, 0.2395]	0.2109	0.1281	0.3389 [0.3323, 0.3448]
	300% of default	0.0577	0.2762	0.3339 [0.3109, 0.3588]	0.2593	0.1967	0.4560 [0.4468, 0.4615]
	400% of default	0.0684	0.3855	0.4538 [0.4267, 0.5032]	0.3044	0.2604	0.5649 [0.5561, 0.5730]
Vertical Position and Velocity Error	200% of default	0.0794	0.2086	0.288 [0.2603, 0.3052]	0.2613	0.1495	0.4107 [0.4034, 0.42]
	400% of default	0.1815	0.4303	0.6118 [0.586, 0.644]	0.4003	0.2606	0.6609 [0.6525, 0.6672]
Horizontal Maneuvers Only	Vertical position error 200%	0.1063	0.1101	0.2164 [0.2057, 0.2311]	0.2471	0.0656	0.3126 [0.3082, 0.3167]
	Vertical velocity error 200%	0.0824	0.1182	0.2006 [0.182, 0.2174]	0.2245	0.0704	0.2949 [0.2905, 0.302]
	Vertical position and velocity error 200%	0.1183	0.1369	0.2552 [0.2404, 0.2764]	0.2599	0.0699	0.3298 [0.3242, 0.3342]
	Vertical position error 400%	0.2248	0.1266	0.3515 [0.3353, 0.3709]	0.357	0.0644	0.4214 [0.415, 0.4265]
	Vertical velocity error 400%	0.1065	0.1684	0.2749 [0.2603, 0.2935]	0.2749	0.086	0.3608 [0.3558, 0.3676]

	Scenario	Unresolved	Induced	Total [lower CI, upper CI]	Unresolved	Induced	Total [lower CI, upper CI]
	Vertical position and velocity error 400%	0.2135	0.1679	0.3814 [0.3608, 0.398]	0.3605	0.0766	0.4371 [0.4295, 0.4414]

Table 39. GBSS correlated track error sensitivity analysis metrics.

		Risk Ratio			**Loss of Well Clear Ratio**		
	Scenario	**Unresolved**	**Induced**	**Total [lower CI, upper CI]**	**Unresolved**	**Induced**	**Total [lower CI, upper CI]**
Default Configuration	Total Error 1-σ (from DO-365B) Horizontal Position: 80.91 m Vertical Position: 68.57 m Horizontal Velocity: 2.89 m/s Vertical Rate: 2.76 m/s	0.0321	0.2386	0.2707 [0.2062, 0.3283]	0.5826	0.0814	0.664 [0.6605, 0.67]
Zero Errors	Horizontal Position: 0 m Vertical Position: 0 m Horizontal Velocity: 0 m/s Vertical Rate: 0 m/s	0.024	0.0516	0.0756 [0.0564, 0.1026]	0.4788	0.0365	0.5153 [0.5116, 0.5195]
Horizontal Position Error	50% of default	0.0259	0.2409	0.2668 [0.2243, 0.3431]	0.5822	0.0815	0.6637 [0.6595, 0.6678]
	75% of default	0.0283	0.2481	0.2763 [0.2121, 0.3339]	0.5826	0.0818	0.6644 [0.6605, 0.6694]
	125% of default	0.0322	0.24	0.2722 [0.226, 0.3459]	0.5827	0.0818	0.6645 [0.6607, 0.6692]
	150% of default	0.0339	0.2465	0.2804 [0.2323, 0.4069]	0.5818	0.0821	0.6639 [0.6603, 0.6681]
	200% of default	0.0333	0.2562	0.2895 [0.2381, 0.3551]	0.5827	0.0821	0.6648 [0.6613, 0.6684]
	300% of default	0.0339	0.2751	0.309 [0.243, 0.3601]	0.5844	0.0828	0.6672 [0.6635, 0.6716]
	400% of default	0.0357	0.3048	0.3404 [0.2691, 0.4107]	0.5878	0.0831	0.6709 [0.665, 0.6743]
Horizontal Velocity Error	50% of default	0.0311	0.2432	0.2743 [0.2121, 0.3176]	0.5811	0.082	0.6631 [0.6583, 0.6674]
	75% of default	0.0341	0.2466	0.2807 [0.2238, 0.3328]	0.5809	0.0824	0.6633 [0.6593, 0.6672]
	125% of default	0.0284	0.2554	0.2838 [0.214, 0.3367]	0.5838	0.0819	0.6657 [0.6621, 0.6707]
	150% of default	0.0263	0.242	0.2683 [0.2132, 0.3214]	0.585	0.0814	0.6664 [0.6633, 0.6712]

	200% of default	0.0286	0.2645	0.2931 [0.2327, 0.3599]	0.588	0.0823	0.6704 [0.6665, 0.6747]
	300% of default	0.0284	0.2926	0.321 [0.2553, 0.3971]	0.5971	0.0827	0.6798 [0.6754, 0.6844]
	400% of default	0.0295	0.3276	0.3571 [0.2723, 0.4557]	0.6093	0.0814	0.6907 [0.6871, 0.6949]
Vertical Position Error	50% of default	0.0249	0.1558	0.1806 [0.1441, 0.2312]	0.5645	0.0771	0.6416 [0.6385, 0.6459]
	75% of default	0.0238	0.1611	0.1848 [0.1494, 0.2351]	0.5728	0.0792	0.652 [0.6476, 0.6558]
	125% of default	0.0311	0.352	0.3831 [0.3214, 0.4565]	0.5924	0.087	0.6794 [0.6761, 0.684]
	150% of default	0.0363	0.4312	0.4675 [0.3885, 0.6558]	0.6043	0.0932	0.6974 [0.6929, 0.7012]
	200% of default	0.0762	0.6105	0.6867 [0.6, 0.8328]	0.627	0.1074	0.7344 [0.7306, 0.7382]
	300% of default	0.1216	1.0573	1.1789 [1.0389, 1.3644]	0.674	0.1412	0.8153 [0.8112, 0.8202]
	400% of default	0.1893	1.4732	1.6625 [1.4838, 1.947]	0.7146	0.1759	0.8905 [0.8862, 0.8958]
Vertical Velocity Error	50% of default	0.0237	0.1325	0.1562 [0.1143, 0.1958]	0.5422	0.0497	0.5919 [0.5872, 0.5961]
	75% of default	0.027	0.1476	0.1746 [0.1464, 0.2199]	0.5613	0.064	0.6252 [0.6211, 0.6288]
	125% of default	0.0309	0.3786	0.4096 [0.3286, 0.499]	0.6038	0.1041	0.7079 [0.7033, 0.712]
	150% of default	0.0345	0.6018	0.6363 [0.5271, 0.775]	0.623	0.1275	0.7506 [0.747, 0.7558]
	200% of default	0.0401	0.8022	0.8423 [0.7356, 0.9886]	0.6591	0.1733	0.8324 [0.827, 0.8378]
	300% of default	0.0641	1.4139	1.478 [1.3297, 1.7029]	0.7125	0.2382	0.9506 [0.9448, 0.9568]
	400% of default	0.0681	2.1041	2.1722 [1.8547, 2.5194]	0.7503	0.2809	1.0312 [1.027, 1.0368]

Table 40 through Table 42 show the metrics for the primary final safety scenario results discussed in Section 4.1 through Section 4.12 (Figure 17-Figure 28). Table 40 shows the safety metrics, Table 41 shows the operational suitability metrics, and Table 42 shows some additional metrics.

Note: Best Sensor metrics are not available for runs with ATAR performed with the Phase I tracker, because sensor selection information is not output by the Phase I tracker.

Table 40. Final safety primary scenario safety metrics.

Scenario	Sim ID	Sensors Encounter Set Platform DAA Logic	Risk Ratio			Loss of Well Clear Ratio		
			Unresolved	Induced	Total [lower CI, upper CI]	Unresolved	Induced	Total [lower CI, upper CI]
DAA Class 1+6 ATAR Combined	1	ATAR + AST (100 ft), Correlated, HALE, DAIDALUS	0.0218	0.091	0.1129 [0.0852, 0.1809]	0.5686	0.0777	0.6463 [0.6401, 0.6504]
	2	ATAR + AST (100 ft) + ADS-B, Correlated, HALE, DAIDALUS	0.0133	0.151	0.1643 [0.1031, 0.2217]	0.4949	0.0927	0.5875 [0.5827, 0.5931]
	3	ATAR + AST (25 ft) + ADS-B, Correlated, HALE, DAIDALUS	0.0121	0.0599	0.072 [0.0478, 0.1061]	0.466	0.0636	0.5297 [0.5243, 0.5349]
	4	ATAR + AST (100 ft), Correlated, MALE, DAIDALUS	0.0668	0.0908	0.1576 [0.1257, 0.222]	0.5818	0.0648	0.6465 [0.6428, 0.6511]
	5	ATAR + AST (100 ft) + ADS-B, Correlated, MALE, DAIDALUS	0.0301	0.3128	0.3429 [0.2647, 0.4018]	0.5133	0.0698	0.5832 [0.5793, 0.5864]
	6	ATAR + AST (25 ft) + ADS-B, Correlated, MALE, DAIDALUS	0.0255	0.1068	0.1323 [0.0816, 0.1763]	0.4747	0.0463	0.521 [0.5177, 0.5259]
	7	ATAR + AST (100 ft), Correlated, LEPR, DAIDALUS	0.0556	0.3674	0.423 [0.364, 0.471]	0.6404	0.0764	0.7168 [0.7136, 0.7196]
	8	ATAR + AST (100 ft) + ADS-B, Correlated, LEPR, DAIDALUS	0.0438	0.4278	0.4716 [0.4245, 0.5348]	0.5366	0.0497	0.5863 [0.583, 0.5897]
	9	ATAR + AST (25 ft) + ADS-B, Correlated, LEPR, DAIDALUS	0.0337	0.2151	0.2488 [0.2143, 0.2939]	0.5122	0.0429	0.555 [0.5522, 0.5578]
DAA Class 1+6 GBSS Combined	10	GBSS + AST (100 ft), Correlated, HALE, DAIDALUS	0.0094	0.0935	0.1029 [0.0660, 0.1591]	0.4061	0.1290	0.5351 [0.5310, 0.5415]
	11	GBSS + AST (100 ft) + ADS-B, Correlated, HALE, DAIDALUS	0.0113	0.0835	0.0948 [0.0665, 0.1634]	0.4258	0.1147	0.5405 [0.5349, 0.5461]
	12	GBSS + AST (25 ft) + ADS-B, Correlated, HALE, DAIDALUS	0.0205	0.0708	0.0914 [0.0632, 0.1513]	0.4430	0.1086	0.5516 [0.5443, 0.5579]
	13	GBSS + AST (100 ft), Correlated, MALE, DAIDALUS	0.0164	0.1720	0.1883 [0.1402, 0.2385]	0.4329	0.1134	0.5463 [0.5422, 0.5508]

	14	GBSS + AST (100 ft) + ADS-B, Correlated, MALE, DAIDALUS	0.0203	0.1695	0.1898 [0.1483, 0.2376]	0.4489	0.0992	0.5481 [0.5449, 0.5526]
	15	GBSS + AST (25 ft) + ADS-B, Correlated, MALE, DAIDALUS	0.0176	0.1842	0.2018 [0.1574, 0.2497]	0.4641	0.0936	0.5576 [0.5529, 0.5618]
	16	GBSS + AST (100 ft), Correlated, LEPR, DAIDALUS	0.0280	0.4340	0.4620 [0.3974, 0.5157]	0.4736	0.1309	0.6044 [0.6009, 0.6095]
	17	GBSS + AST (100 ft) + ADS-B, Correlated, LEPR, DAIDALUS	0.0306	0.3913	0.4218 [0.3772, 0.5002]	0.4875	0.1060	0.5935 [0.5902, 0.5964]
	18	GBSS + AST (25 ft) + ADS-B, Correlated, LEPR, DAIDALUS	0.0361	0.3612	0.3972 [0.3482, 0.4530]	0.4999	0.0921	0.5920 [0.5882, 0.5962]
DAA Class 2+6 ATAR Combined	19	ATAR + AST (100 ft), Correlated, HALE, DAIDALUS/TCAS RA Logic	0.0161	0.0726	0.0887 [0.0578, 0.1425]	0.4767	0.1114	0.5881 [0.5818, 0.5931]
	20	ATAR + AST (100 ft) + ADS-B, Correlated, HALE, DAIDALUS/TCAS RA Logic	0.0097	0.1131	0.1228 [0.0902, 0.203]	0.4203	0.1262	0.5465 [0.5415, 0.5547]
	21	ATAR + AST (100 ft), Correlated, MALE, DAIDALUS/TCAS RA Logic	0.0281	0.1069	0.1351 [0.1003, 0.1844]	0.4996	0.0815	0.5811 [0.577, 0.5846]
	22	ATAR + AST (100 ft) + ADS-B, Correlated, MALE, DAIDALUS/TCAS RA Logic	0.0122	0.1583	0.1706 [0.1274, 0.2149]	0.4484	0.0882	0.5366 [0.5325, 0.5409]
	23	ATAR + AST (100 ft), Correlated, LEPR, DAIDALUS/TCAS RA Logic	0.0476	0.6893	0.7369 [0.6668, 0.8156]	0.6166	0.1048	0.7214 [0.7183, 0.7249]
	24	ATAR + AST (100 ft) + ADS-B, Correlated, LEPR, DAIDALUS/TCAS RA Logic	0.0348	0.656	0.6909 [0.6227, 0.7533]	0.5293	0.0825	0.6118 [0.6083, 0.6144]
DAA Class 2+6 GBSS Combined	25	GBSS + AST (100 ft), Correlated, HALE, DAIDALUS/TCAS RA Logic	0.008	0.0932	0.1011 [0.063, 0.1507]	0.3592	0.1523	0.5115 [0.5048, 0.5174]
	26	GBSS + AST (100 ft) + ADS-B, Correlated, HALE, DAIDALUS/TCAS RA Logic	0.0095	0.0802	0.0897 [0.0551, 0.1297]	0.3717	0.1411	0.5128 [0.506, 0.5192]
	27	GBSS + AST (100 ft), Correlated, MALE, DAIDALUS/TCAS RA Logic	0.0115	0.1274	0.1389 [0.0814, 0.1828]	0.389	0.1209	0.5099 [0.5037, 0.5128]

	28	GBSS + AST (100 ft) + ADS-B, Correlated, MALE, DAIDALUS/TCAS RA Logic	0.0096	0.1263	0.1359 [0.0979, 0.2005]	0.4011	0.1097	0.5108 [0.504, 0.5151]
	29	GBSS + AST (100 ft), Correlated, LEPR, DAIDALUS/TCAS RA Logic	0.0259	0.6791	0.7051 [0.6373, 0.8381]	0.4816	0.1491	0.6307 [0.6264, 0.6352]
	30	GBSS + AST (100 ft) + ADS-B, Correlated, LEPR, DAIDALUS/TCAS RA Logic	0.0266	0.6503	0.6768 [0.595, 0.7425]	0.4929	0.1281	0.621 [0.617, 0.6251]
DAA Class 8 GBSS Combined	31	GBSS + ADS-B, Correlated, HALE, DAIDALUS	0.0103	0.0519	0.0622 [0.0422, 0.0962]	0.4753	0.0892	0.5644 [0.5583, 0.57]
	32	GBSS + ADS-B, Correlated, MALE, DAIDALUS	0.0197	0.1326	0.1523 [0.1072, 0.1933]	0.4951	0.0766	0.5716 [0.5665, 0.5755]
	33	GBSS + ADS-B, Correlated, LEPR, DAIDALUS	0.0347	0.4931	0.5278 [0.4441, 0.5933]	0.5157	0.0505	0.5662 [0.5623, 0.5692]
DAA Class 1+6+5 GBSS Combined Terminal	34	GBSS + AST (100 ft), Terminal, HALE, DAIDALUS	0.0434	0.0458	0.0892 [0.087, 0.0919]	0.291	0.0107	0.3016 [0.2999, 0.3031]
	35	GBSS + AST (100 ft) + ADS-B, Terminal, HALE, DAIDALUS	0.0431	0.0467	0.0898 [0.087, 0.0922]	0.2922	0.0108	0.303 [0.3015, 0.3044]
	36	GBSS + AST (25 ft) + ADS-B, Terminal, HALE, DAIDALUS	0.0473	0.0496	0.0969 [0.0951, 0.0996]	0.3025	0.0108	0.3133 [0.3119, 0.3148]
	37	GBSS + AST (100 ft), Terminal, MALE, DAIDALUS	0.041	0.0486	0.0896 [0.0881, 0.0912]	0.3648	0.0107	0.3755 [0.3739, 0.3772]
	38	GBSS + AST (100 ft) + ADS-B, Terminal, MALE, DAIDALUS	0.0414	0.0508	0.0921 [0.0906, 0.0941]	0.3743	0.0107	0.385 [0.383, 0.3862]
	39	GBSS + AST (25 ft) + ADS-B, Terminal, MALE, DAIDALUS	0.0477	0.0536	0.1013 [0.0998, 0.1032]	0.3827	0.0106	0.3933 [0.3917, 0.3947]
	40	GBSS + AST (100 ft), Terminal, LEPR, DAIDALUS	0.0793	0.1285	0.2078 [0.2058, 0.2099]	0.772	0.0113	0.7834 [0.7824, 0.7844]
	41	GBSS + AST (100 ft) + ADS-B, Terminal, LEPR, DAIDALUS	0.0834	0.1344	0.2178 [0.215, 0.2202]	0.7813	0.0109	0.7922 [0.7911, 0.7931]
	42	GBSS + AST (25 ft) + ADS-B, Terminal, LEPR, DAIDALUS	0.0904	0.1338	0.2242 [0.2219, 0.2267]	0.7787	0.0105	0.7893 [0.7884, 0.7902]
DAA Class 8+5 GBSS	43	GBSS + ADS-B, Terminal, HALE, DAIDALUS	0.0555	0.054	0.1095 [0.1071, 0.1113]	0.3285	0.0107	0.3392 [0.3374, 0.3407]

Combined Terminal	44	GBSS + ADS-B, Terminal, MALE, DAIDALUS	0.0591	0.0594	0.1185 [0.117, 0.1205]	0.4143	0.0106	0.425 [0.4234, 0.4263]
	45	GBSS + ADS-B, Terminal, LEPR, DAIDALUS	0.1113	0.141	0.2524 [0.2503, 0.2549]	0.7842	0.0105	0.7947 [0.7937, 0.7954]
DAA Class 1+6 GBSS and ATAR Correlated with Noncoop DWC (up to FL100)	46	ATAR, Correlated, HALE, DAIDALUS	0.0690	0.3465	0.4155 [0.2606, 0.5469]	0.1615	0.1680	0.3295 [0.3195, 0.3432]
	47	ATAR, Correlated, MALE, DAIDALUS	0.1176	0.4658	0.5833 [0.4731, 0.7105]	0.2058	0.1313	0.3371 [0.3293, 0.3444]
	48	ATAR, Correlated, LEPR, DAIDALUS	0.1529	0.7799	0.9327 [0.8628, 0.9991]	0.3832	0.0935	0.4767 [0.4723, 0.4811]
	49	GBSS, Correlated, HALE, DAIDALUS	0.0121	0.1639	0.176 [0.1157, 0.2581]	0.1115	0.0807	0.1923 [0.1847, 0.1992]
	50	GBSS, Correlated, MALE, DAIDALUS	0.0282	0.3018	0.33 [0.2718, 0.4096]	0.1389	0.0746	0.2135 [0.2062, 0.2189]
	51	GBSS, Correlated, LEPR, DAIDALUS	0.0457	0.7059	0.7516 [0.6745, 0.8294]	0.2097	0.0791	0.2889 [0.2837, 0.2936]
DAA Class 1+6 GBSS and ATAR Noncoop (up to FL100)	52	ATAR, Uncorrelated, HALE, DAIDALUS	0.0579	0.0914	0.1493 [0.1377, 0.1662]	0.1551	0.0954	0.2505 [0.2456, 0.2562]
	53	ATAR, Uncorrelated, MALE, DAIDALUS	0.118	0.0796	0.1976 [0.1873, 0.2125]	0.2353	0.0955	0.3309 [0.325, 0.3365]
	54	ATAR, Uncorrelated, LEPR, DAIDALUS	0.1476	0.1622	0.3099 [0.2981, 0.3312]	0.4299	0.0985	0.5284 [0.5218, 0.5335]
	55	GBSS, Uncorrelated, HALE, DAIDALUS	0.0311	0.0357	0.0668 [0.0601, 0.0783]	0.1141	0.0534	0.1675 [0.1636, 0.1731]
	56	GBSS, Uncorrelated, MALE, DAIDALUS	0.032	0.0456	0.0776 [0.069, 0.0878]	0.1338	0.0628	0.1966 [0.1918, 0.2019]
	57	GBSS, Uncorrelated, LEPR, DAIDALUS	0.0364	0.1003	0.1367 [0.1249, 0.1493]	0.169	0.0628	0.2318 [0.2252, 0.2369]
DAA Class 8 GBSS Correlated with Noncoop DWC (up to FL100)	58	GBSS, Correlated, HALE, DAIDALUS	0.0112	0.1151	0.1263 [0.0836, 0.1966]	0.0991	0.0688	0.1679 [0.1604, 0.1735]
	59	GBSS, Correlated, MALE, DAIDALUS	0.0223	0.2272	0.2494 [0.1874, 0.3232]	0.1228	0.0686	0.1913 [0.1852, 0.1966]
	60	GBSS, Correlated, LEPR, DAIDALUS	0.0394	0.661	0.7004 [0.6269, 0.7777]	0.1922	0.0745	0.2667 [0.2625, 0.2711]
DAA Class 1+6+5 GBSS	61	GBSS, Terminal, HALE, DAIDALUS	0.0761	0.0586	0.1346 [0.132, 0.1375]	0.3724	0.0111	0.3835 [0.3819, 0.3851]

Combined Terminal	62	GBSS, Terminal, MALE, DAIDALUS	0.0854	0.0673	0.1527 [0.1505, 0.1552]	0.4677	0.0111	0.4788 [0.4776, 0.4802]
	63	GBSS, Terminal, LEPR, DAIDALUS	0.1578	0.157	0.3148 [0.3121, 0.3171]	0.8118	0.0105	0.8223 [0.8214, 0.8231]
DAA Class 8+5 GBSS Only Terminal	64	GBSS, Terminal, HALE, DAIDALUS	0.0684	0.0569	0.1253 [0.1229, 0.1283]	0.3497	0.0109	0.3606 [0.3591, 0.3625]
	65	GBSS, Terminal, MALE, DAIDALUS	0.0761	0.0641	0.1401 [0.1379, 0.1422]	0.4381	0.0111	0.4491 [0.4475, 0.4505]
	66	GBSS, Terminal, LEPR, DAIDALUS	0.1411	0.1484	0.2895 [0.2871, 0.2928]	0.7881	0.0111	0.7991 [0.7982, 0.7999]

Table 41. Final safety primary scenario operational suitability metrics.

Scenario	Sim ID	Alert Rate [lower CI, upper CI]	SLoWC Metrics			
			# LoWC (P(LoWC|ENC*))	# SLoWC1s (P(SLoWC1|LoWC))	# SLoWC2s (P(SLoWC2|SLoWC1))	# NMAC (P(NMAC|SLoWC2))
DAA Class 1+6 ATAR Combined	1	1410.65 [960.37, 1952.65]	181079 (2.74%)	112783 (53.09%)	6454 (2.01%)	834 (4.24%)
	2	953.94 [720.5, 1252.3]	156384 (2.49%)	92323 (49.79%)	5973 (3.08%)	675 (5.4%)
	3	870.88 [583.01, 1172.71]	143347 (2.24%)	84198 (49.27%)	4475 (2%)	492 (4.27%)
	4	1869.11 [1702.69, 2061.98]	192109 (3.45%0	86583 (34.28%)	5197 (2.25%)	951 (5.08%)
	5	1300 [1185.09, 1471.19]	165599 (3.12%)	71139 (32.39%)	4903 (3.22%)	1024 (5.28%)
	6	1205.44 [1109.6, 1327.56]	151349 (2.78%)	63877 (31.67%)	3644 (2.12%)	649 (5.99%)
	7	2125.21 [2084.59, 2177.6]	211853 (4%)	54737 (17.32%)	4526 (2.85%)	1506 (7.02%)
	8	1456.13 [1434.52, 1495.84]	171324 (3.27%)	42830 (16.44%)	3104 (2.7%)	1492 (10.16%)
	9	1358.31 [1318.92, 1383]	162953 (3.1%)	38824 (15.99%)	2519 (2.37%)	978 (8.24%)
DAA Class 1+6 GBSS Combined	10	1830.89 [1329.22, 2362.56]	129473 (2.26%)	75311 (49.05%)	3671 (2.35%)	352 (5.98%)
	11	1656 [1178.94, 2231.4]	134893 (2.29%)	79622 (49.04%)	4019 (2.35%)	401 (5.31%)

	12	1529.9 [1097.39, 2034.32]	137420 (2.33%)	81529 (48.95%)	4096 (2.39%)	403 (4.57%)
	13	2286.3 [2009.85, 2473.15]	142904 (2.92%)	58628 (31.5%)	2802 (2.26%)	466 (5.37%)
	14	2097.05 [1915.3, 2280.09]	147367 (2.93%)	61651 (31.55%)	3169 (2.35%)	509 (5.31%)
	15	1965.47 [1776.19, 2210.88]	149657 (2.98%)	63128 (31.81%)	3288 (2.19%)	525 (5.58%)
	16	2405.63 [2343.54, 2447.85]	164336 (3.37%)	39022 (16.59%)	2643 (2.89%)	1061 (9.29%)
	17	2211.87 [2158.11, 2263.71]	165123 (3.31%)	39855 (16.34%)	2822 (2.76%)	1098 (8.72%)
	18	2072.66 [2032.84, 2113.87]	165443 (3.3%)	40384 (16.49%)	2854 (2.85%)	1159 (8.48%)
DAA Class 2+6 ATAR Combined	19	1581.99 [1071.82, 2054.52]	145522 (2.49%)	88710 (52.3%)	3948 (2.05%)	472 (3.29%)
	20	1246.62 [844.36, 1657.64]	127355 (2.32%)	74033 (49.79%)	3658 (2.67%)	337 (5.4%)
	21	2052.16 [1833.16, 2249.47]	155915 (3.11%)	67664 (33.52%)	3201 (2.05%)	513 (4.06%)
	22	1635 [1498.02, 1835.2]	140716 (2.87%)	58108 (31.78%)	3001 (2.71%)	417 (3.66%)
	23	2290.6 [2236.29, 2335.75]	207312 (4.03%)	51816 (17.42%)	4039 (3.6%)	1653 (7.98%)
	24	1755.93 [1714.41, 1785.59]	174905 (3.41%)	41967 (16.67%)	2917 (3.38%)	1407 (9.19%)
DAA Class 2+6 GBSS Combined	25	1979.92 [1393.11, 2599.29]	110729 (2.17%)	63154 (49.22%)	2536 (2.17%)	225 (5.81%)
	26	1829.68 [1369.07, 2605.83]	113918 (2.17%)	65791 (49.32%)	2673 (2.04%)	237 (5.03%)
	27	2456.41 [2226.86, 2787.52]	124537 (2.72%)	49597 (30.99%)	1980 (2.12%)	285 (4.64%)
	28	2294.47 [2092.82, 2506.4]	127365 (2.73%)	51564 (31.05%)	2171 (2.14%)	312 (5.2%)
	29	2571.61 [2512.41, 2618.53]	171194 (3.52%)	39636 (16.81%)	2532 (3.42%)	1125 (10.56%)

	30	2402.58 [2357.47, 2456.71]	171550 (3.47%)	40089 (16.55%)	2620 (3.42%)	1145 (10.14%)
DAA Class 8 GBSS Combined	31	928.9 [693.53, 1361.53]	147949 (2.39%)	85965 (48.32%)	3689 (1.89%)	327 (2.59%)
	32	1284.22 [1181.25, 1393.35]	160009 (3.05%)	66144 (31.12%)	3226 (2.13%)	494 (4.98%)
	33	1458.68 [1428.79, 1492.33]	164987 (3.16%)	40196 (16.24%)	2888 (2.93%)	1269 (11.16%)
DAA Class 1+6+5 GBSS Combined Terminal	34	8.72 [8.67,8.79]	99688 (4.98%)	11600 (11.64%)	173 (1.49%)	6497 (64.74%)
	35	8.66 [8.61,8.73]	100133 (5.01%)	11787 (11.77%)	202 (1.71%)	6546 (65.84%)
	36	8.51 [8.46,8.57]	103542 (5.18%)	12503 (12.08%)	217 (1.74%)	7060 (59.45%)
	37	7.36 [7.32,7.41]	188325 (9.42%)	18483 (9.81%)	175 (0.95%)	10506 (65.71%)
	38	7.29 [7.26,7.32]	193083 (9.65%)	19042 (9.86%)	212 (1.11%)	10799 (66.51%)
	39	7.2 [7.17,7.24]	197247 (9.86%)	20720 (10.5%)	211 (1.02%)	11869 (65.4%)
	40	6.54 [6.51,6.56]	560805 (28.04%)	64870 (11.57%)	182 (0.28%)	36203 (65.93%)
	41	6.49 [6.45,6.51]	567134 (28.36%)	67540 (11.91%)	198 (0.29%)	37945 (65.66%)
	42	6.45 [6.43,6.48]	565043 (28.25%)	69023 (12.22%)	202 (0.29%)	39069 (67.82%)
DAA Class 8+5 GBSS Combined Terminal	43	7.98 [7.93,8.02]	112087 (5.6%)	14025 (12.51%)	227 (1.62%)	7980 (59.91%)
	44	6.77 [6.74,6.81]	213144 (10.66%)	23916 (11.22%)	243 (1.02%)	13889 (68.31%)
	45	6.13 [6.1,6.15]	568936 (28.45%)	75743 (13.31%)	219 (0.29%)	43970 (70.32%)
DAA Class 1+6 GBSS and ATAR Correlated with Noncoop DWC (up to FL100)	46	1314.37 [1015.2, 1672.92]	28371 (0.38%)	14704 (36.58%)	1576 (7.89%)	1477 (46.18%)
	47	1617.62 [1488.9, 1781.74]	42921 (0.56%)	18379 (23.93%)	2044 (6.28%)	2361 (51.11%)
	48	1514.96 [1484.07, 1545.91]	83722 (0.94%)	21576 (11.84%)	2422 (4.59%)	4457 (49.58%)
	49	990.62 [723.48, 1418.41]	17040 (0.22%)	7247 (28.3%)	608 (5.47%)	491 (52.86%)
	50	1351.89 [1207.66, 1468.1]	23281 (0.36%)	7448 (18.34%)	679 (6.7%)	731 (40.47%)
	51	1468.25 [1437.49, 1498.69]	43964 (0.57%)	9426 (11.85%)	819 (5.38%)	1789 (44.3%)

DAA Class 1+6 GBSS and ATAR Noncoop (up to FL100)	52	146.54 [145.26, 147.7]	68478 (1.17%)	27357 (35.23%)	2580 (7.96%)	4631 (47.92%)
	53	129.41 [128.22, 130.73]	96079 (1.66%)	27275 (20.38%)	1867 (6.59%)	7989 (48.58%)
	54	115.53 [114.25, 116.96]	163931 (2.63%)	33341 (14.28%)	1640 (5.06%)	10800 (43.8%)
	55	140.07 [138.41, 141.2]	47992 (0.78%)	15900 (27%)	1142 (5.85%)	2496 (41.14%)
	56	132.25 [130.94, 133.43]	56480 (0.99%)	11465 (16.81%)	710 (6.29%)	2748 (41.39%)
	57	123.13 [121.71, 124.25]	67189 (1.15%)	10419 (12.41%)	332 (3.6%)	3462 (62.53%)
DAA Class 8 GBSS Correlated with Noncoop DWC (up to FL100)	58	990.93 [706.99, 1216.22]	14389 (0.19%)	6009 (27.96%)	457 (4.68%)	361 (42.51%)
	59	1352.49 [1234, 1476.87]	20253 (0.32%)	6381 (18.1%)	510 (6.33%)	568 (38.02%)
	60	1468.91 [1438.79, 1500.41]	40283 (0.52%)	8577 (11.76%)	763 (4.8%)	1597 (48.45%)
DAA Class 1+6+5 GBSS Terminal	61	7.91 [7.86,7.96]	126735 (6.34%)	17245 (13.61%)	273 (1.58%)	9810 (63%)
	62	6.72 [6.7, 6.75]	240115 (12.01%)	30651 (12.77%)	280 (0.91%)	17895 (66.07%)
	63	6.08 [6.05, 6.1]	587757 (29.43%)	92241 (15.69%)	241 (0.26%)	54763 (68.88%)
DAA Class 8+5 GBSS Only Terminal	64	7.92 [7.87,7.98]	119148 (5.96%)	16035 (13.46%)	262 (1.63%)	9128 (64.12%)
	65	6.73 [6.71,6.78]	225258 (11.26%)	28206 (12.52%)	257 (0.91%)	16427 (66.15%)
	66	6.09 [6.07,6.12]	572111 (28.61%)	85220 (14.9%)	221 (0.26%)	50438 (71.95%)

* ENC is defined as the start of the simulation. Probabilities are weighted; raw numbers of event severity are not.

Table 42. Final safety primary scenario additional metrics.

Scenario	Sim ID	Best Sensor (% of encounters where each sensor was selected most often) Note: This metric is not available (N/A) for runs performed with the Phase I tracker.				Number of Alerts (Overall Number, % issued when ADS-B is best % issued when ATAR is best % issued when AST is best % issued when GBSS is best) Note: TCAS RAs are always issued based on AST data Note: For terminal encounters, only Warning alerts are issued when the intruder is in the DTA.			
		ADS-B	**ATAR**	**Active (AST)**	**GBSS**	**Preventive**	**Corrective**	**Warning**	**TCAS RAs**
DAA Class 1+6 ATAR Combined	1	N/A	N/A	N/A	N/A	525237 (N/A, N/A, N/A, N/A)	534983 (N/A, N/A, N/A, N/A)	477994 (N/A, N/A, N/A, N/A)	--
	2	N/A	N/A	N/A	N/A	466633 (N/A, N/A, N/A, N/A)	395773 (N/A, N/A, N/A, N/A)	388424 (N/A, N/A, N/A, N/A)	--
	3	N/A	N/A	N/A	N/A	446934 (N/A, N/A, N/A, N/A)	380948 (N/A, N/A, N/A, N/A)	362929 (N/A, N/A, N/A, N/A)	--
	4	N/A	N/A	N/A	N/A	519360 (N/A, N/A, N/A, N/A)	528882 (N/A, N/A, N/A, N/A)	477048 (N/A, N/A, N/A, N/A)	--
	5	N/A	N/A	N/A	N/A	457669 (N/A, N/A, N/A, N/A)	390119 (N/A, N/A, N/A, N/A)	389277 (N/A, N/A, N/A, N/A)	--
	6	N/A	N/A	N/A	N/A	443481 (N/A, N/A, N/A, N/A)	379061 (N/A, N/A, N/A, N/A)	366230 (N/A, N/A, N/A, N/A)	--
	7	N/A	N/A	N/A	N/A	450631 (N/A, N/A, N/A, N/A)	524130 (N/A, N/A, N/A, N/A)	474578 (N/A, N/A, N/A, N/A)	--
	8	N/A	N/A	N/A	N/A	401148 (N/A, N/A, N/A, N/A)	385058 (N/A, N/A, N/A, N/A)	393676 (N/A, N/A, N/A, N/A)	--
	9	N/A	N/A	N/A	N/A	373555 (N/A, N/A, N/A, N/A)	371857 (N/A, N/A, N/A, N/A)	371961 (N/A, N/A, N/A, N/A)	--
DAA Class 1+6 GBSS Combined	10	--	--	50.78	49.22	698682 (0, 0, 67.43, 32.57)	638509 (0, 0, 66.63, 33.37)	533518 (0, 0, 68.32, 31.68)	--
	11	13.86	--	37.76	48.38	652509 (10.57, 0, 56.31, 33.12)	591078 (10.68, 0, 55.52, 33.8)	512204 (12.02, 0, 56.88, 31.09)	--
	12	14.56	--	31.39	54.05	635047 (11.31, 0, 50.77, 37.93)	563778 (11.57, 0, 49.35, 39.07)	504961 (12.66, 0, 51.95, 35.38)	--

	13	--	--	50.09	49.91	678631 (0, 0, 66.15, 33.85)	613308 (0, 0, 65.05, 34.95)	507941 (0, 0, 65.5, 34.5)	--
	14	13.82	--	37.81	48.36	636701 (10.52, 0, 55.58, 33.89)	572093 (10.72, 0, 54.35, 34.94)	490868 (12.16, 0, 54.63, 33.21)	--
	15	14.56	--	31.17	54.27	618743 (11.27, 0, 49.68, 39.04)	545775 (11.64, 0, 47.75, 40.61)	485313 (12.73, 0, 49.24, 38.03)	--
	16	--	--	48.8	51.2	592397 (0, 0, 63.23, 36.77)	588431 (0, 0, 63.14, 36.86)	501116 (0, 0, 62.99, 37.01)	--
	17	14.18	--	36.67	49.15	553036 (10.45, 0, 52.71, 36.84)	550439 (10.96, 0, 52.24, 36.8)	481918 (12.6, 0, 51.7, 35.7)	--
	18	15.05	--	29.72	55.23	535020 (11.21, 0, 45.97, 42.82)	524037 (11.97, 0, 44.84, 43.19)	473810 (13.37, 0, 45.21, 41.42)	--
DAA Class 2+6 ATAR Combined	19	N/A	N/A	N/A	N/A	542385 (N/A, N/A, N/A, N/A)	529075 (N/A, N/A, N/A, N/A)	440859 (N/A, N/A, N/A, N/A)	330873
	20	N/A	N/A	N/A	N/A	460585 (N/A, N/A, N/A, N/A)	388361 (N/A, N/A, N/A, N/A)	357599 (N/A, N/A, N/A, N/A)	325129
	21	N/A	N/A	N/A	N/A	533519 (N/A, N/A, N/A, N/A)	513592 (N/A, N/A, N/A, N/A)	433237 (N/A, N/A, N/A, N/A)	295782
	22	N/A	N/A	N/A	N/A	463419 (N/A, N/A, N/A, N/A)	386829 (N/A, N/A, N/A, N/A)	365490 (N/A, N/A, N/A, N/A)	304583
	23	N/A	N/A	N/A	N/A	470148 (N/A, N/A, N/A, N/A)	516415 (N/A, N/A, N/A, N/A)	461909 (N/A, N/A, N/A, N/A)	291634
	24	N/A	N/A	N/A	N/A	406151 (N/A, N/A, N/A, N/A)	379179 (N/A, N/A, N/A, N/A)	383148 (N/A, N/A, N/A, N/A)	276051
DAA Class 2+6 GBSS Combined	25	--	--	50.91	49.09	706316 (0, 0, 67.97, 32.03)	643177 (0, 0, 67.33, 32.67)	513512 (0, 0, 69.12, 30.88)	279646
	26	13.85	--	37.87	48.28	660704 (10.52, 0, 56.99, 32.49)	595100 (10.53, 0, 56.36, 33.12)	489013 (11.84, 0, 57.68, 30.48)	290777
	27	--	--	50.22	49.78	685948 (0, 0, 66.6, 33.4)	615398 (0, 0, 65.8, 34.2)	490183 (0, 0, 66.32, 33.68)	262820

	28	13.84	--	37.91	48.25	645237 (10.53, 0, 56.1, 33.36)	573337 (10.57, 0, 55.2, 34.24)	470259 (11.98, 0, 55.4, 32.62)	270972
	29	--	--	48.97	51.03	601311 (0, 0, 63.51, 36.49)	584385 (0, 0, 63.5, 36.5)	496111 (0, 0, 63.6, 36.4)	261389
	30	14.16	--	36.82	49.03	562690 (10.57, 0, 52.94, 36.5)	546076 (10.9, 0, 52.6, 36.49)	475608 (12.5, 0, 52.29, 35.21)	264381
DAA Class 8 GBSS Combined	31	19.45	--	--	80.55	461240 (19.32, 0, 0, 80.68)	378032 (18.48, 0, 0, 81.52)	365077 (20.29, 0, 0, 79.71)	--
	32	19.14	--	--	80.86	461351 (18.8, 0, 0, 81.2)	377547 (18.18, 0, 0, 81.82)	373260 (19.48, 0, 0, 80.52)	--
	33	19.17	--	--	80.83	410787 (18.13, 0, 0, 81.87)	377504 (18.06, 0, 0, 81.94)	380888 (19.24, 0, 0, 80.76)	--
DAA Class 1+6+5 GBSS Combined Terminal	34	--	--	46.94	53.06	132902 (0, 0, 45.43, 54.57)	142676 (0, 0, 42.43, 57.57)	557633 (0, 0, 49.94, 50.06)	--
	35	21.82	--	30.43	47.75	127216 (12.93, 0, 33.2, 53.87)	138861 (12.55, 0, 31.33, 56.12)	553850 (10.76, 0, 42.02, 47.23)	--
	36	22.91	--	20.92	56.17	122044 (13.04, 0, 23.87, 63.09)	134213 (12.77, 0, 22.29, 64.94)	544325 (11.04, 0, 31.8, 57.16)	--
	37	--	--	45.85	54.15	129203 (0, 0, 47.74, 52.26)	142897 (0, 0, 46.25, 53.75)	785834 (0, 0, 54.46, 45.54)	--
	38	19.26	--	30.12	50.62	122674 (13.49, 0, 33.92, 52.6)	138166 (13.89, 0, 32.89, 53.21)	780025 (13.17, 0, 43.72, 43.11)	--
	39	20.28	--	21.04	58.68	118243 (13.66, 0, 24.42, 61.92)	133562 (14.29, 0, 23.33, 62.38)	770696 (13.76, 0, 33.77, 52.47)	--
	40	--	--	49.15	50.85	98039 (0, 0, 50.34, 49.66)	116463 (0, 0, 51.66, 48.34)	1081951 (0, 0, 59.21, 40.79)	--
	41	18	--	32.44	49.56	92844 (15.03, 0, 34, 50.97)	112034 (16.27, 0, 34.79, 48.94)	1073999 (15.88, 0, 45.4, 38.71)	--

	42	19.42	--	24.13	56.46	89883 (15.14, 0, 25.11, 59.75)	108698 (16.81, 0, 25.04, 58.16)	1069011 (16.72, 0, 36.99, 46.3)	--
DAA Class 8+5 GBSS Combined Terminal	43	25.72	--	--	74.28	110516 (15.25, 0, 0, 84.75)	121679 (14.61, 0, 0, 85.39)	505000 (17.26, 0, 0, 82.74)	--
	44	23.93	--	--	76.07	107163 (16.28, 0, 0, 83.72)	121058 (16.79, 0, 0, 83.21)	719656 (21.43, 0, 0, 78.57)	--
	45	24.56	--	--	75.44	82439 (18.5, 0, 0, 81.5)	99070 (20.56, 0, 0, 79.44)	1010278 (26.3, 0, 0, 73.7)	--
DAA Class 1+6 GBSS and ATAR Correlated with Noncoop DWC (up to FL100)	46	--	100	--	--	383516 (0, 100, 0, 0)	222243 (0, 100, 0, 0)	410219 (0, 100, 0, 0)	--
	47	--	100	--	--	396937 (0, 100, 0, 0)	214776 (0, 100, 0, 0)	436701 (0, 100, 0, 0)	--
	48	--	100	--	--	346046 (0, 100, 0, 0)	163728 (0, 100, 0, 0)	439720 (0, 100, 0, 0)	--
	49	--	--	--	100	399408 (0, 0, 0, 100)	321770 (0, 0, 0, 100)	325026 (0, 0, 0, 100)	--
	50	--	--	--	100	429961 (0, 0, 0, 100)	348645 (0, 0, 0, 100)	358554 (0, 0, 0, 100)	--
	51	--	--	--	100	398232 (0, 0, 0, 100)	362163 (0, 0, 0, 100)	377708 (0, 0, 0, 100)	--
DAA Class 1+6 GBSS and ATAR Noncoop (up to FL100)	52	--	100	--	--	678904 (0, 100, 0, 0)	434621 (0, 100, 0, 0)	639097 (0, 100, 0, 0)	--
	53	--	100	--	--	630998 (0, 100, 0, 0)	398121 (0, 100, 0, 0)	596214 (0, 100, 0, 0)	--
	54	--	100	--	--	572721 (0, 100, 0, 0)	320791 (0, 100, 0, 0)	612769 (0, 100, 0, 0)	--
	55	--	--	--	100	692197 (0, 0, 0, 100)	541109 (0, 0, 0, 100)	534275 (0, 0, 0, 100)	--
	56	--	--	--	100	696332 (0, 0, 0, 100)	542655 (0, 0, 0, 100)	529658 (0, 0, 0, 100)	--
	57	--	--	--	100	637099 (0, 0, 0, 100)	555919 (0, 0, 0, 100)	495073 (0, 0, 0, 100)	--
DAA Class 8 GBSS Correlated with Noncoop	58	--	--	--	100	396395 (0, 0, 0, 100)	321706 (0, 0, 0, 100)	317272 (0, 0, 0, 100)	--
	59	--	--	--	100	429703 (0, 0, 0, 100)	348599 (0, 0, 0, 100)	350532 (0, 0, 0, 100)	--

DWC (up to FL100)	60	--	--	--	100	398096 (0, 0, 0, 100)	363257 (0, 0, 0, 100)	371259 (0, 0, 0, 100)	--
DAA Class 1+6+5 GBSS Combined Terminal	61	--	--	--	100	109802 (0, 0, 0, 100)	120744 (0, 0, 0, 100)	500857 (0, 0, 0, 100)	--
	62	--	--	--	100	106992 (0, 0, 0, 100)	120219 (0, 0, 0, 100)	714169 (0, 0, 0, 100)	--
	63	--	--	--	100	83440 (0, 0, 0, 100)	98170 (0, 0, 0, 100)	1000548 (0, 0, 0, 100)	--
DAA Class 8+5 GBSS Only Terminal	64	--	--	--	100	110430 (0, 0, 0, 100)	120669 (0, 0, 0, 100)	501127 (0, 0, 0, 100)	--
	65	--	--	--	100	107548 (0, 0, 0, 100)	120196 (0, 0, 0, 100)	715265 (0, 0, 0, 100)	--
	66	--	--	--	100	83663 (0, 0, 0, 100)	98295 (0, 0, 0, 100)	1003789 (0, 0, 0, 100)	--

Table 43 – Table 45 show the metrics for the secondary final safety scenario results discussed in Section 4.13 (Figure 29 and Figure 30). Table 43 shows the safety metrics, Table 44 shows the operational suitability metrics, and Table 45 shows some additional metrics. Note that the best sensor metrics are not applicable here, since EO/IR was the only sensor used in these runs.

Table 43. Final safety secondary scenario safety metrics.

Scenario	**Sim ID**	**Sensors Encounter Set Platform DAA Logic**	**Risk Ratio**			**Loss of Well Clear Ratio**		
			Unresolved	**Induced**	**Total [lower CI, upper CI]**	**Unresolved**	**Induced**	**Total [lower CI, upper CI]**
DAA Class 1+6 EO/IR Noncoop (up to 1200 ft)	73	EO/IR, Uncorrelated, HALE, DAIDALUS	0.1301	0.4866	0.6167 [0.588, 0.6916]	0.47	0.2182	0.6882 [0.6782, 0.7025]
	74	EO/IR, Uncorrelated, MALE, DAIDALUS	0.1117	0.4082	0.5199 [0.4895, 0.5709]	0.4124	0.2058	0.6182 [0.6086, 0.634]
	75	EO/IR, Uncorrelated, LEPR, DAIDALUS	0.1471	0.2469	0.394 [0.3744, 0.4378]	0.4345	0.11	0.5445 [0.5346, 0.556]
DAA Class 1+6 EO/IR Noncoop (All Altitudes, Saturation Filtering)	73	EO/IR, Uncorrelated, HALE, DAIDALUS	0.0316	0.0196	0.0512 [0.0479, 0.0562]	0.4313	0.1353	0.5666 [0.5582, 0.5748]
	74	EO/IR, Uncorrelated, MALE, DAIDALUS	0.0423	0.0192	0.0615 [0.0558, 0.0763]	0.3647	0.1588	0.5235 [0.5303, 0.5341]
	75	EO/IR, Uncorrelated, LEPR, DAIDALUS	0.0751	0.0098	0.0849 [0.0803, 0.0926]	0.4037	0.1054	0.5092 [0.5012, 0.5175]

Table 44. Final safety secondary scenario operational suitability metrics.

Scenario	Sim ID	Alert Rate [lower CI, upper CI]	SLoWC Metrics			
			# LoWC (P(LoWC|ENC*))	# SLoWC1s (P(SLoWC1|LoWC))	# SLoWC2s (P(SLoWC2|SLoWC1))	# NMAC (P(NMAC|SLoWC2))
DAA Class 1+6 EO/IR Noncoop (up to 1200 ft)	73	145.51 [142.7, 148.46]	54112 (3.29%)	23197 (31.46%)	3172 (10.3%)	4806 (52.37%)
	74	147.47 [145.05, 150.03]	59904 (3.2%)	16434 (20.19%)	1392 (6.77%)	4814 (53.15%)
	75	146.38 [142.9, 148.69]	60625 (2.98%)	13015 (14.21%)	500 (4.12%)	4796 (49.61%)
DAA Class 1+6 EO/IR Noncoop (All Altitudes, Saturation Filtering)	73	323.43 [318.6, 327.71]	90988 (1.81%)	27559 (24.72%)	266 (0.55%)	914 (30.77%)
	74	241.59 [238.85, 244.83]	99476 (1.99%)	14804 (11.96%)	123 (0.67%)	1479 (25.07%)
	75	235.58 [232.87, 238.13]	114625 (2.16%)	10519 (6.4%)	56 (0.39%)	2738 (37.95%)

Table 45. Final safety secondary scenario additional metrics.

Scenario	Sim ID	Number of Alerts			
		Preventive	**Corrective**	**Warning**	**TCAS RAs**
DAA Class 1+6 EO/IR Noncoop (up to 1200 ft)	73	174262	81110	198156	--
	74	215804	134068	247787	--
	75	209595	164960	259705	--
DAA Class 1+6 EO/IR Noncoop (All Altitudes, Saturation Filtering)	73	503302	223169	572087	--
	74	549670	327579	627207	--
	75	563270	431331	676594	--

APPENDIX E SINGLE SENSOR AND LEPR RERUNS

This appendix discusses a follow-on analysis that was performed to understand the DAA performance that can be achieved without conflation from tracker best source selection. The sensor selection algorithm within the FAA Tech Center tracker only considers horizontal position error accuracy and may not select the sensor that results in the best DAA performance. Using only horizontal position error accuracy results in the following typical order for best sensor selection (from best to worst): 1) ATAR, 2) GBSS, 3) ADS-B (NACp of 7), 4) Active Surveillance (AS). Moreover, switching between sensors can also result in a large amount of jitter in the state estimates, causing abrupt changes in maneuver direction when the best sensor changes. There was particular concern that these tracker issues may have contributed to the poor LEPR performance that was observed. Thus, the runs in this appendix were performed using a single sensor (as was done in SC-228 Phase 1) to eliminate the influence of the tracker sensor selection algorithm on the results.

A subset of final safety evaluation scenarios, selected in coordination with MITRE (shown in Table 46), was rerun using a single sensor. These runs assume that the tracker would normally select the same single best source out of a group of sensor sensors (e.g., ADS-B), so it is not necessary to perform a multi-sensor run. These runs can be weighted in MITRE's safety assessment to account for the fact that different percentages of aircraft will be equipped with each type of sensor. This analysis was performed with correlated, uncorrelated, and terminal encounters. All runs were performed with DAIDALUS, and assume a Class 6 ownship with a 5 sec integrated delay. The same interruptions scheme and pilot model settings from the Phase 2 SRM analysis were used. In general, the results show that using a single sensor reduces the risk ratio, as expected.

Table 46. Single sensor runs.

Description	DWC	Altitude	Encounter Model	Sensor	UAS Type
Cooperative sensors with correlated encounters	En route	1,200 ft AGL to FL180	Correlated	AS	HALE
	En route	1,200 ft AGL to FL180	Correlated	AS	MALE
	En route	1,200 ft AGL to FL180	Correlated	AS	LEPR
	En route	1,200 ft AGL to FL180	Correlated	ADS-B	HALE
	En route	1,200 ft AGL to FL180	Correlated	ADS-B	MALE
	En route	1,200 ft AGL to FL180	Correlated	ADS-B	LEPR
Cooperative sensors with uncorrelated encounters	En route	1,200 ft AGL to FL180	Uncorrelated	AS	HALE
	En route	1,200 ft AGL to FL180	Uncorrelated	AS	MALE
	En route	1,200 ft AGL to FL180	Uncorrelated	AS	LEPR
	En route	1,200 ft AGL to FL180	Uncorrelated	ADS-B	HALE
	En route	1,200 ft AGL to FL180	Uncorrelated	ADS-B	MALE

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	En route	1,200 ft AGL to FL180	Uncorrelated	ADS-B	LEPR
Noncoop sensors with correlated encounters	Noncooperative	Surface to 10,000 ft AGL	Correlated	ATAR A1	HALE
	Noncooperative	Surface to 10,000 ft AGL	Correlated	ATAR A2	MALE
	Noncooperative	Surface to 10,000 ft AGL	Correlated	ATAR A3	LEPR
	Noncooperative	Surface to 10,000 ft AGL	Correlated	GBSS	HALE
	Noncooperative	Surface to 10,000 ft AGL	Correlated	GBSS	MALE
	Noncooperative	Surface to 10,000 ft AGL	Correlated	GBSS	LEPR
Noncoop sensors with uncorrelated encounters	Noncooperative	Surface to 10,000 ft AGL	Uncorrelated	ATAR A1	HALE
	Noncooperative	Surface to 10,000 ft AGL	Uncorrelated	ATAR A2	MALE
	Noncooperative	Surface to 10,000 ft AGL	Uncorrelated	ATAR A3	LEPR
	Noncooperative	Surface to 10,000 ft AGL	Uncorrelated	GBSS	HALE
	Noncooperative	Surface to 10,000 ft AGL	Uncorrelated	GBSS	MALE
	Noncooperative	Surface to 10,000 ft AGL	Uncorrelated	GBSS	LEPR
Terminal encounter runs	Terminal	Surface to 5,000 ft AGL	Terminal	AS	HALE
	Terminal	Surface to 5,000 ft AGL	Terminal	AS	MALE
	Terminal	Surface to 5,000 ft AGL	Terminal	AS	LEPR
	Terminal	Surface to 5,000 ft AGL	Terminal	ADS-B	HALE
	Terminal	Surface to 5,000 ft AGL	Terminal	ADS-B	MALE
	Terminal	Surface to 5,000 ft AGL	Terminal	ADS-B	LEPR
	Terminal	Surface to 5,000 ft AGL	Terminal	GBSS	HALE
	Terminal	Surface to 5,000 ft AGL	Terminal	GBSS	MALE
	Terminal	Surface to 5,000 ft AGL	Terminal	GBSS	LEPR
EO/IR runs	Noncooperative	Surface to 10,000 ft AGL	Correlated	EO/IR	HALE
	Noncooperative	Surface to 10,000 ft AGL	Correlated	EO/IR	MALE
	Noncooperative	Surface to 10,000 ft AGL	Correlated	EO/IR	LEPR
	Noncooperative	Surface to 10,000 ft AGL	Uncorrelated	EO/IR	HALE
	Noncooperative	Surface to 10,000 ft AGL	Uncorrelated	EO/IR	MALE
	Noncooperative	Surface to 10,000 ft AGL	Uncorrelated	EO/IR	LEPR
	Terminal	Surface to 5,000 ft AGL	Terminal	EO/IR	HALE
	Terminal	Surface to 5,000 ft AGL	Terminal	EO/IR	MALE
	Terminal	Surface to 5,000 ft AGL	Terminal	EO/IR	LEPR

In addition, an analysis of potential mitigations for poor LEPR DAA performance with noncooperative sensors (i.e., ATAR, GBSS, EO/IR) in the en route environment was performed. These mitigations were comprised of three ATAR-only special cases from DO-365:

1. Perform horizontal only maneuvers (i.e., saturate vertical guidance) (DO-365B §2.2.4.4.3.2.1). Note: DAIDALUS does not account for this case in the MOPS that states that vertical guidance based on ATAR must be saturated when the error measurements exceed a certain inequality; thus, this case is considered in the pilot response model by only maneuvering horizontally.

2. Treat intruders as co-altitude when they are within 3000 feet vertically (DO-365B §2.2.4.3.7.1); vertical separation is estimated using tracker output. In the implementation, the intruder is assumed to be at the same altitude as the ownship. Both ownship and intruder are assumed to have zero vertical rate.

3. Assess the effect of increasing the DAIDALUS vertical alerting threshold to 3000 feet (DO-365B §2.2.4.4.3.1.1.2). This is similar to the MOPS recommendation for encounters with noncooperative aircraft. The specific parameters in DAIDALUS that were set to 3000 feet were:
    - min_vertical_recovery

- DWC_Phase_I_det_1_WCV_ZTHR
- DWC_Phase_I_det_2_WCV_ZTHR
- DWC_Phase_I_det_3_WCV_ZTHR
- DWC_Phase_II_det_1_WCV_ZTHR
- DWC_Phase_II_det_2_WCV_ZTHR
- DWC_Phase_II_det_3_WCV_ZTHR
- DWC_Non_Coop_det_1_WCV_ZTHR
- DWC_Non_Coop_det_2_WCV_ZTHR
- DWC_Non_Coop_det_3_WCV_ZTHR

These parameters affect the DWC that is used within DAIDALUS.

Table 47 summarizes the LEPR mitigation scenarios that were run. In all of the runs, the noncooperative DWC was used, altitudes were constrained from surface to 10,000 ft AGL, the UAS platform is LEPR, and only horizontal maneuvers are performed. Because the ATAR and GBSS results did not show a large improvement in the horizontal maneuver only results when DAIDALUS vertical alerting limits and the co-altitude assumption were implemented, these two mitigations were not evaluated for EOIR.

Table 47. LEPR mitigation runs.

Description	Mitigation	Encounter Model	Sensor
Correlated Encounters	Horizontal only maneuvers	Correlated	ATAR
	DAIDALUS vertical limits & horizontal only maneuvers	Correlated	ATAR
	Co-altitude assumption & horizontal only maneuvers	Correlated	ATAR
	Horizontal only maneuvers	Correlated	GBSS
	DAIDALUS vertical limits & horizontal only maneuvers	Correlated	GBSS
	Co-altitude assumption & horizontal only maneuvers	Correlated	GBSS
	Horizontal only maneuvers	Correlated	EO/IR
Uncorrelated Encounters	Horizontal only maneuvers	Uncorrelated	ATAR
	DAIDALUS vertical limits & horizontal only maneuvers	Uncorrelated	ATAR
	Co-altitude assumption & horizontal only maneuvers	Uncorrelated	ATAR
	Horizontal only maneuvers	Uncorrelated	GBSS
	DAIDALUS vertical limits & horizontal only maneuvers	Uncorrelated	GBSS
	Co-altitude assumption & horizontal only maneuvers	Uncorrelated	GBSS
	Horizontal only maneuvers	Uncorrelated	EO/IR

Note: since the Phase 2 SRM analysis, there were a couple updates made to the simulation. One change is that the DAIDALUS dynamics parameters were updated to match each UAS platform's respective climb and turn rate limits. This change reduces the risk ratios. Another change is that in the Phase 2 analysis, any time the Phase II tracker (Version 7.5.1) would select AS as the best sensor, AS measurements from the sensor would be used directly (i.e., bypassing the tracker processing) due to errant tracker output for AS. In this follow-on analysis, the Phase I tracker was used to process measurements from the AS sensor, such that the tracker is no longer bypassed.

Section E.1 discusses the results of the single runs. Section E.2 discusses the results of the LEPR performance mitigations analysis. Section E.3 provides the numerical values of the metrics (risk ratios, LoWC ratios, etc.) that are shown in figures in Section E.1 and Section E.2.

E.1 Single Sensor Runs

This section describes the results of the single sensor runs performed to eliminate the influence of the tracker sensor selection algorithm on the results.

Figure 54 shows the results for correlated encounters run with either ATAR, AS, or ADS-B, compared with final safety evaluation simulations 3, 6, and 9, where ATAR, AS, and ADS-B were run simultaneously. Figure 55 shows the results for correlated encounters run with either GBSS, AS, or ADS-B, compared with final safety evaluation simulations 12, 15, and 18, where ATAR, AS, and GBSS were run simultaneously. The ADS-B and AS results are the same in both figures. AS and ADS-B single-sensor runs were performed using the en route LoWC volume, whereas GBSS and ATAR single-sensor runs were performed using the noncooperative LoWC volume. The discrepancies in the LoWC ratios are due to using different LoWC volumes for cooperative and noncooperative sensors. Note that the multi-sensor results are from the Phase 2 SRM analysis and were not rerun.

The risk ratio for LEPR when run with ADS-B only is approximately 29% lower than the multi-sensor run with ATAR+AS+ADS-B. However, running with AS or ATAR only increases the risk ratio. Likewise, the risk ratio for LEPR when run with ADS-B only is approximately 55% lower than the multi-sensor run with GBSS+AS+ADS-B, but running with AS or GBSS only increases the risk ratio. This corroborates the hypothesis that the best performance can be achieved when ADS-B is chosen as best sensor.

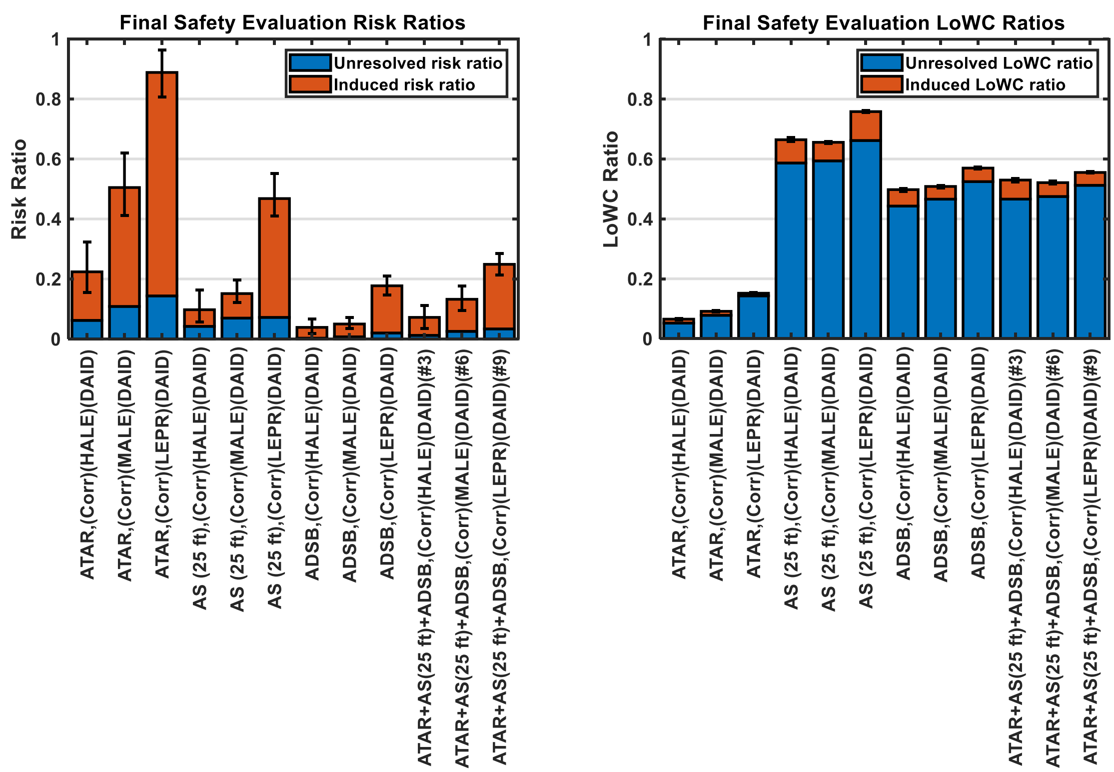

Figure 54. Correlated single sensor runs (ATAR, AS, ADS-B).

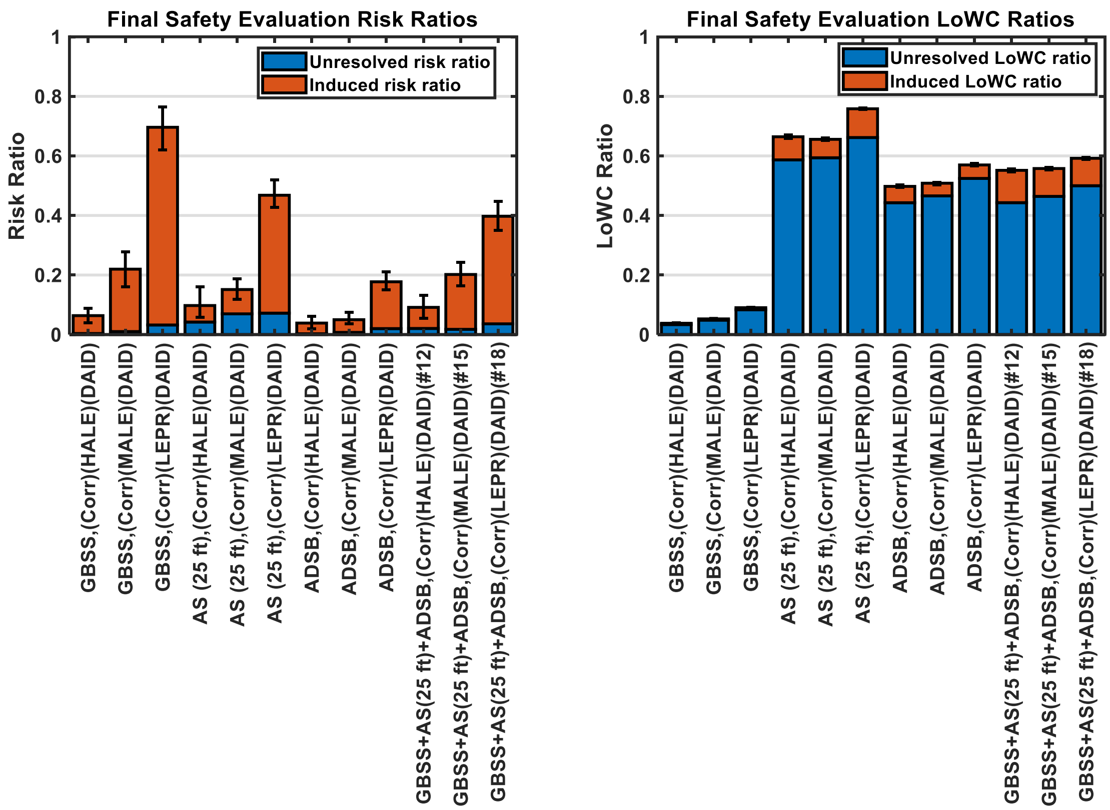

Figure 55. Correlated single sensor runs (GBSS, AS, ADS-B).

Figure 56 shows the results for uncorrelated encounters run with ATAR, AS, GBSS, or ADS-B only. AS and ADS-B single-sensor runs were performed using the en route LoWC volume, whereas GBSS and ATAR single-sensor runs were performed using the noncooperative LoWC volume. The discrepancies in the LoWC ratios are due to using different LoWC volumes. Unlike with the correlated encounters, there were no multi-sensor runs performed with the uncorrelated encounters in the SRM final safety evaluation.

The single sensor results show that LEPR performs best with ADS-B and worst with ATAR. In general, the trend is that HALE performs better than MALE, which performs better than LEPR. However, for AS, MALE actually performs worst out of the three platforms. This is because the AS results include encounters where the intruder track becomes invalid in the middle of the encounter (and thus DAIDALUS is acting on coasted information, which is inaccurate). When encounters where the AS track is not valid at the end of the encounter are excluded, the results are much more comparable among HALE, MALE, and LEPR, as shown in Figure 57. This again shows that the best performance can be achieved when ADS-B is chosen as best sensor.

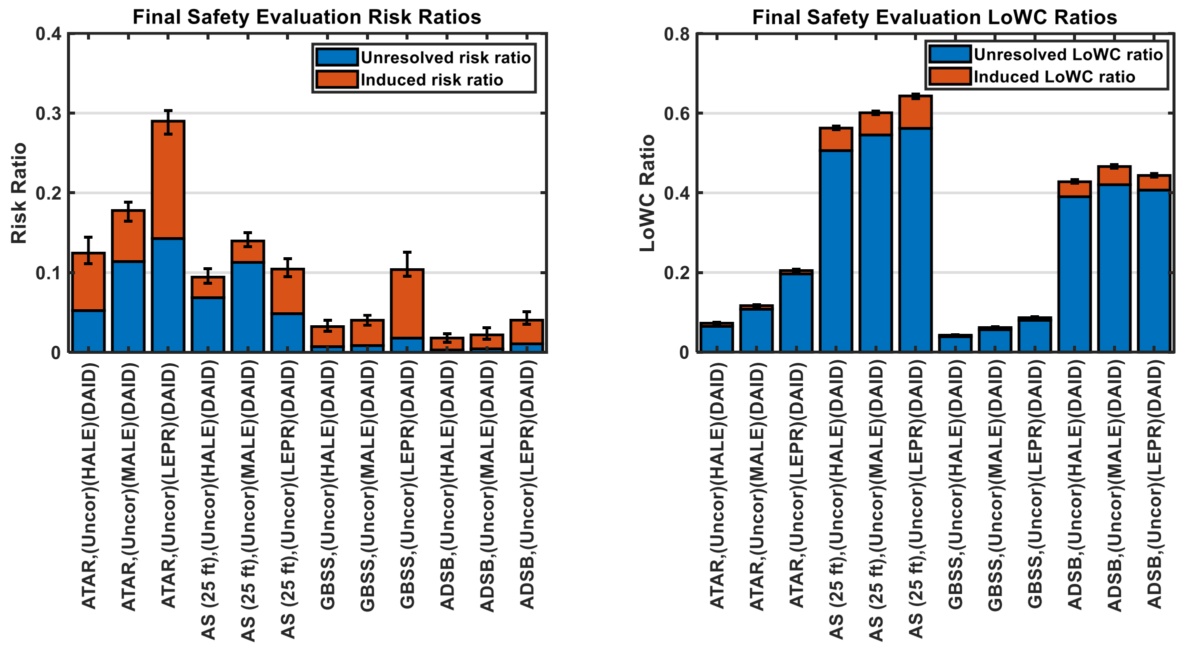

Figure 56. Uncorrelated single sensor runs (ATAR, AS, GBSS, ADS-B).

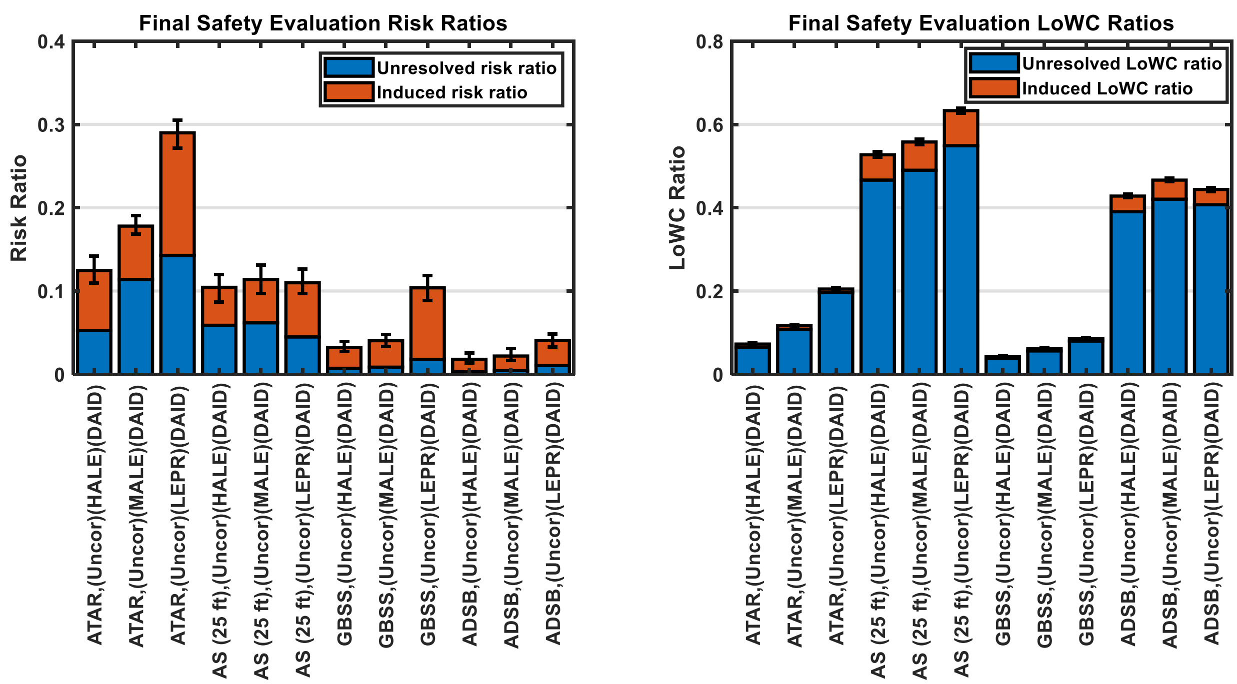

Figure 57. Uncorrelated single sensor runs (encounters with invalid AS tracks excluded).

Figure 58 shows the results for terminal encounters run with either AS, ADS-B, or GBSS using the terminal LoWC volume. (ATAR is not used in the terminal environment). These results are compared to final safety evaluation runs 36, 39, and 42, where AS, ADS-B, and GBSS were run simultaneously. Note that the multi-sensor results are from the Phase 2 SRM analysis and were not rerun.

Similar to the results for correlated and uncorrelated encounters, the risk ratio for LEPR run with ADS-B only is lower than the multi-sensor run with GBSS+AS+ADS-B (by approximately 17%). However, running AS or GBSS only generally increases the risk ratio. This once again shows that the best performance can be achieved when ADS-B is chosen as best sensor.

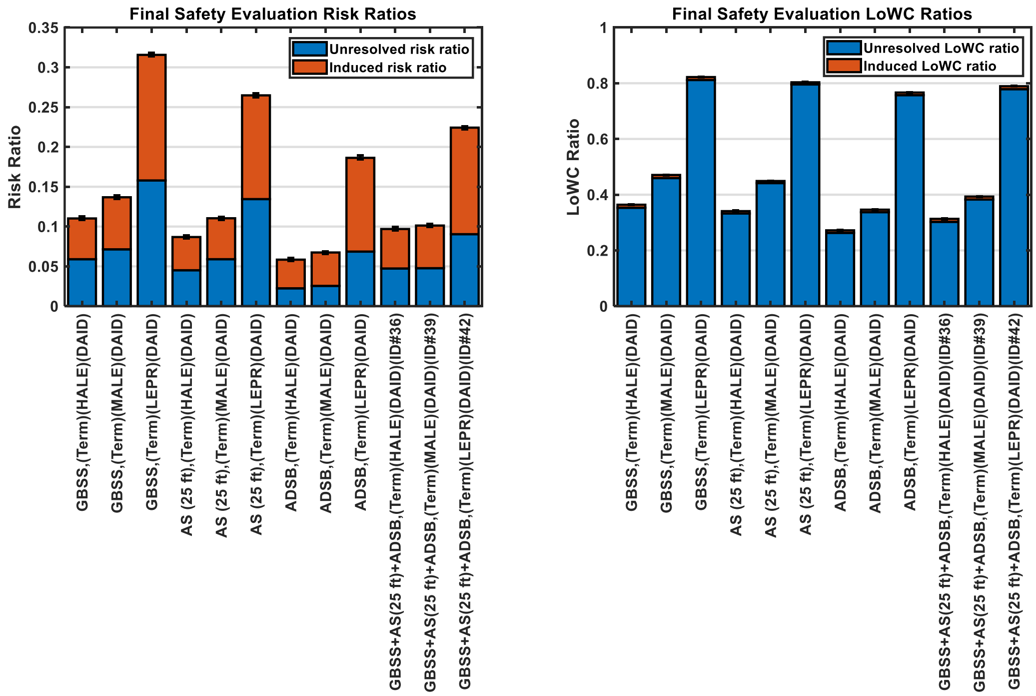

Figure 58. Terminal single sensor runs (GBSS, AS, ADS-B).

The results throughout this section showed that using ADS-B alone results in better performance than including ADS-B in a multi-sensor run. Figure 59 shows a particularly compelling example of this. Scenario 33 from the final safety evaluation is LEPR with GBSS+ADS-B, using correlated encounters. When ADS-B is run by itself, the multi-sensor risk ratio is reduced by approximately 71%. However, running GBSS alone is approximately 13% higher than the multi-sensor. This suggests the tracker is frequently choosing GBSS as the best sensor instead of ADS-B. Note: the discrepancies in the LoWC ratios are due to using different LoWC volumes—en route for GBSS+ADS-B and ADS-B only, and noncooperative for GBSS only.

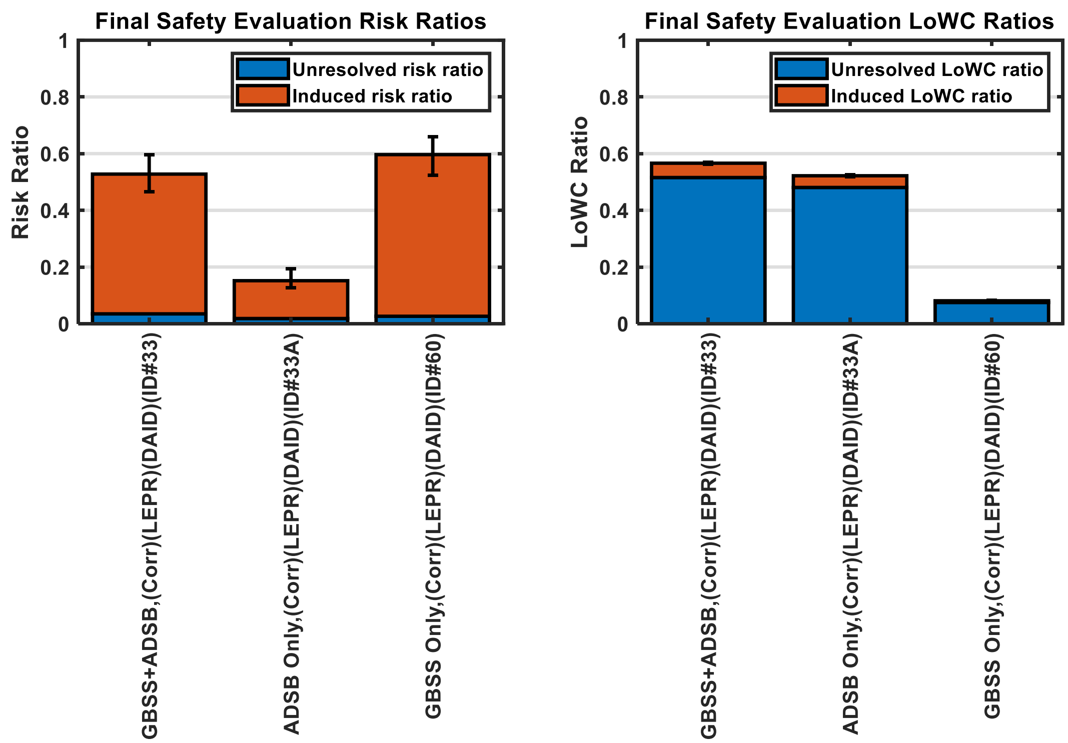

Figure 59. Scenario 33 case study.

In addition to performing single sensor runs with ADS-B, AS, ATAR, and GBSS, runs with EO/IR were also performed. (Note: there were no multi-sensor runs performed with EO/IR in the final safety evaluation). Figure 60 shows the results for correlated, uncorrelated, and terminal encounters run with EO/IR. The correlated and uncorrelated results use the noncooperative LoWC volume, and the terminal results use the terminal LoWC volume. The discrepancies in the LoWC ratios are due to using different LoWC volumes.

Due to peculiarities in the EO/IR track estimates output from the FAA Tech Center tracker, EO/IR sensor outputs were used directly (i.e., bypassing the tracker). In addition, correlated and uncorrelated runs were performed with horizontal only maneuvers as vertical maneuvers with the noisy EO/IR vertical estimates lead to high risk ratios. However, terminal encounters were still performed with vertical maneuvers since the terminal pilot model does not execute horizontal maneuvers in the terminal environment.

The EO/IR results show that the risk and LoWC ratios are especially high for the terminal encounters. The uncorrelated LEPR risk ratio (≈0.15) is higher than the numbers in the EOIR safety analysis (≈0.05) in Appendix E of DO-387 (EO/IR MOPS). The difference could be caused by several factors, including:

- Using interruptions and a 5-sec integrated delay in the SRM runs vs. no latencies in DO-387
- Using stochastic mode (SRM) vs. deterministic mode (DO-387) in the pilot model
- Using DAIDALUS v202 (including SUM) for SRM vs. DAIDALUS v101 for DO-387
- Including Radar Detection Range (RDR) in the SRM runs but not in the DO-387 analysis.

Finally, for the correlated/uncorrelated encounters, LEPR performs better than HALE and MALE. This is counter to the trends observed in the other single sensor runs, where HALE performs better than MALE, which performs better than LEPR. This happens because EO/IR sensor noise is dependent on range and range rate—i.e., because HALE encounters have the higher range rates, they also have the most noise.

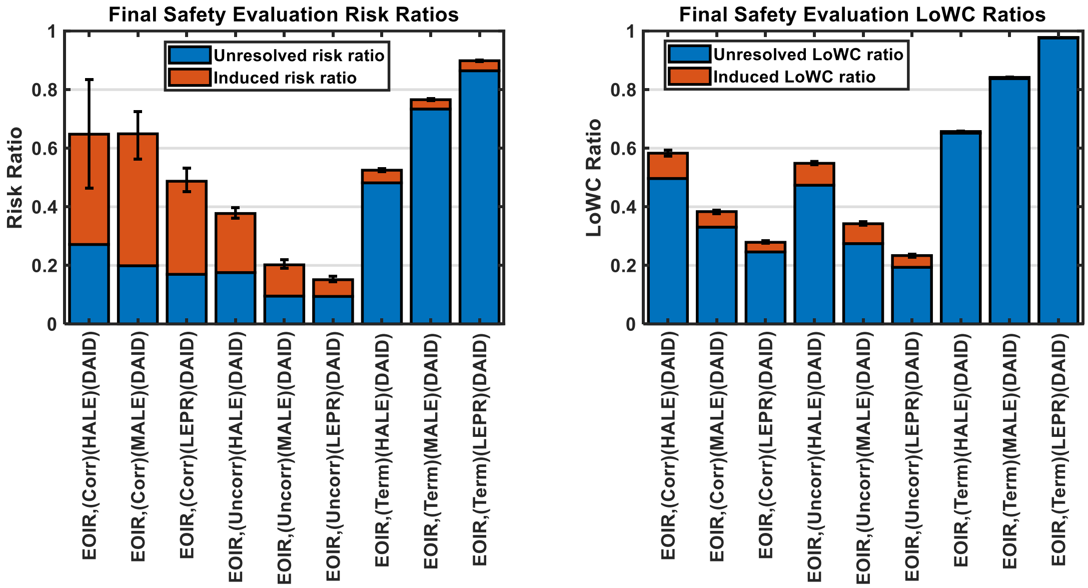

Figure 60. EO/IR single sensor runs.

E.2 LEPR Performance Mitigations

This section describes the results of the LEPR performance mitigation analysis, performed to better understand whether LEPR en route performance with noncooperative sensors could be improved using special cases described in DO-365. LEPR encounters were rerun with one of three mitigation strategies:

1) Horizontal maneuvers only.
2) Setting DADIALUS vertical alerting thresholds to 3000 ft & horizontal maneuvers only.
3) Co-altitude assumption & horizontal maneuvers only.

These runs were performed using correlated and uncorrelated encounters and the noncooperative LoWC definition, using ATAR and GBSS. EO/IR results using horizontal only maneuvers from Figure 60 are shown for comparison. However, because the ATAR and GBSS results did not show a large improvement in the horizontal maneuver only results when DAIDALUS vertical alerting limits and the co-altitude assumption were implemented, these two mitigations were not evaluated for EOIR.

Figure 61 shows the results for correlated encounters and Figure 62 shows the results for uncorrelated encounters. The risk ratios and LoWC ratios with the mitigations are lower than the risk ratios and LoWC ratios without the mitigations. Note that while the magnitude of the correlated risk ratios is large, the noncooperative sensor is not expected to be the primary sensor in correlated encounters (i.e., at least one cooperative sensor is expected).

Table 48 and Table 49 summarize the percentage decrease achieved by each mitigation strategy. GBSS has the best performance, followed by EO/IR, followed by ATAR. Setting the DAIDALUS vertical alerting thresholds and applying the co-altitude assumption result in slight improvement over using horizontal maneuvers only; the similar numbers in Table 48 and Table 49 for DAIDALUS vertical alerting thresholds and the co-altitude assumption indicate that these two mitigations essentially have the same effort. However, even just using horizontal maneuvers results in significant reductions in the risk and LoWC ratios. Thus, a reasonable recommendation for LEPR seems to be using horizontal maneuvers in the en route environment when using noncooperative sensors.

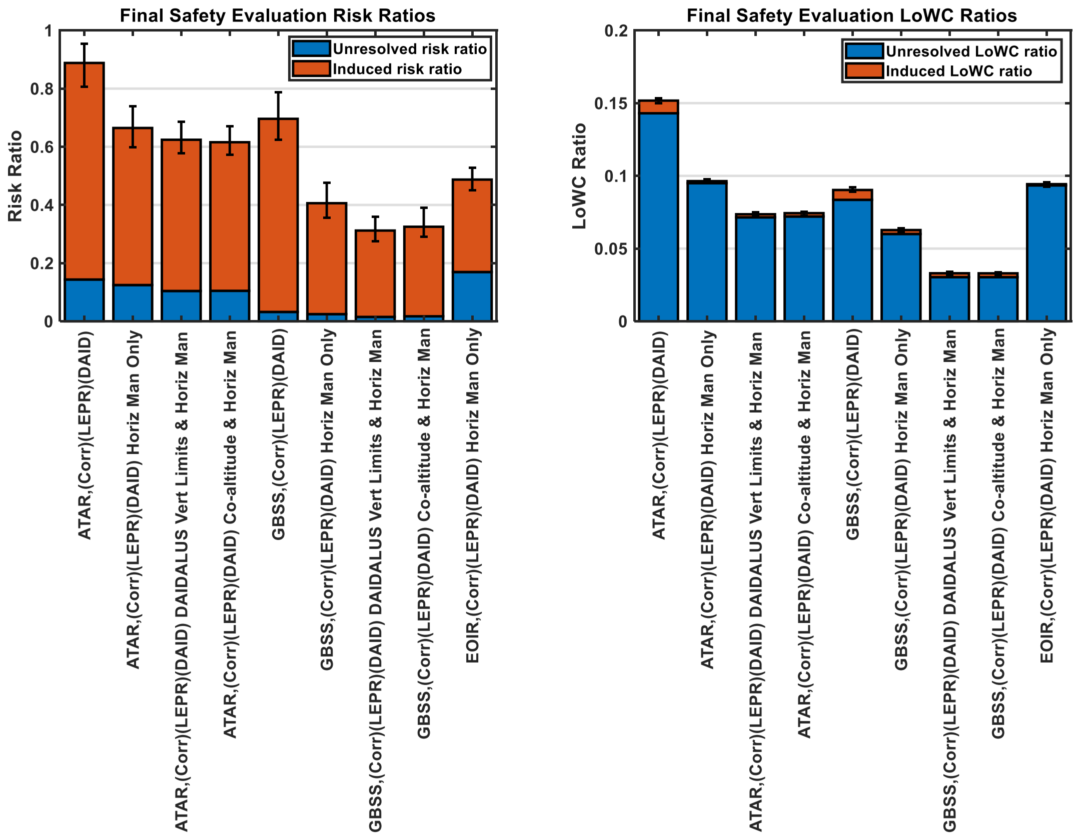

Figure 61. LEPR mitigation results (correlated encounters).

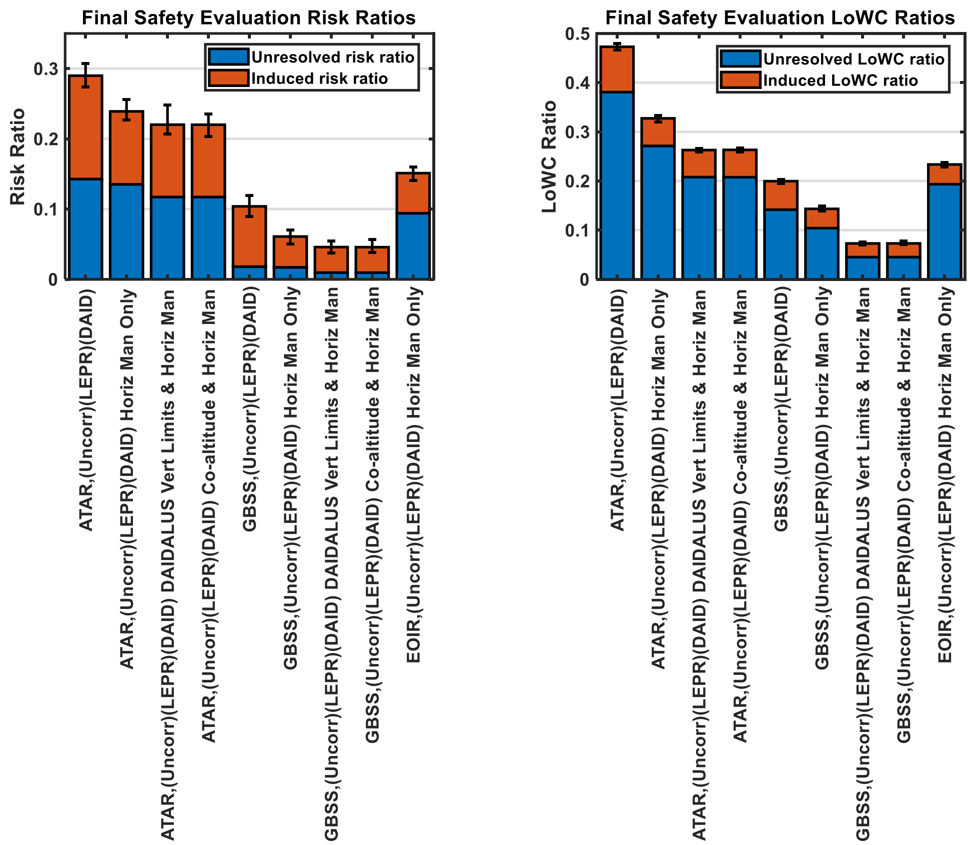

Figure 62. LEPR mitigation results (uncorrelated encounters).

Table 48. Percent change in risk ratio and LoWC ratio for LEPR mitigation analysis with correlated encounters.

		ATAR		**GBSS**	
		Risk Ratio	LoWC Ratio	Risk Ratio	LoWC Ratio
Mitigation Strategy	Horizontal Maneuvers Only	-25%	-36%	-42%	-31%
	DAIDALUS vertical alerting threshold & horizontal maneuvers	-30%	-51%	-55%	-63%
	Co-altitude assumption & horizontal maneuvers	-31%	-51%	-53%	-63%

Table 49. Percent change in risk ratio and LoWC ratio for LEPR mitigation analysis with uncorrelated encounters.

		ATAR		**GBSS**	
		Risk Ratio	LoWC Ratio	Risk Ratio	LoWC Ratio
Mitigation Strategy	Horizontal Maneuvers Only	-18%	-31%	-41%	-28%
	DAIDALUS vertical alerting threshold & horizontal maneuvers	-24%	-44%	-56%	-63%
	Co-altitude assumption & horizontal maneuvers	-24%	-44%	-56%	-63%

E.3 Rerun Results Metrics

This section provides the numerical values of the metrics (risk ratios, LoWC ratios, etc.) that were shown in figures throughout Appendix E. These metrics can be extracted for use in other analyses, including MITRE's fault trees. The safety metrics also include 95% confidence intervals (CI).

Table 43 – Table 52 show the metrics for the single sensor results discussed in this appendix (

Figure 54 – Figure 60). Table 50 shows the safety metrics, Table 51 shows the operational suitability metrics, and Table 52 shows some additional metrics. Note that the best sensor metrics are not applicable here, since these are all single sensor runs.

Table 50. Single sensor runs safety metrics.

Encounter Set, DWC Volume	**Sensor, Platform**	**Risk Ratio**			**Loss of Well Clear Ratio**		
		Unresolved	**Induced**	**Total [lower CI, upper CI]**	**Unresolved**	**Induced**	**Total [lower CI, upper CI]**
Correlated En route	AS, HALE	0.0421	0.0554	0.0975 [0.0573, 0.1626]	0.5867	0.0777	0.6644 [0.6588, 0.6717]
	AS, MALE	0.0696	0.0817	0.1513 [0.1215, 0.1964]	0.5938	0.0619	0.6557 [0.6521, 0.6593]
	AS, LEPR	0.072	0.3959	0.4679 [0.4104, 0.5514]	0.6617	0.0965	0.7583 [0.7557, 0.7618]
	ADS-B, HALE	0.0028	0.0359	0.0386 [0.0188, 0.0664]	0.4429	0.0548	0.4977 [0.4918, 0.5018]
	ADS-B, MALE	0.0073	0.0427	0.05 [0.0343, 0.072]	0.4658	0.0425	0.5083 [0.5039, 0.5116]
	ADS-B, LEPR	0.0201	0.1571	0.1773 [0.1464, 0.2099]	0.5244	0.0453	0.5697 [0.5672, 0.5727]
	ATAR, HALE	0.062	0.1619	0.2239 [0.1543, 0.3236]	0.0519	0.0132	0.0652 [0.0622, 0.0677]
	ATAR, MALE	0.1084	0.3962	0.5047 [0.4121, 0.6196]	0.078	0.0133	0.0913 [0.0893, 0.0933]
	ATAR, LEPR	0.1436	0.7445	0.8882 [0.8058, 0.9627]	0.143	0.0087	0.1517 [0.1495, 0.1533]
	GBSS, HALE	0.0036	0.0601	0.0636 [0.04, 0.0887]	0.0337	0.0043	0.038 [0.0365, 0.04]
	GBSS, MALE	0.0101	0.2096	0.2197 [0.1602, 0.2779]	0.0485	0.0041	0.0527 [0.0511, 0.0544]
	GBSS, LEPR	0.0322	0.6639	0.6961 [0.6208, 0.7649]	0.0835	0.0068	0.0903 [0.0889, 0.0914]

	EOIR, HALE	0.2714	0.3764	0.6478 [0.463, 0.8336]	0.4967	0.0863	0.583 [0.573, 0.5927]
	EOIR, MALE	0.1988	0.4503	0.6491 [0.5623, 0.7242]	0.3306	0.053	0.3836 [0.3772, 0.3891]
	EOIR, LEPR	0.1695	0.3177	0.4872 [0.452, 0.5312]	0.2459	0.0329	0.2788 [0.2752, 0.2834]
Uncorrelated En route	AS, HALE	0.0686	0.0258	0.0944 [0.087, 0.1048]	0.5063	0.0566	0.5629 [0.5586, 0.5682]
	AS, MALE	0.1129	0.0269	0.1397 [0.1326, 0.15]	0.5457	0.0557	0.6013 [0.5973, 0.6059]
	AS, LEPR	0.0486	0.0559	0.1045 [0.0949, 0.1173]	0.5621	0.0815	0.6436 [0.6373, 0.6487]
	ADS-B, HALE	0.0031	0.015	0.018 [0.0126, 0.0234]	0.3903	0.0376	0.428 [0.4246, 0.4332]
	ADS-B, MALE	0.0045	0.0175	0.022 [0.0166, 0.0307]	0.4205	0.0457	0.4662 [0.4621, 0.4713]
	ADS-B, LEPR	0.0108	0.0297	0.0404 [0.0353, 0.0511]	0.4071	0.0367	0.4438 [0.4395, 0.449]
	ATAR, HALE	0.0524	0.0721	0.1245 [0.1113, 0.1443]	0.0647	0.0079	0.0726 [0.0712, 0.0746]
	ATAR, MALE	0.1139	0.064	0.1779 [0.1647, 0.1884]	0.1078	0.0088	0.1166 [0.1139, 0.1185]
	ATAR, LEPR	0.1428	0.1471	0.2899 [0.2735, 0.303]	0.1964	0.0084	0.2048 [0.2019, 0.2083]
	GBSS, HALE	0.0072	0.0251	0.0324 [0.0264, 0.04]	0.0388	0.0036	0.0424 [0.041, 0.0435]
	GBSS, MALE	0.0086	0.0317	0.0403 [0.0341, 0.0466]	0.0563	0.0053	0.0616 [0.0597, 0.063]
	GBSS, LEPR	0.018	0.0858	0.1038 [0.0957, 0.1255]	0.08	0.0064	0.0864 [0.0842, 0.0889]
	EOIR, HALE	0.1755	0.2016	0.3771 [0.3614, 0.3976]	0.4736	0.0748	0.5484 [0.5433, 0.5551]
	EOIR, MALE	0.0952	0.1066	0.2019 [0.1899, 0.2189]	0.2744	0.0678	0.3422 [0.3365, 0.3486]
	EOIR, LEPR	0.094	0.0571	0.1511 [0.1437, 0.1637]	0.1934	0.0402	0.2335 [0.2286, 0.2382]

Terminal Encounters and LoWC Volume	AS, HALE	0.0451	0.0417	0.0868 [0.0851, 0.0886]	0.3325	0.0085	0.341 [0.3387, 0.3428]
	AS, MALE	0.059	0.0514	0.1104 [0.1083, 0.112]	0.4417	0.0074	0.4491 [0.4471, 0.4503]
	AS, LEPR	0.1345	0.1303	0.2648 [0.2622, 0.2671]	0.7956	0.0078	0.8034 [0.8025, 0.8043]
	ADS-B, HALE	0.0224	0.036	0.0584 [0.0565, 0.0607]	0.2631	0.009	0.2721 [0.2708, 0.2735]
	ADS-B, MALE	0.0255	0.0419	0.0674 [0.0658, 0.069]	0.3374	0.0089	0.3463 [0.345, 0.3477]
	ADS-B, LEPR	0.0685	0.1177	0.1863 [0.1846, 0.1896]	0.7573	0.0093	0.7666 [0.7657, 0.7679]
	GBSS, HALE	0.059	0.0512	0.1102 [0.1084, 0.113]	0.3532	0.0108	0.364 [0.3626, 0.3661]
	GBSS, MALE	0.0714	0.0654	0.1368 [0.1347, 0.1392]	0.4597	0.0111	0.4708 [0.4694, 0.472]
	GBSS, LEPR	0.1579	0.1577	0.3156 [0.3136, 0.318]	0.8116	0.0105	0.8221 [0.8213, 0.8228]
	EOIR, HALE	0.4817	0.0432	0.5249 [0.5203, 0.5299]	0.6513	0.0056	0.657 [0.655, 0.6586]
	EOIR, MALE	0.7337	0.0319	0.7656 [0.7628, 0.7687]	0.8376	0.0041	0.8417 [0.8407, 0.8425]
	EOIR, LEPR	0.8643	0.0343	0.8986 [0.8963, 0.9003]	0.9765	0.0016	0.9781 [0.9777, 0.9784]

Table 51. Single sensor runs operational suitability metrics.

Encounter Set, DWC Volume	**Sensor, Platform**	**Alert Rate [lower CI, upper CI]**	**SLoWC Metrics**			
			# LoWC (P(LoWC|ENC*))	**# SLoWC1s (P(SLoWC1|LoWC))**	**# SLoWC2s (P(SLoWC2|SLoWC1))**	**# NMAC (P(NMAC|SLoWC2))**
Correlated En route	AS, HALE	1210.9 [809.65, 1564.86]	147023	90319	6471	922
	AS, MALE	1829.31 [1687.37, 2068.04]	186026	82228	6040	1216
	AS, LEPR	2087.73 [2043.52, 2135.09]	221022	58199	5158	1982
	ADS-B, HALE	836.92 [611.32, 1037.96]	134126	78168	2766	162

	ADS-B, MALE	1162.17 [1072.17, 1294.85]	146764	60458	2514	204
	ADS-B, LEPR	1318.04 [1298.26, 1347.01]	167526	38896	2348	662
	ATAR, HALE	1314.37 [883.82, 1802.7]	23605	12178	1176	1191
	ATAR, MALE	1617.62 [1480.84, 1791.14]	40999	17844	1961	2149
	ATAR, LEPR	1514.96 [1471.19, 1552.9]	76350	19884	2284	4237
	GBSS, HALE	990.62 [635.54, 1272.61]	13428	5644	411	257
	GBSS, MALE	1351.89 [1240.4, 1486.6]	20395	6548	493	463
	GBSS, LEPR	1468.25 [1441.97, 1500.58]	40063	8238	735	1569
	EOIR, HALE	831.49 [619.65, 1125.16]	90157	47664	6811	5557
	EOIR, MALE	1273.05 [1088.65, 1371.07]	60126	23559	2754	4067
	EOIR, LEPR	1542.08 [1508.97, 1576.71]	44105	12277	929	3367
Uncorrelated En route	AS, HALE	198.33 [196.59, 200.31]	238343	107832	8342	4306
	AS, MALE	173.71 [172.01, 175.35]	252659	68724	6714	6857
	AS, LEPR	172.15 [170.49, 173.81]	245407	36037	1759	3581
	ADS-B, HALE	134.52 [133.2, 136.06]	171998	74268	3417	394
	ADS-B, MALE	126.91 [125.25, 128.06]	183520	39002	1977	530
	ADS-B, LEPR	114.69 [113.72, 115.78]	164084	18635	801	1031
	ATAR, HALE	146.54 [145.06, 147.86]	57621	22793	1884	3925

	ATAR, MALE	129.41 [128.14, 130.4]	90878	25832	1775	7574
	ATAR, LEPR	115.53 [114.43, 116.89]	144012	29706	1473	10109
	GBSS, HALE	140.07 [138.74, 141.65]	33934	10974	742	889
	GBSS, MALE	132.25 [130.83, 133.55]	46131	8017	514	1132
	GBSS, LEPR	123.09 [121.64, 124.52]	57613	7573	272	2208
	EOIR, HALE	120.92 [119.75, 122.09]	193406	83366	11218	12852
	EOIR, MALE	122.49 [121, 123.94]	110762	26699	1989	6786
	EOIR, LEPR	125.89 [125, 127.57]	73271	15061	498	5917
Terminal Encounters and LoWC Volume	AS, HALE	8.72 [8.66, 8.78]	112701	11505	258	6325
	AS, MALE	7.21 [7.16, 7.25]	225245	22555	277	12942
	AS, LEPR	6.29 [6.26, 6.32]	575151	80310	209	46131
	ADS-B, HALE	7.83 [7.77, 7.89]	89928	8077	186	4256
	ADS-B, MALE	6.7 [6.66, 6.74]	173671	14273	212	7903
	ADS-B, LEPR	6.11 [6.08, 6.15]	548800	58045	206	32455
	GBSS, HALE	7.91 [7.85, 7.95]	120309	14282	248	8027
	GBSS, MALE	6.72 [6.68, 6.75]	236138	27328	263	16034
	GBSS, LEPR	6.08 [6.05, 6.11]	588566	92565	242	54989
	EOIR, HALE	5.42 [5.39, 5.46]	217116	60819	345	38240

	EOIR, MALE	4.45 [4.43, 4.47]	422149	138374	384	89742
	EOIR, LEPR	3.34 [3.33, 3.36]	700210	241833	285	156559

Table 52. Single sensor runs additional metrics.

Encounter Set, DWC Volume	**Sensor, Platform**	**Number of Alerts**			
		Preventive	**Corrective**	**Warning**	**TCAS RAs**
Correlated En route	AS, HALE	423243	422501	391865	--
	AS, MALE	505626	505659	468153	--
	AS, LEPR	434607	522089	475274	--
	ADS-B, HALE	447459	371163	344321	--
	ADS-B, MALE	445408	371510	348938	--
	ADS-B, LEPR	361877	367344	358691	--
	ATAR, HALE	390608	221668	410097	--
	ATAR, MALE	402618	214248	436587	--
	ATAR, LEPR	342353	163402	439743	--
	GBSS, HALE	407355	321965	323444	--
	GBSS, MALE	438922	349100	356529	--
	GBSS, LEPR	394921	362233	378332	--
	EOIR, HALE	290063	146432	437765	--
	EOIR, MALE	303316	181694	451873	--
	EOIR, LEPR	326334	218387	455267	--
Uncorrelated En route	AS, HALE	662349	558538	530908	--
	AS, MALE	651168	549462	505652	--
	AS, LEPR	601552	568567	503531	--
	ADS-B, HALE	665927	526450	487075	--
	ADS-B, MALE	685764	533815	480393	--
	ADS-B, LEPR	585925	532914	445212	--
	ATAR, HALE	683293	433975	638759	--
	ATAR, MALE	633444	397429	596175	--
	ATAR, LEPR	567022	319685	612894	--
	GBSS, HALE	697767	541152	531901	--
	GBSS, MALE	703067	543017	528505	--
	GBSS, LEPR	640749	562155	502202	--
	EOIR, HALE	585018	358276	666620	--
	EOIR, MALE	614454	422071	673325	--
	EOIR, LEPR	633721	487545	676515	--
Terminal Encounters and LoWC Volume	AS, HALE	108417	139923	550687	--
	AS, MALE	98151	130678	767563	--
	AS, LEPR	64101	97704	1040482	--
	ADS-B, HALE	97505	111620	496996	--
	ADS-B, MALE	94060	111559	713280	--
	ADS-B, LEPR	72198	92156	1007178	--
	GBSS, HALE	109934	120747	500915	--
	GBSS, MALE	107205	120271	714161	--
	GBSS, LEPR	83587	98327	1002199	--
	EOIR, HALE	10329	10089	393110	--
	EOIR, MALE	8873	8621	521043	--
	EOIR, LEPR	4097	3867	584309	--

Table 53 – Table 55 show the metrics for the LEPR performance mitigation analysis results (Figure 61 – Figure 62). Table 53 shows the safety metrics, Table 54 shows the operational suitability metrics, and Table 55 shows some additional metrics. Note that the best sensor metrics are not applicable here, since these are all single sensor runs.

Table 53. LEPR performance mitigation analysis safety metrics.

Sensor, Encounter Set	**Mitigation**	**Risk Ratio**			**Loss of Well Clear Ratio**		
		Unresolved	**Induced**	**Total [lower CI, upper CI]**	**Unresolved**	**Induced**	**Total [lower CI, upper CI]**
ATAR, Correlated	Horizontal only maneuvers	0.1247	0.5399	0.6646 [0.5972, 0.71]	0.095	0.0014	0.0964 [0.0939, 0.0973]
	DAIDALUS vertical limits & horizontal only maneuvers	0.1043	0.5198	0.6241 [0.5785, 0.6854]	0.0715	0.0021	0.0736 [0.0721, 0.0749]
	Co-altitude assumption & horizontal only maneuvers	0.1048	0.5109	0.6157 [0.5587, 0.6545]	0.0721	0.0023	0.0744 [0.0731, 0.0759]
GBSS, Correlated	Horizontal only maneuvers	0.0247	0.3813	0.406 [0.366, 0.4678]	0.0601	0.0027	0.0627 [0.0614, 0.0643]
	DAIDALUS vertical limits & horizontal only maneuvers	0.0151	0.2968	0.312 [0.2746, 0.3602]	0.0304	0.0027	0.033 [0.032, 0.0339]
	Co-altitude assumption & horizontal only maneuvers	0.0172	0.3079	0.3251 [0.2844, 0.3721]	0.0304	0.0026	0.033 [0.0322, 0.0339]
EOIR, Correlated (same as Correlated EOIR, LEPR in Table 50)	Horizontal only maneuvers	0.1695	0.3177	0.4872 [0.4455, 0.5294]	0.0935	0.0009	0.0943 [0.0927, 0.0956]
ATAR, Uncorrelated	Horizontal only maneuvers	0.1353	0.1038	0.2391 [0.2232, 0.2539]	0.2713	0.056	0.3273 [0.3225, 0.3323]
	DAIDALUS vertical limits & horizontal only maneuvers	0.1172	0.1030	0.2202 [0.2070, 0.2485]	0.2079	0.0550	0.2629 [0.2584, 0.2659]
	Co-altitude assumption & horizontal only maneuvers	0.1172	0.1029	0.2201 [0.2045, 0.2362]	0.2076	0.0557	0.2633 [0.2582, 0.2679]
GBSS, Uncorrelated	Horizontal only maneuvers	0.017	0.0438	0.0609 [0.0528, 0.0699]	0.104	0.0392	0.1433 [0.1402, 0.1477]
	DAIDALUS vertical limits & horizontal only maneuvers	0.0095	0.0363	0.0458 [0.0373, 0.0548]	0.0451	0.0278	0.0729 [0.0694, 0.0757]
	Co-altitude assumption & horizontal only maneuvers	0.0094	0.0363	0.0457 [0.0364, 0.0543]	0.0451	0.0279	0.073 [0.0695, 0.0758]

EOIR, Uncorrelated (same as Uncorrelated EOIR, LEPR in Table 50)	Horizontal only maneuvers	0.094	0.0571	0.1511 [0.1413, 0.159]	0.1934	0.0402	0.2335 [0.2287, 0.2381]

Table 54. LEPR performance mitigation analysis operational suitability metrics.

Sensor, Encounter Set	**Test Case**	**Alert Rate [lower CI, upper CI]**	**SLoWC Metrics**			
			# LoWC (P(LoWC|ENC*))	**# SLoWC1s (P(SLoWC1|LoWC))**	**# SLoWC2s (P(SLoWC2|SLoWC1))**	**# NMAC (P(NMAC|SLoWC2))**
ATAR, Correlated	Horizontal only maneuvers	1514.96 [1477.45, 1551.94]	45497	12526	1215	2980
	DAIDALUS vertical limits & horizontal only maneuvers	2147.01 [2102.33, 2200.42]	36448	10117	891	2586
	Co-altitude assumption & horizontal only maneuvers	2175.92 [2137.07, 2238.27]	36541	10151	901	2595
GBSS, Correlated	DAIDALUS vertical limits & horizontal only maneuvers	1468.25 [1439.06, 1491.25]	24382	5013	411	933
	Co-altitude assumption & horizontal only maneuvers	2557.44 [2515.74, 2624.28]	14504	3201	293	640
	Horizontal only maneuvers	2544.12 [2493.12, 2605.73]	14476	3201	305	649
EOIR, Correlated (same as Correlated EOIR, LEPR in Table 51)	Horizontal only maneuvers	1523.43 [1499.64, 1562.21]	42598	11607	852	3268
ATAR, Uncorrelated	DAIDALUS vertical limits & horizontal only maneuvers	115.48 [114.34, 116.65]	100921	21579	753	8481
	Co-altitude assumption & horizontal only maneuvers	140.47 [139.15, 141.89]	76229	17781	551	7358

	Horizontal only maneuvers	142.14 [140.85, 143.56]	75862	17748	540	7393
GBSS, Uncorrelated	DAIDALUS vertical limits & horizontal only maneuvers	123.1 [121.87, 124.23]	40604	4976	166	1476
	Co-altitude assumption & horizontal only maneuvers	150.78 [150, 153.33]	18004	2630	117	867
	Horizontal only maneuvers	151.87 [150.23, 153.44]	17999	2669	118	892
EOIR, Uncorrelated (same as Uncorrelated EOIR, LEPR in Table 51)	Horizontal only maneuvers	125.67 [124.48, 127.13]	72256	14743	472	5838

Table 55. LEPR performance mitigation analysis additional metrics.

Sensor, Encounter Set	**Test Case**	**Number of Alerts**			
		Preventive	**Corrective**	**Warning**	**TCAS RAs**
ATAR, Correlated	Horizontal only maneuvers	325756	165681	439868	--
	DAIDALUS vertical limits & horizontal only maneuvers	0	132958	551252	--
	Co-altitude assumption & horizontal only maneuvers	66	137666	551853	--
GBSS, Correlated	Horizontal only maneuvers	369152	363949	373867	--
	DAIDALUS vertical limits & horizontal only maneuvers	0	443395	492657	--
	Co-altitude assumption & horizontal only maneuvers	577	442076	492681	--
EOIR, Correlated (same as Correlated EOIR, LEPR in Table 52)	Horizontal only maneuvers	314589	210632	440967	--
ATAR, Uncorrelated	Horizontal only maneuvers	544655	320814	611851	--
	DAIDALUS vertical limits & horizontal only maneuvers	0	237400	781981	--
	Co-altitude assumption & horizontal only maneuvers	10	242242	782169	--
GBSS, Uncorrelated	Horizontal only maneuvers	611338	563273	487078	--
	DAIDALUS vertical limits & horizontal only maneuvers	0	681573	672039	--
	Co-altitude assumption & horizontal only maneuvers	29	681427	672220	--

EOIR, Uncorrelated (same as Uncorrelated EOIR, LEPR in Table 52)	Horizontal only maneuvers	626841	482570	669001	--