Evaluation of Non-Cooperative DWC with Open-Loop and Closed Loop Simulations

NASA
Lincoln Lab
Cal Analytics

Background

- NASA's well clear trade study recommended four candidate Detect-and-Avoid (DAA) Well Clear (DWC) definitions for non-cooperative aircraft
- This briefing reports latest results that evaluate candidate DWCs in terms of alerting and guidance performance

Name	HMD* (ft)	τ_{mod}* (sec)	P	MIR (nmi)	Comment	Selection
DWC1	2000	15	5%	1.8	With a τ_{mod}*	Primary
DWC2	2200	0	5%	1.9	Cylindrical	Primary
DWC3	1500	15	6.9%	1.6	NASA terminal WC candidate	Secondary
DWC4	2500	25	3.7%	2.3	"Safer" backup	Secondary

MIR: maneuver initiation range
P: unmitigated P(NMAC|LoWC)
Note: h* = 450 ft for all DWCs

Fast Time Simulation Schedule

Simulation Type		Low C-SWaP Operations	Phase 1 Operations
Unmitigated	Truth Tracks	NASA Briefing Mar. 2019	NASA Briefing Jul. 2019
	Noisy Tracks	NASA TBD	
Mitigated	Truth Tracks with a Simple Phase 1 Pilot Model	Lincoln Lab Briefing Mar. 2019	Cal Analytics Briefing Mar. 2019
	Noisy Tracks with an improved Pilot Model	NASA Oct. 2019	

Computed Metrics

Metric Type	Metric	Data	Importance for ranking DWCs	Comments
Safety	Unmitigated P(NMAC|LoDWC)	NASA FTS1	Medium	
	Mitigated P(NMaC|LoDWC)	LL and Cal	Medium	
	NMAC Risk Ratio	LL (low C-SWaP), Cal (Phase 1)	High	
	LoDWC Risk Ratio	LL (low C-SWaP), Cal (Phase 1)	Medium	
	MCD	LL and Cal	Medium	
Operational Suitability	Open Loop Alerting Metrics	NASA FTS2	Medium	
	Alert Ratio	LL and Cal	Low	
	Pilot's acceptability	HSI, Santiago & Mueller	Medium	
	Path Deviation	LL and Cal	Low	
	Controllers' acceptability	NASA Langley	Low	
Surveillance Requirements		NASA FTS2	Medium	

Trade Off between Alerting Performance and Surveillance Volume

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Acknowledgment

- NASA Modeling and Simulation Team
  - Seungman Lee
  - Andrew Cone
  - Mohamad Refai
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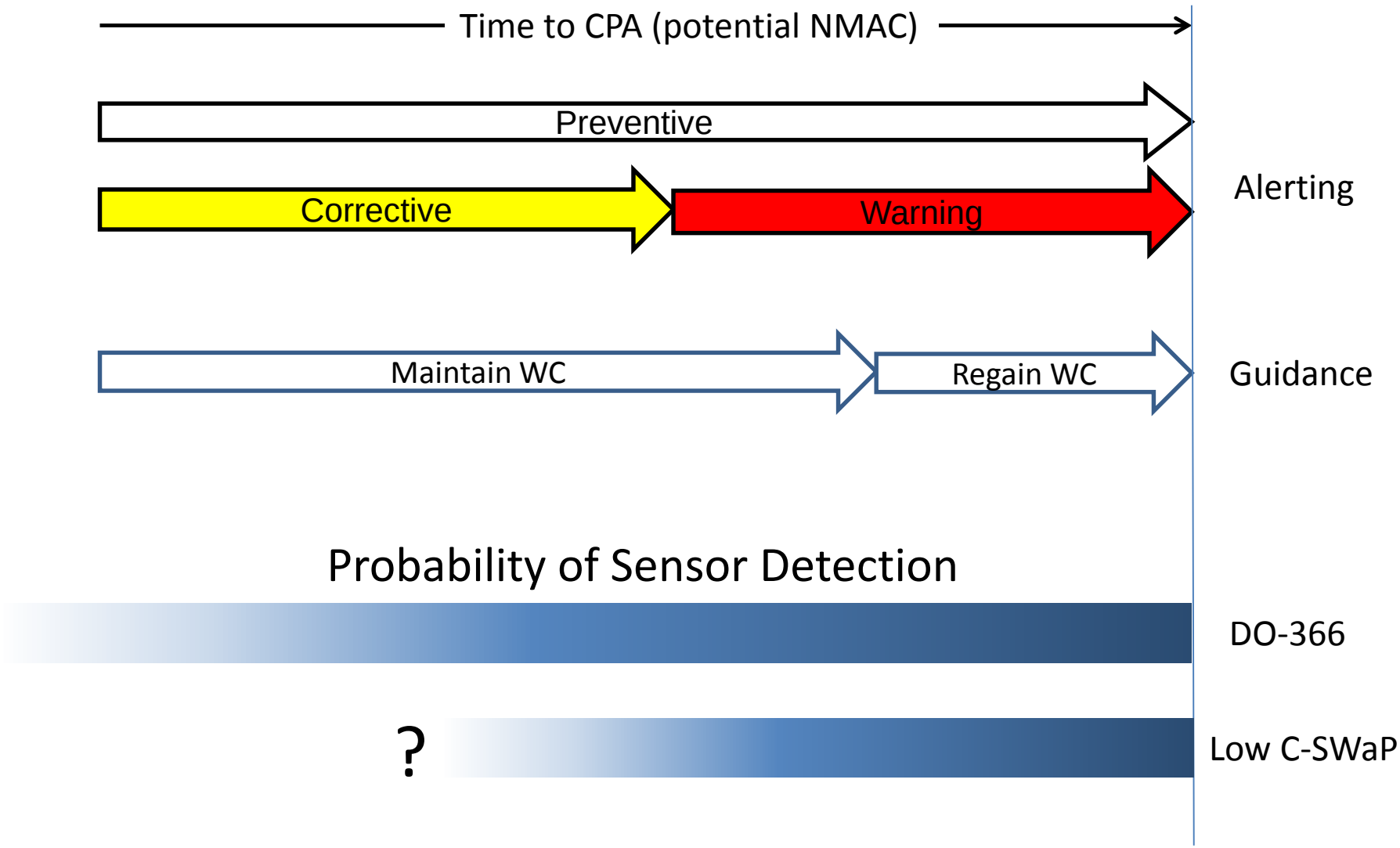
  - Eric Wahl
  - Jennifer Lock
  - Jim phillips

Objectives

- Investigate the trade space between DAA alerting timeline and the surveillance volume of a low cost, size, weight, and power (Low C-SWaP) sensor
- Inform the SC-228 WG1 of recommendations to alerting and low C-SWaP sensor requirements
- Rank candidate DWCs

DAA Alerting and Guidance Timeline



NMAC: near mid-air collision

Low C-SWaP Operations

- At or above 500 ft AGL and at or below 10,000 ft MSL
- Extended operations in airspace classes D, E (non-terminal), or G (non-terminal), or
- Transit operations in classes B and C
- For UAS within a certain speed range (assumed to be [40, 100] kts)

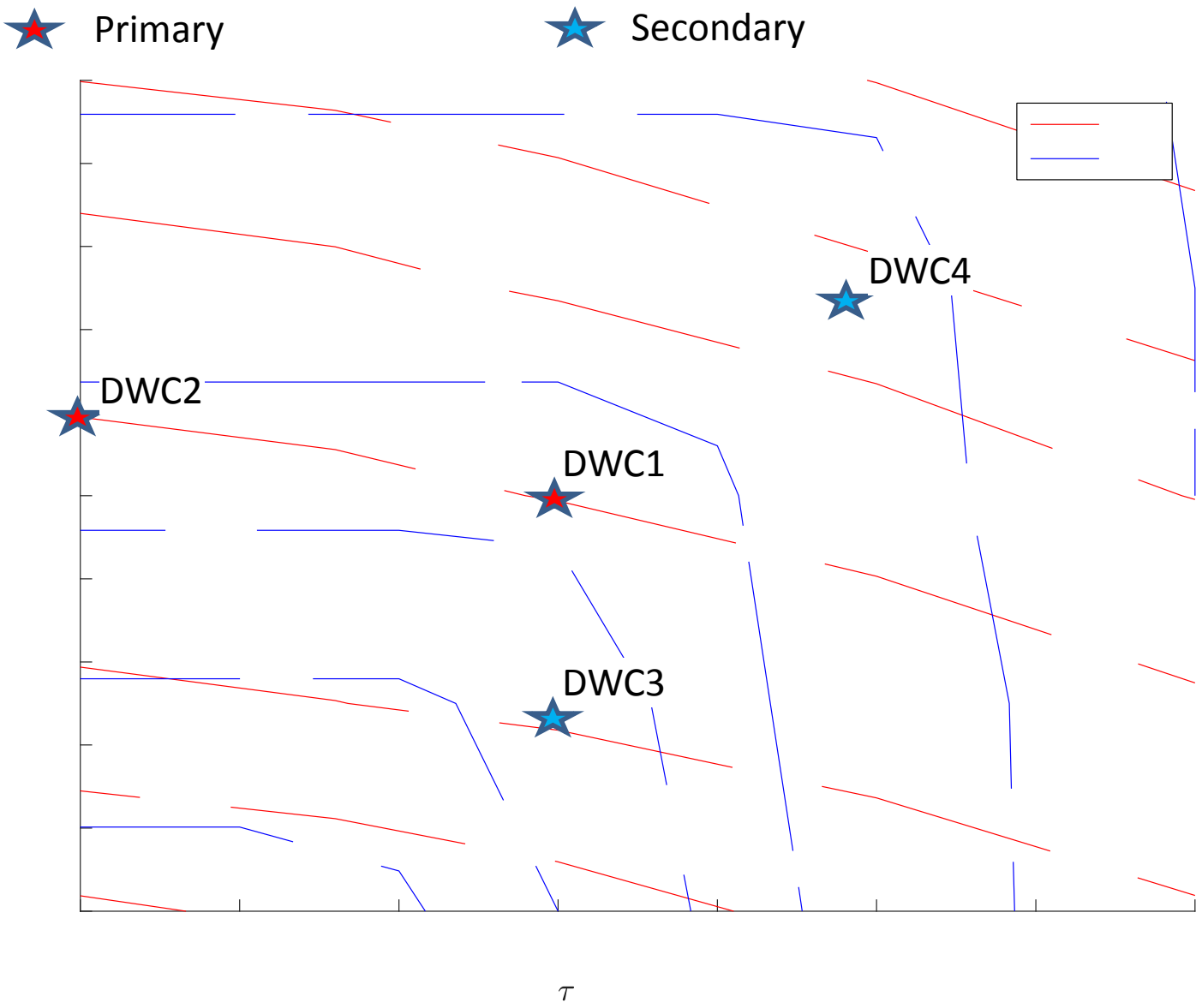
Approach

- Evaluate the alerting performance as a function of the surveillance volume
  - For each DWC
  - ACES-generated encounters
- Answer questions such as
  - What surveillance volume would allow enough alerting time for maintaining DWC?
  - How do results vary among candidate DWCs?

Independent Variables

- Four candidate DWCs (2 primary and 2 secondary)
  - Different horizontal parameters; same vertical (450 ft)
- Sensor surveillance volume
  - Range, bearing, and elevation

Candidate DWCs



Performance Metrics

- Open-Loop Metrics for Corrective and Warning alerts
  - Average time of alert before LoDWC
  - Percentage of late alerts
  - Percentage of missed alerts
  - Percentage of warning alerts without prior corrective alerts (C-21)
  - Percentage of short corrective alerts (C-20)
- Sensor range, bearing, and elevation to support warning alerts

Hazard Zone Definition

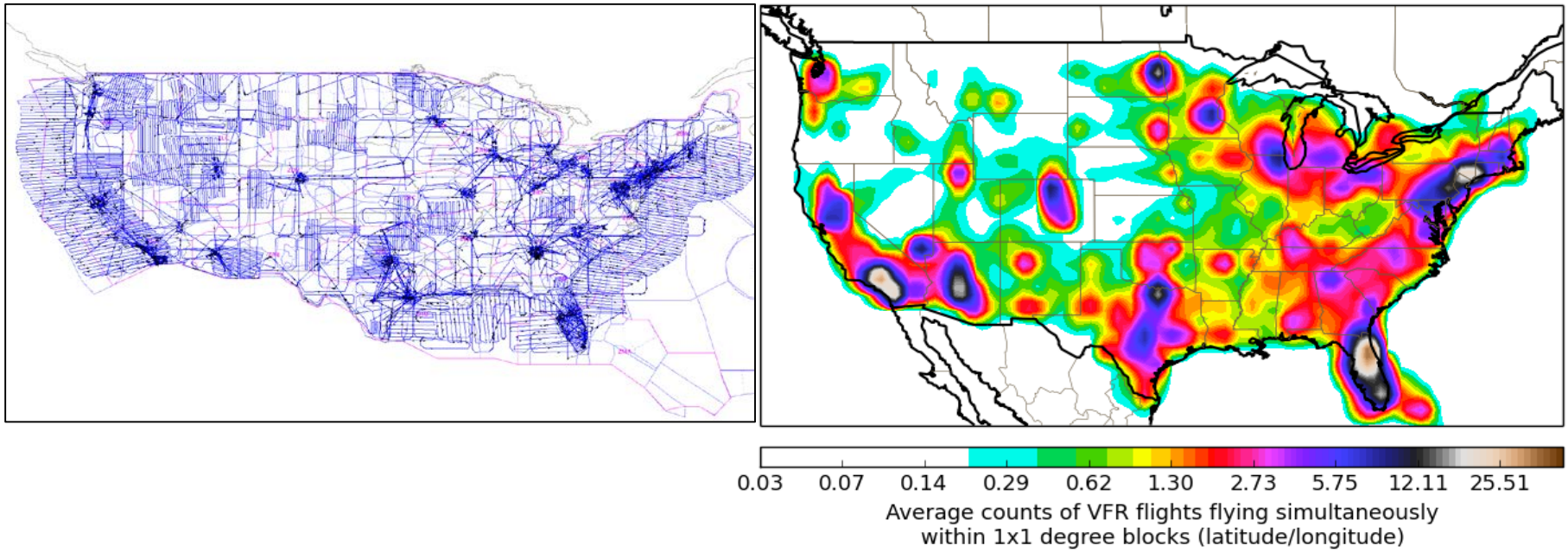
- Hazard Zone (HAZ) depends on the DWC
  - Set HAZ for Corrective and Warning alert types to the DWC itself
  - Set HAZ for Preventive alert type to the DWC but with 700 ft altitude separation
- Non-Hazard Zone (HAZNot) is not defined yet

Alerting and Guidance Algorithm

- Detect and AvoID Alerting Logic for Unmanned Systems (DAIDALUS) as reference DAA algorithm
- Parameters for Corrective and Warning based on standard configuration for Phase 1
  - τ_{mod}* and h* are not buffered
  - HMD* for alerting ~ 1.519 x HMD* for DWC
  - Time to the volume defined by HMD*, τ_{mod}*, and h* for alerting
    - 30 seconds for Warning
    - 60 seconds for Corrective
- Guidance based on 7 deg/sec turn rate
- 4 second persistence and 2-of-4 (m of n) alerts

Encounter Set

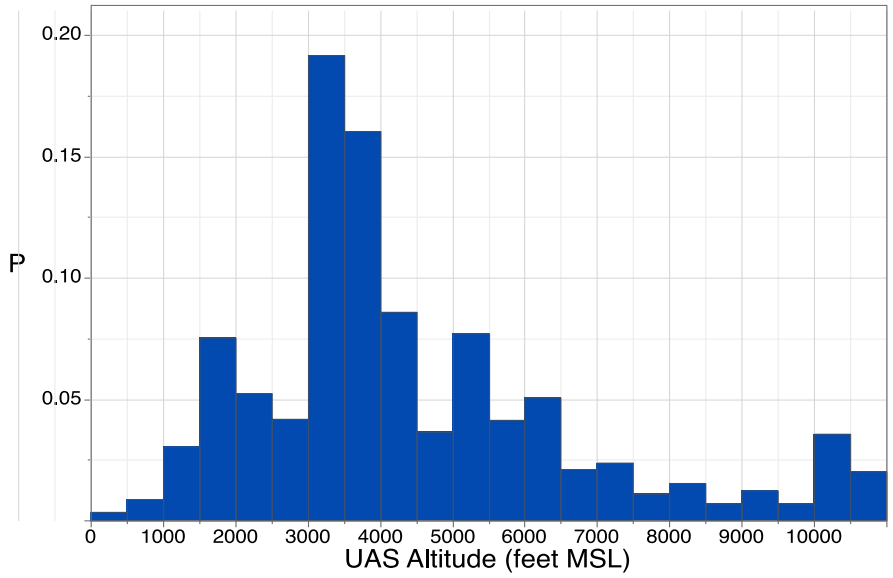
- Projected UAS mission trajectories overlaid with radar recorded VFR traffic
- Low C-SWaP encounters are a subset of the full encounter set

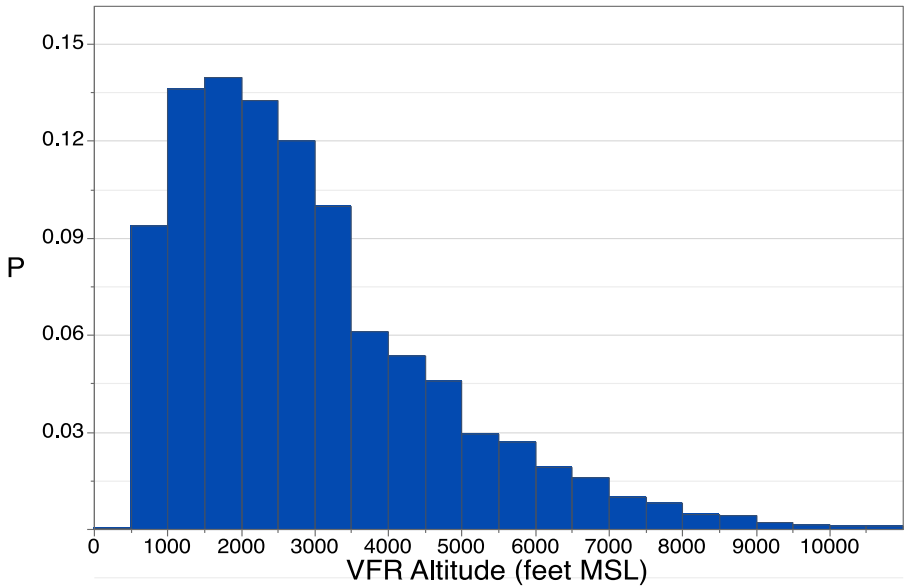


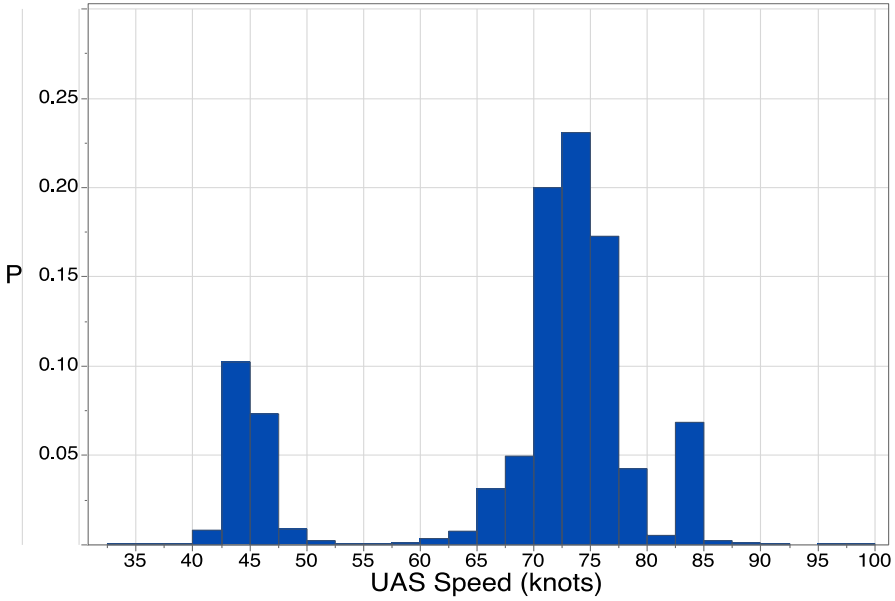
Low C-SWaP UAS Missions

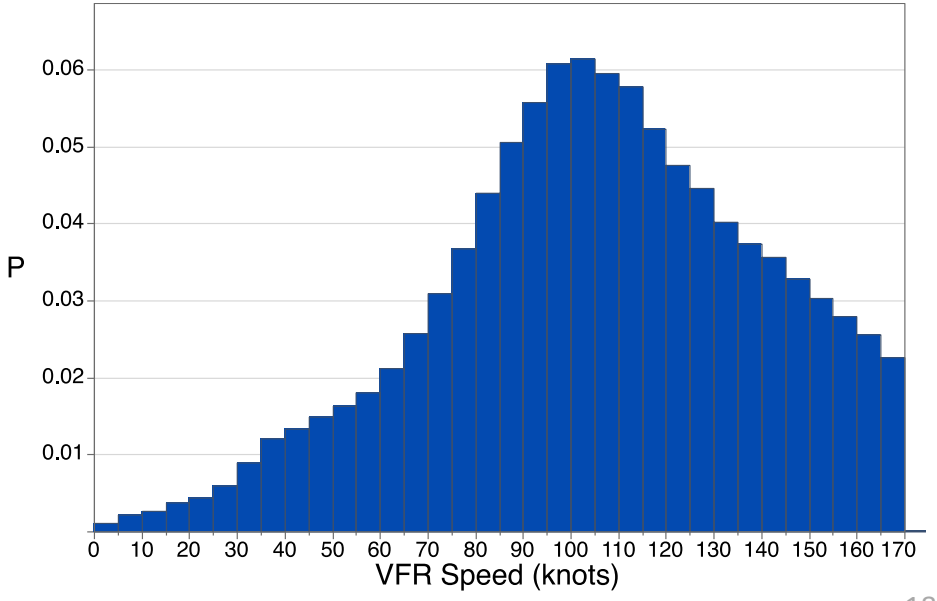
Number	Mission Types	Airspace	UAS Group	Cruise Altitude	Cruise Speed (KTAS)	Flight Pattern
1	Aerial Imaging and Mapping	Flights depart from and return to a regional airport located within 40 nmi. of OEP 35 airports; Class D, E, and G (including Mode C Veil) with Class B or C transition	Aerosonde Mk 4.7	3000 ft. AGL	44 to 51	Radiator-grid pattern or circular pattern
2	Air Qualtiy Monitoring	Flights depart from and return to a regional airport located within 40 nmi. of OEP 35 airports; Class D, E, and G (including Mode C Veil) with Class B or C transition	Shadow-B (RQ7B)/NASA Sierra	4k, 5k, and 6k ft AGL	74 to 89	Radiator-grid pattern
3	Airborne Pathogen Tracking	Flights depart from and return to a regional airport located within 40 nmi. of OEP 35 airports; Class D, E, and G (including Mode C Veil) with Class B or C transition	Shadow-B (RQ7B)/NASA Sierra	3,000 ft., 5,000 ft. and 10,000 ft. AGL	72 to 97	Radiator-grid pattern
4	Flood Inund. Mapping	Flights depart from and return to a regional airport located within 40 nmi. of OEP 35 airports; Class D, Mode C Veil, E, and G	Aerosonde Mk 4.7	4,000 ft. AGL	46 to 51	Grid pattern
5	Flood Stream Flow	Flights depart from and return to a regional airport located within 40 nmi. of OEP 35 airports; Class D, Mode C Veil, E, and G	Aerosonde Mk 4.7	4,000 ft. AGL	46 to 51	Grid pattern and/or along stream direction
6	Law Enforcement	Flights depart from and return to a regional airport located within 40 nmi. of OEP 35 airports; Class D, E, and G (including Mode C Veil) with Class B or C transition	Aerosonde Mk 4.7	3,000 ft. AGL	44 to 51	Three types of pattern: 1) grid pattern, 2) random, 3) outward spirial
7	Point Source Emission	Flights depart from and return to a regional airport located within 40 nmi. of OEP 35 airports; Class D, Mode C Veil, E, and G	Shadow-B	3,000 ft. AGL	72 to 80	Grid pattern and/or along stream direction
8	Spill Monitoring	Flights depart from and return to a regional airport located within 40 nmi. of OEP 35 airports; Class D, Mode C Veil, E, and G	Shadow-B/Sierra	3,000 ft. to 13,000 ft. AGL	72 to 93	Up and down-wind flights in a radiator-grid pattern, Round-the-clock
9	Tactical Fire Monitoring	Flights depart from and return to a regional airport located within 40 nmi. of OEP 35 airports; Class D, E, and G (including Mode C Veil) with Class B or C transition	ScanEagle/Shadow-B	3,000 ft. AGL	72 to 75	Circular flight path following the perimeter of a wildfire
10	Traffic Monitoring	Flights depart from and return to a regional airport located within 40 nmi. of OEP 35 airports; Class D, E, and G (including Mode C Veil) with Class B or C transition	Shadow-B	1,500 ft. AGL	58 to 84	Geo-spatial monitoring flight path
11	Wildlife Monitoring	Flights depart from and return to a regional airport located within 40 nmi. of OEP 35 airports; Class D, Mode C Veil, E, and G	Aerosonde Mk 4.7	3,000 ft. AGL	44 to 51	Radiator-grid pattern
12	News Gathering	Flights depart from and return to a regional airport located within 40 nmi. of OEP 35 airports; Class D, E, and G (including Mode C Veil) with Class B or C transition	Aerosonde Mk 4.7	1,500 ft. to 3,000 ft. AGL	44 to 51	Random-path: e.g., police-chase; Circular orbit:

UAS and VFR Altitude and Speed Distributions









Test Matrix

		Planned
DWC		DWC1, DWC2, DWC3, and DWC4
Surveillance Volume	Range (nmi)	1, 2, 3, 4, 8
	Bearing (deg)	±180, ±140, ±110
	Elevation (deg)	±90, ±15
VFR		21 days
UAS Missions		low C-SWaP UAS

Results

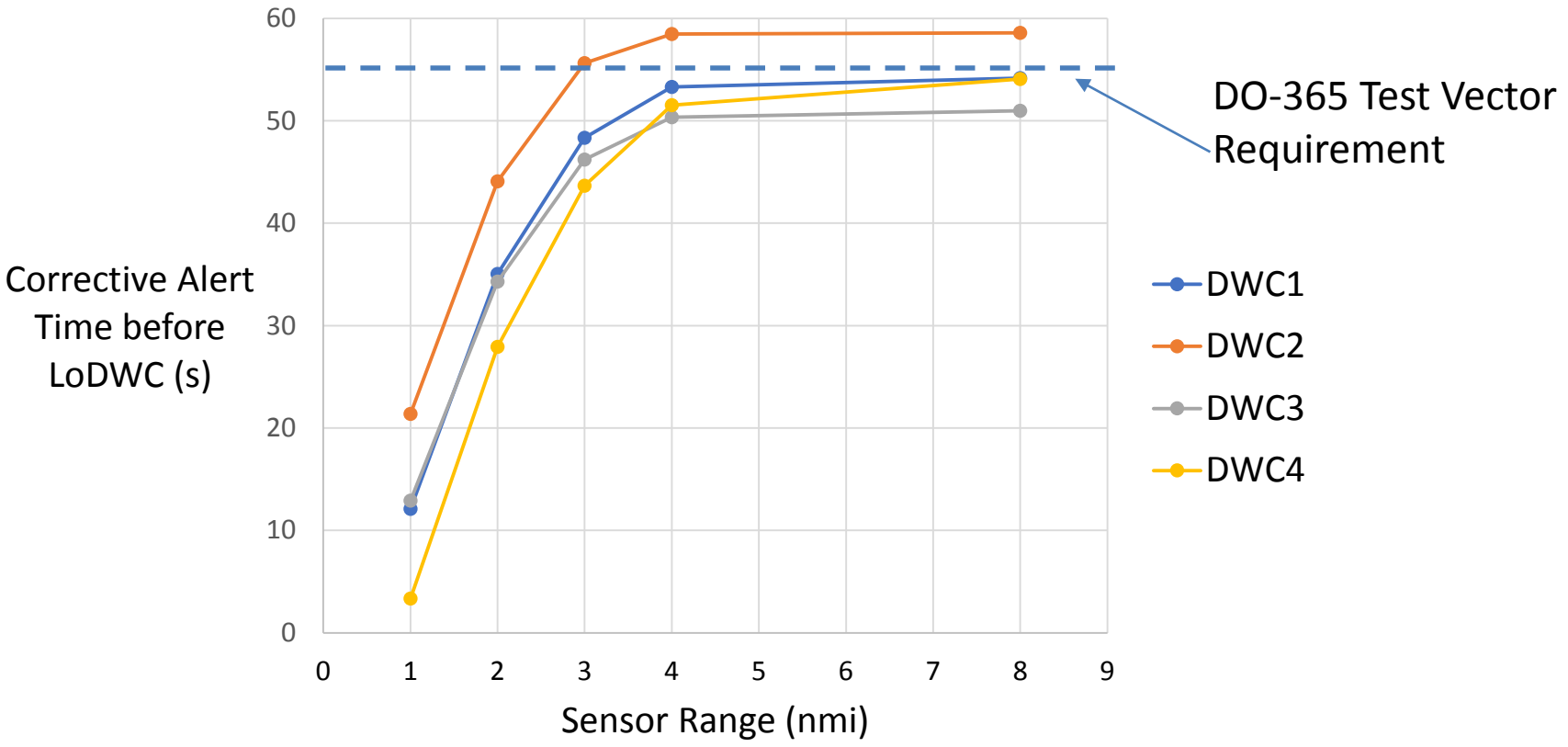
Encounters Analyzed

- 434 encounters have near mid-air collisions (NMAC)
- Number of loss of DWC (LoDWC) varies with candidate DWCs

	DWC1	DWC2	DWC3	DWC4
HMD*	2,000 ft	2,200 ft	1,500 ft	2,500 ft
τ_{mod}*	15 s	0 s	15 s	25 s
No. of LoDWCs	8,120	8,170	6,200	11,020

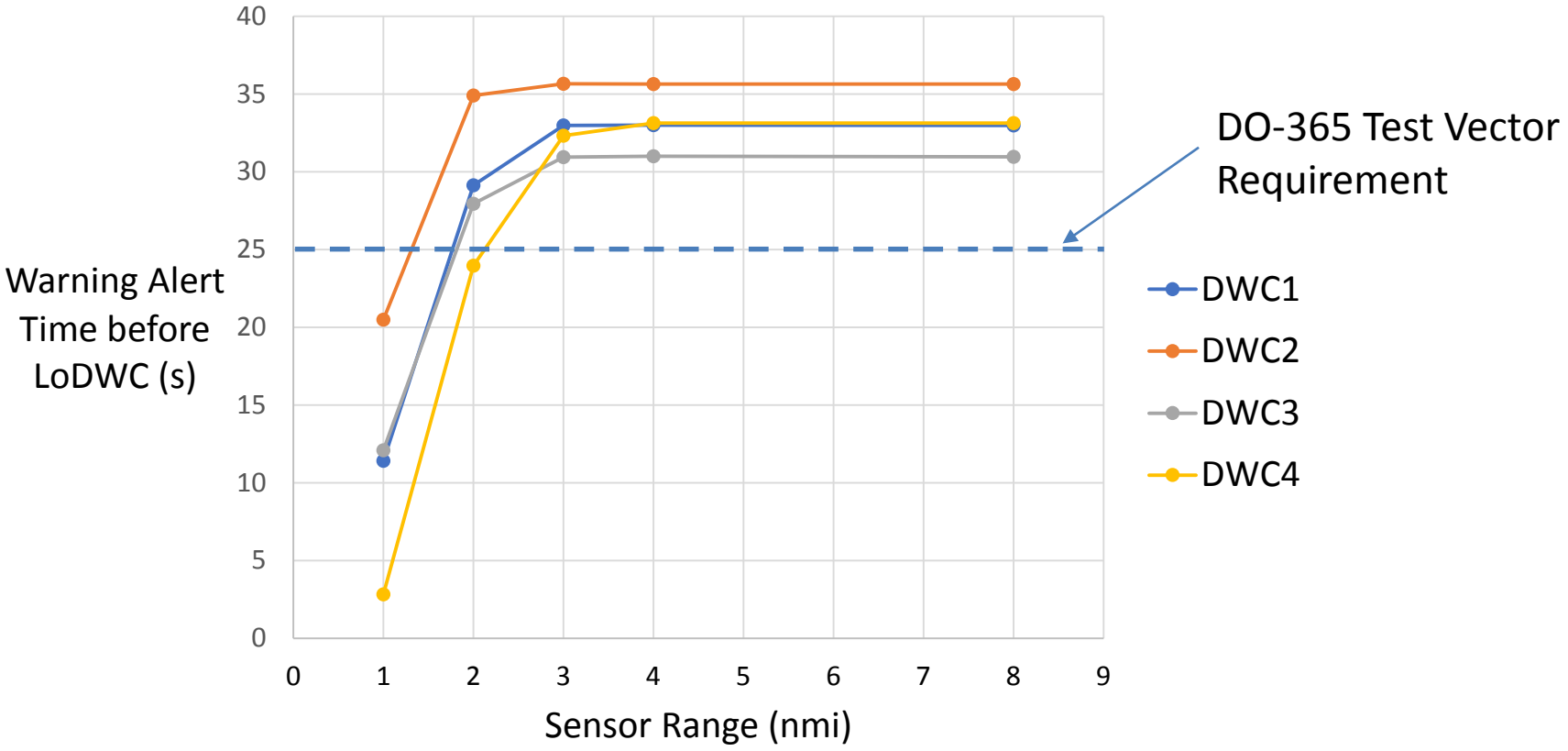
Results with Full Bearing and Elevation Ranges

Average Corrective Alert Time before LoDWC



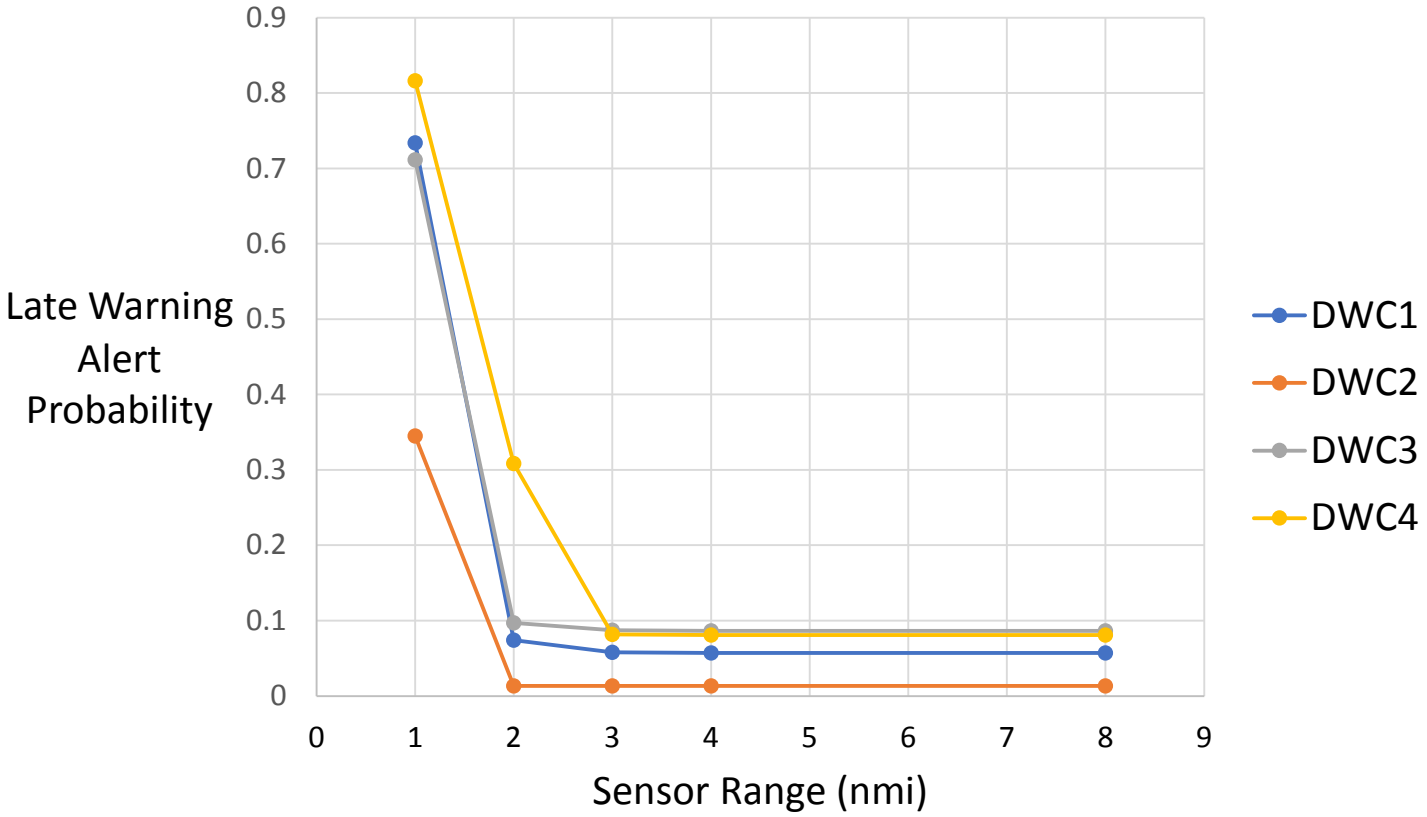
	DWC1	DWC2	DWC3	DWC4
HMD*	2000 ft	2200 ft	1500 ft	2500 ft
τ_{mod}*	15 s	0 s	15 s	25 s

Average Warning Alert Time before LoDWC



	DWC1	DWC2	DWC3	DWC4
HMD*	2000 ft	2200 ft	1500 ft	2500 ft
τ_{mod}*	15 s	0 s	15 s	25 s

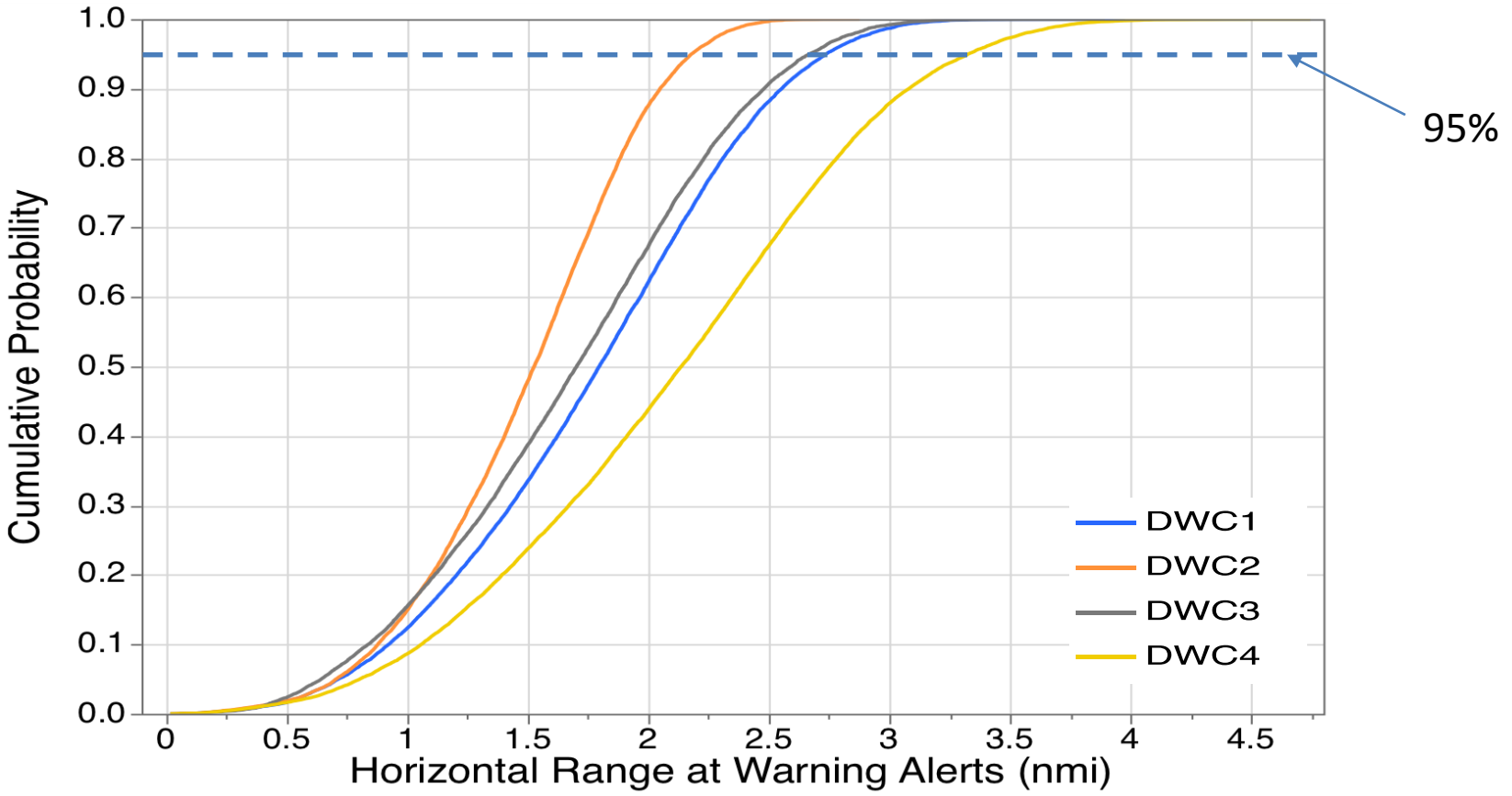
Late Warning Alert Probability



	DWC1	DWC2	DWC3	DWC4
HMD*	2000 ft	2200 ft	1500 ft	2500 ft
τ_{mod}*	15 s	0 s	15 s	25 s

Late alert threshold 15 seconds

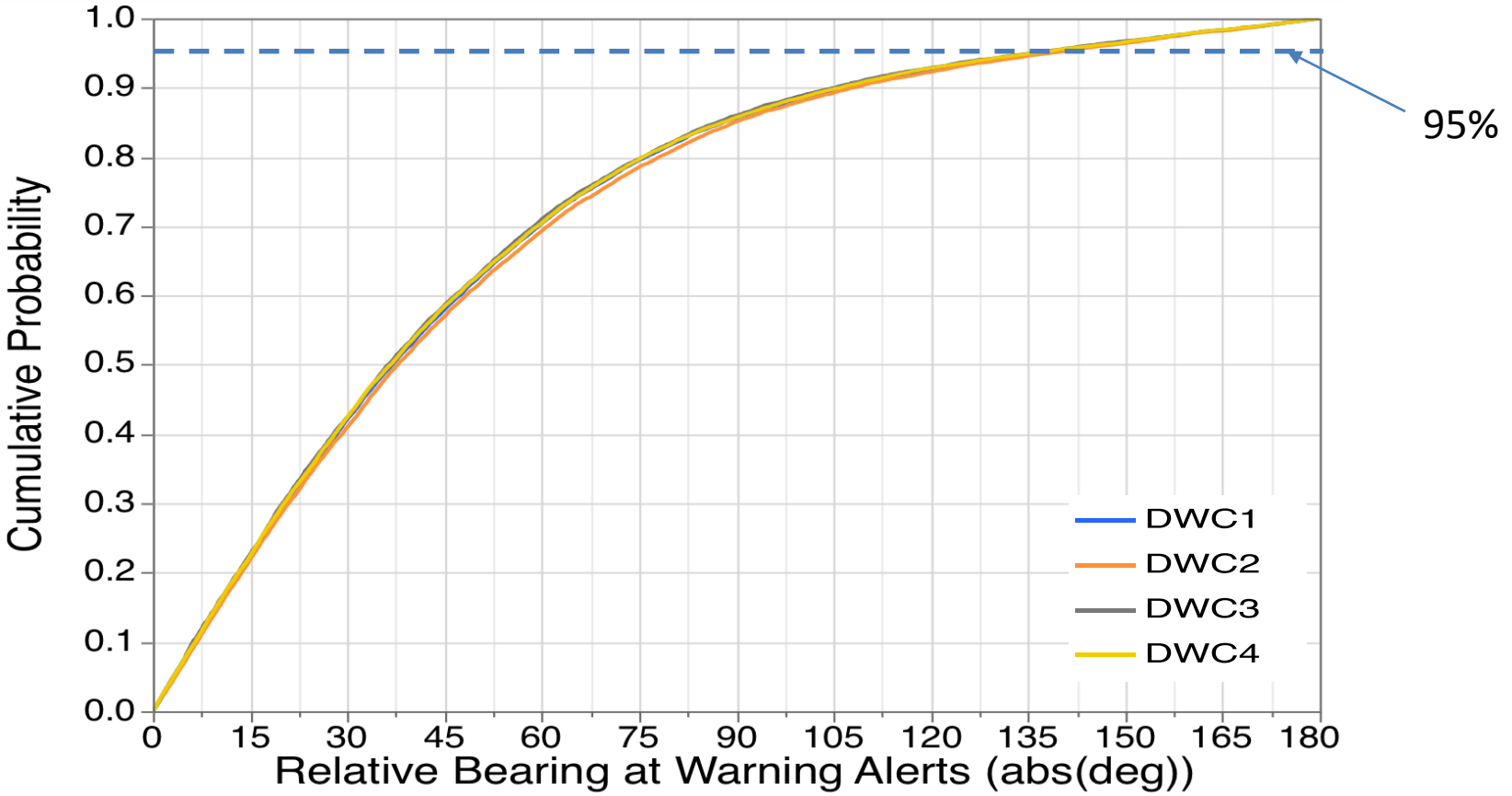
Range at First Warning Alert



Results with ±180 bearing and ±90 elevation

	DWC1	DWC2	DWC3	DWC4
HMD*	2000 ft	2200 ft	1500 ft	2500 ft
τ_{mod}*	15 s	0 s	15 s	25 s
95% (nmi)	2.8	2.2	2.7	3.3

Bearing at First Warning Alert

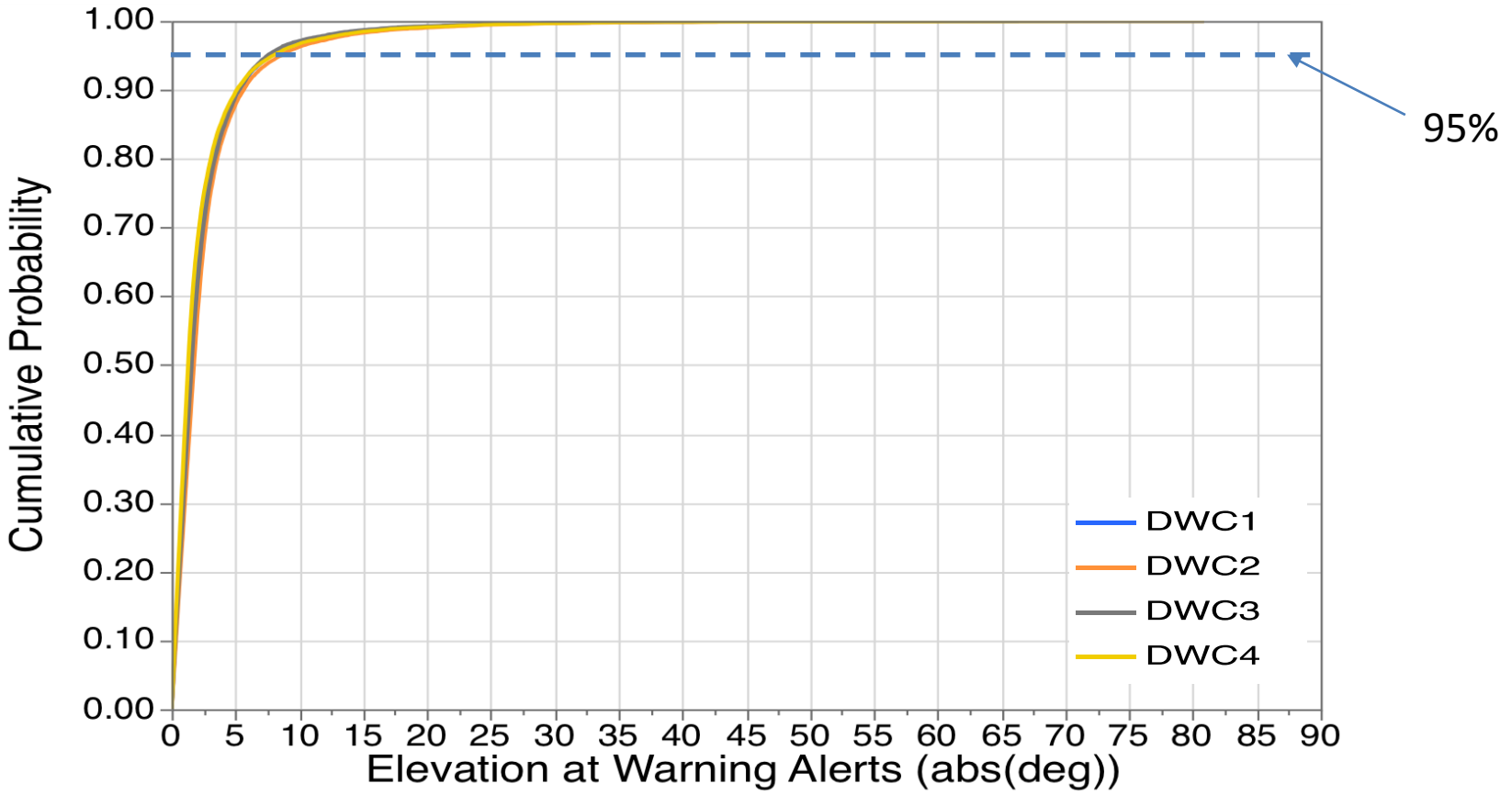


with ±180 bearing and ±90 elevation

DO-366 requires ±110°

	DWC1	DWC2	DWC3	DWC4
HMD*	2000 ft	2200 ft	1500 ft	2500 ft
τ_{mod}*	15 s	0 s	15 s	25 s
95% (deg)	140	140	140	140

Elevation at First Warning Alert



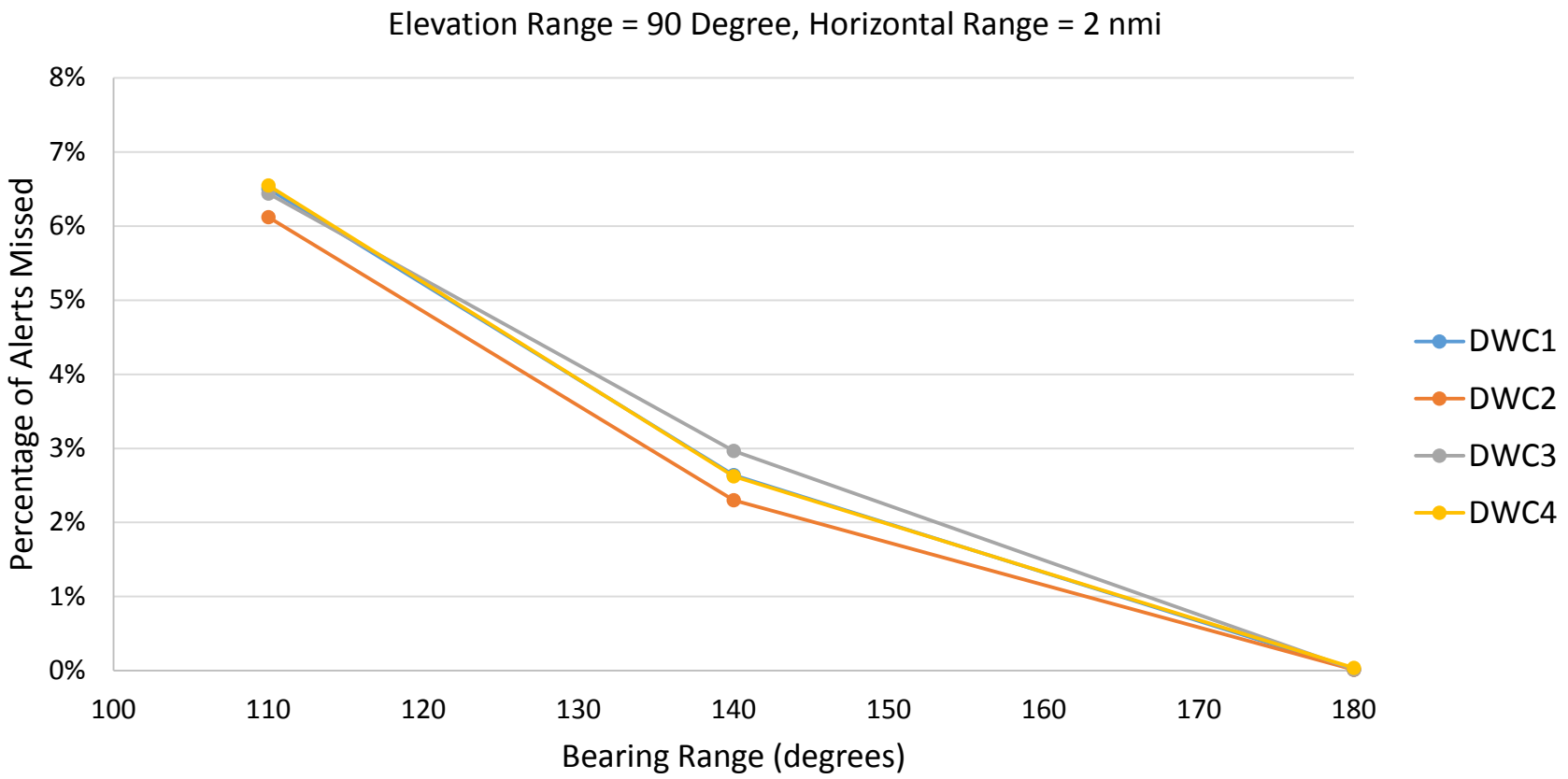
with ±180 bearing and ±90 elevation

DO-366 requires ±15°

	DWC1	DWC2	DWC3	DWC4
HMD*	2000 ft	2200 ft	1500 ft	2500 ft
τ_{mod}*	15 s	0 s	15 s	25 s
95% (deg)	8	8.5	8	8

Results with Varying Bearing and Elevation Ranges

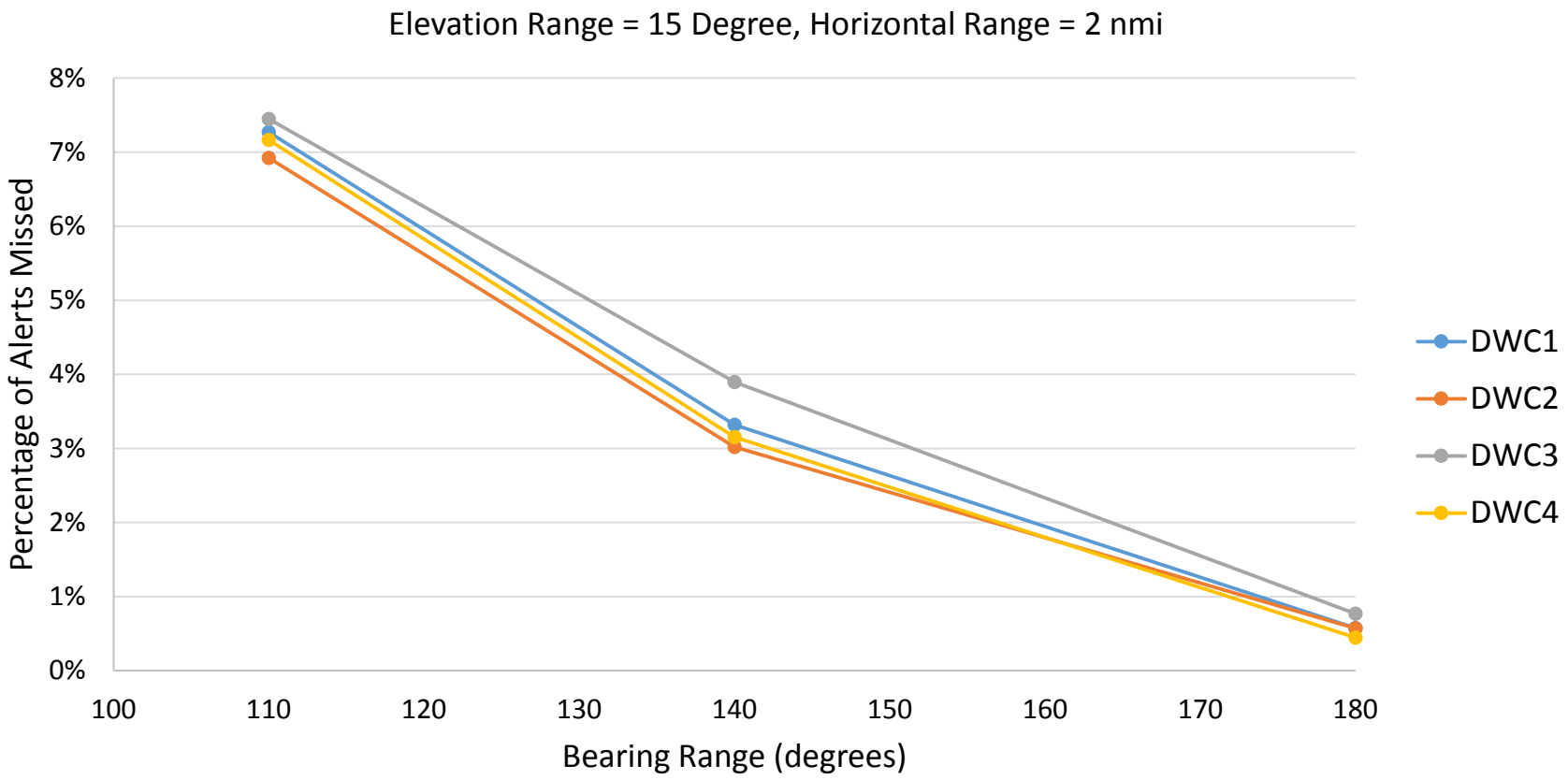
Missed Alert



Results insensitive to range > 2 nmi

	DWC1	DWC2	DWC3	DWC4
HMD*	2000 ft	2200 ft	1500 ft	2500 ft
τ_{mod}*	15 s	0 s	15 s	25 s

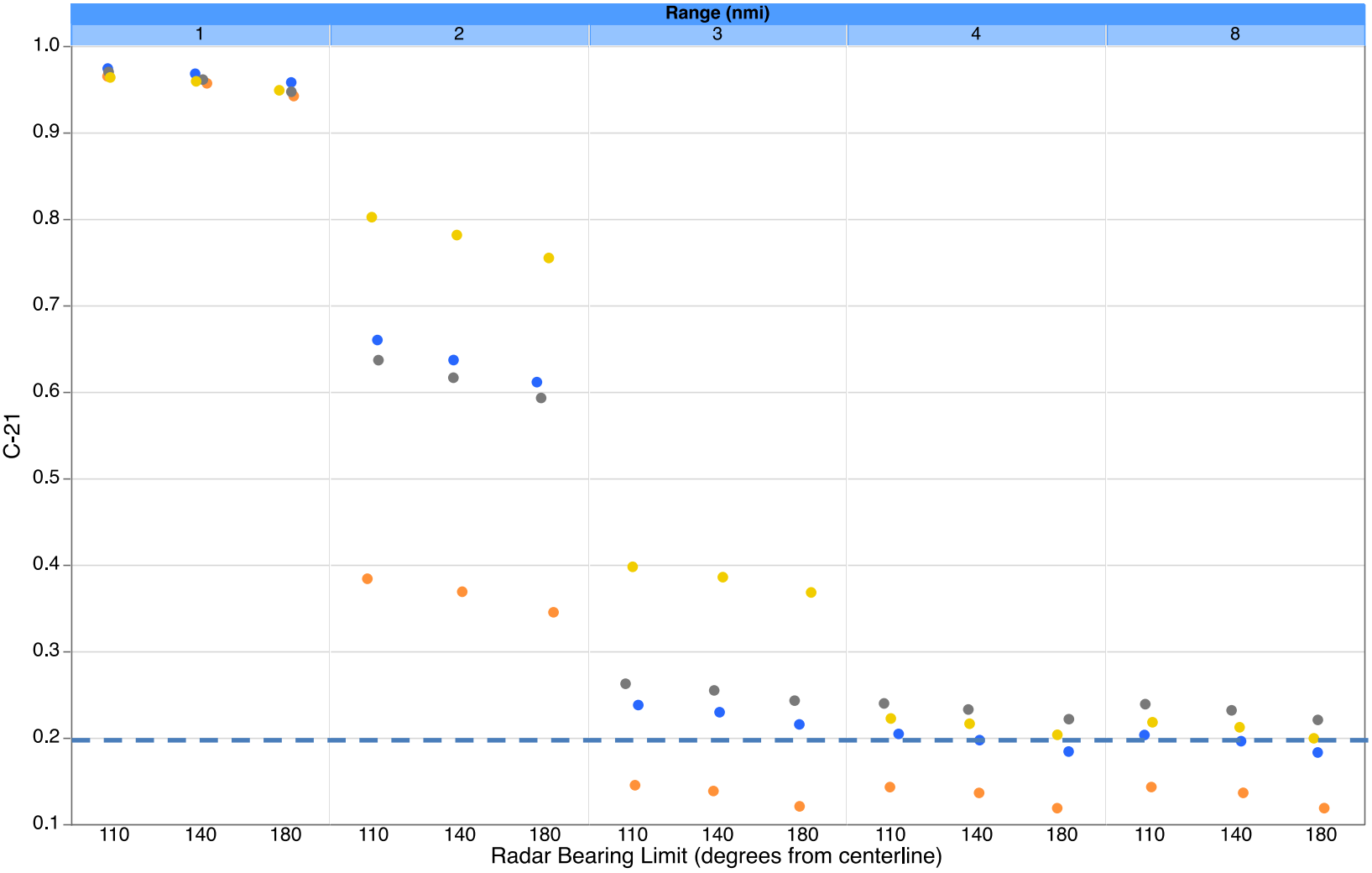
Missed Alert



Results insensitive to range > 2 nmi

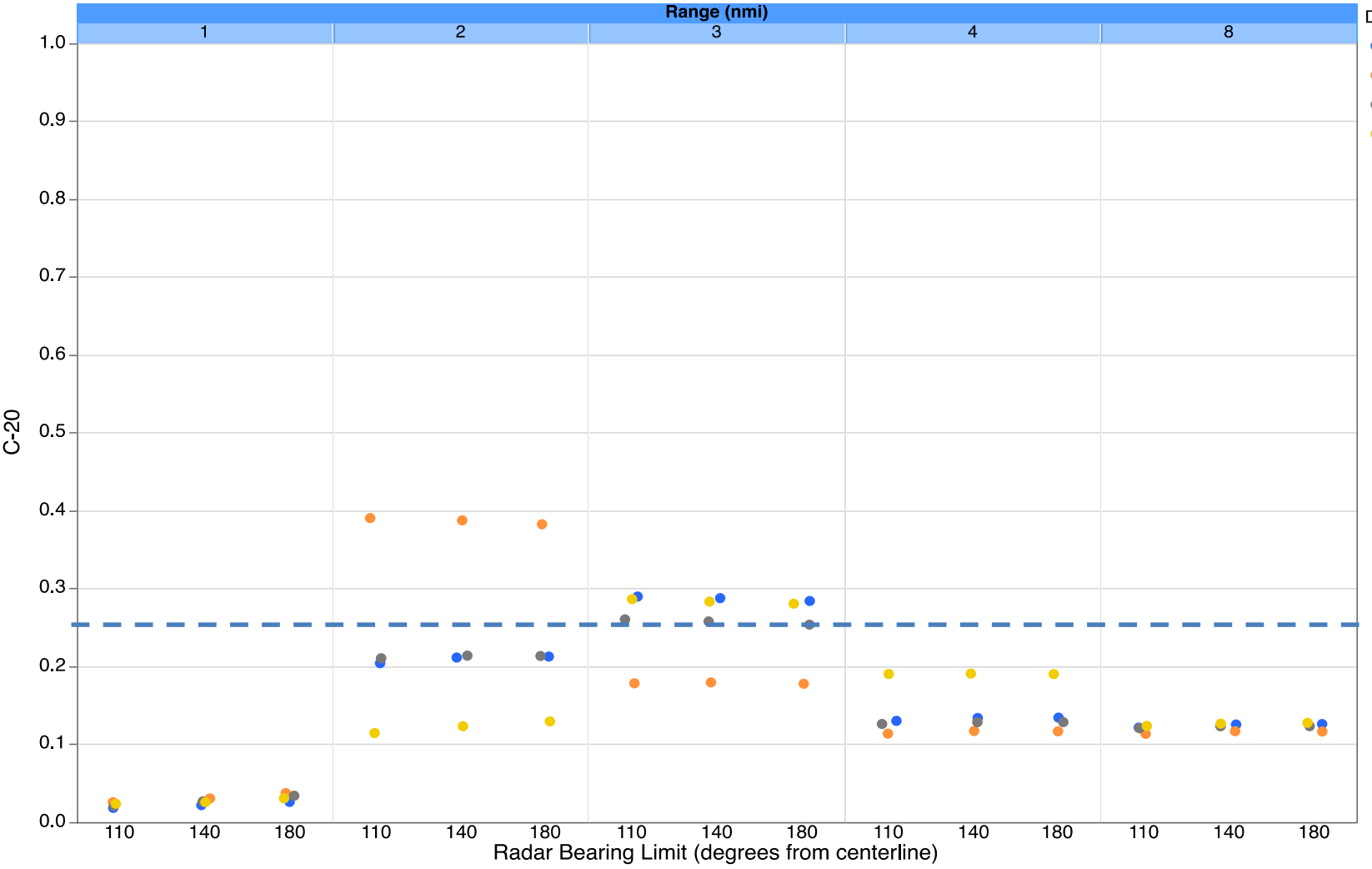
	DWC1	DWC2	DWC3	DWC4
HMD*	2000 ft	2200 ft	1500 ft	2500 ft
τ_{mod}*	15 s	0 s	15 s	25 s

C-21 (Percentage of No Corrective)



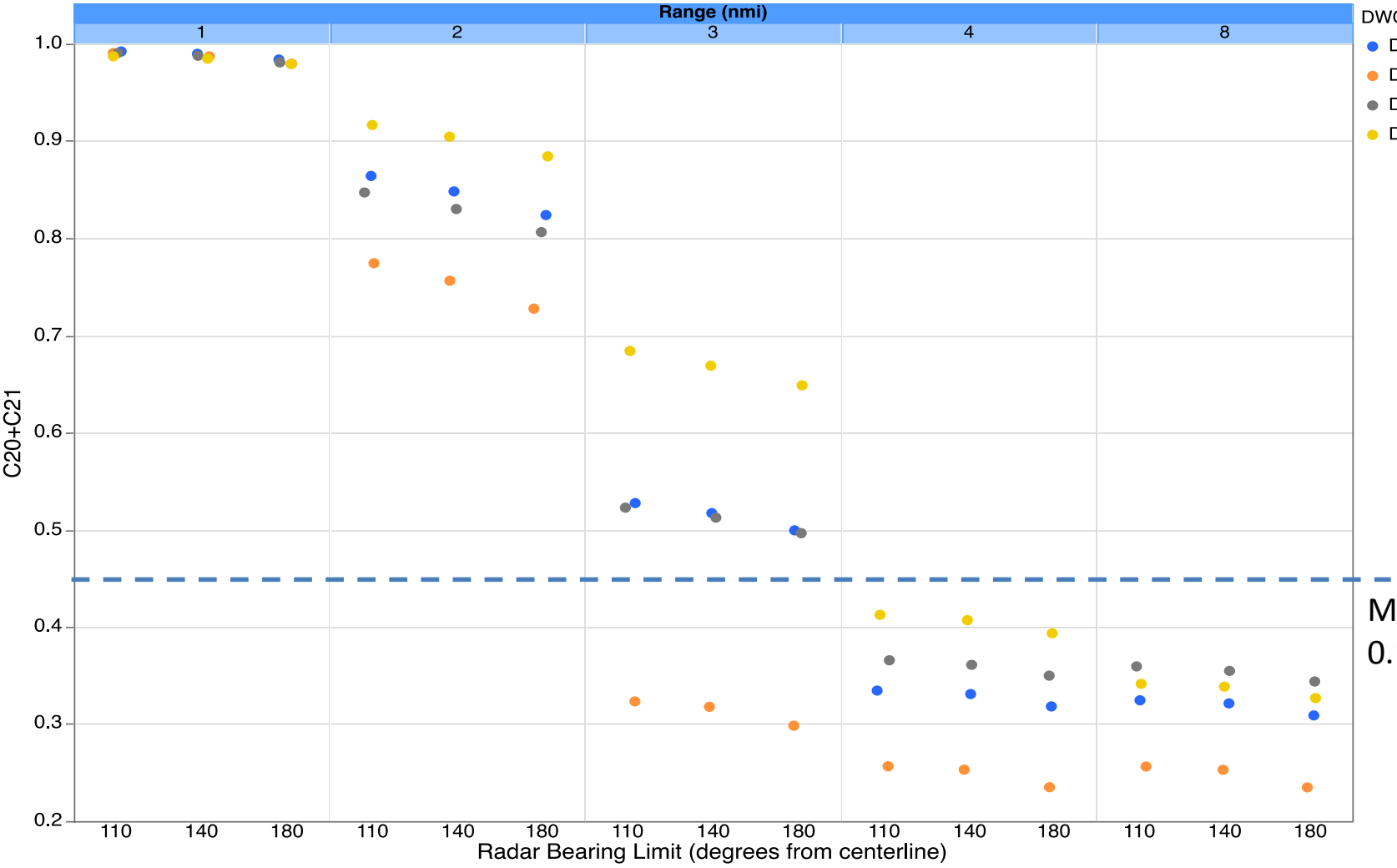
MITRE Study 5
0.19866

C-20 (Percentage of Short Corrective)



MITRE Study 5
0.2516

C20 + C21 (Short + No Corrective)



MITRE Study 5
0.19866+0.2516

Summary

- Alerting timeline
  - Corrective alerts need a least 4 nmi to maintain 90% of alerting time and Phase 1 comparable C-21 and C-20
  - Warning alerts
    - 3 nmi can maintain ~100% alerting time for all but DWC4
    - 2 nmi degrades alert time for all DWCs but still yields > 25 seconds avg. for all but DWC4
- Missed alert: sensitive to bearing range only
  - DWC2 yields slightly lower percentage
- Variation across DWC
    - DWC2 least impacted by surveillance range
    - DWC4 most impacted by surveillance range
    - DWC2 yields longer alert time and fewer missed and late alerts
- Range/bearing/elevation
  - 3 nmi range, ±140° bearing, and ±9° elevation enough for supporting first warning alerts in 95% of encounters for all but DWC4

Backup Slides

C20 in FAA SRMD Document

- Description
  - PIC does not contact ATC after corrective alert

- Comments
  - The sequence of alerts from the DAA equipment when it encounters an intruder aircraft is Preventive alert; Corrective alert; Warning alert. The PIC should contact ATC after a Corrective alert to obtain a clearance to possibly deviate from its current clearance and stay well clear of intruder aircraft. If the corrective alert does not give sufficient time before a Warning alert, then the PIC will not have time to contact ATC

- Rationale/Frequency per flight hour
  - 0.19866
  - This probability was updated from MITRE Study 5 results and sets the threshold at warning alert less than or equal to 14 seconds after corrective alert.

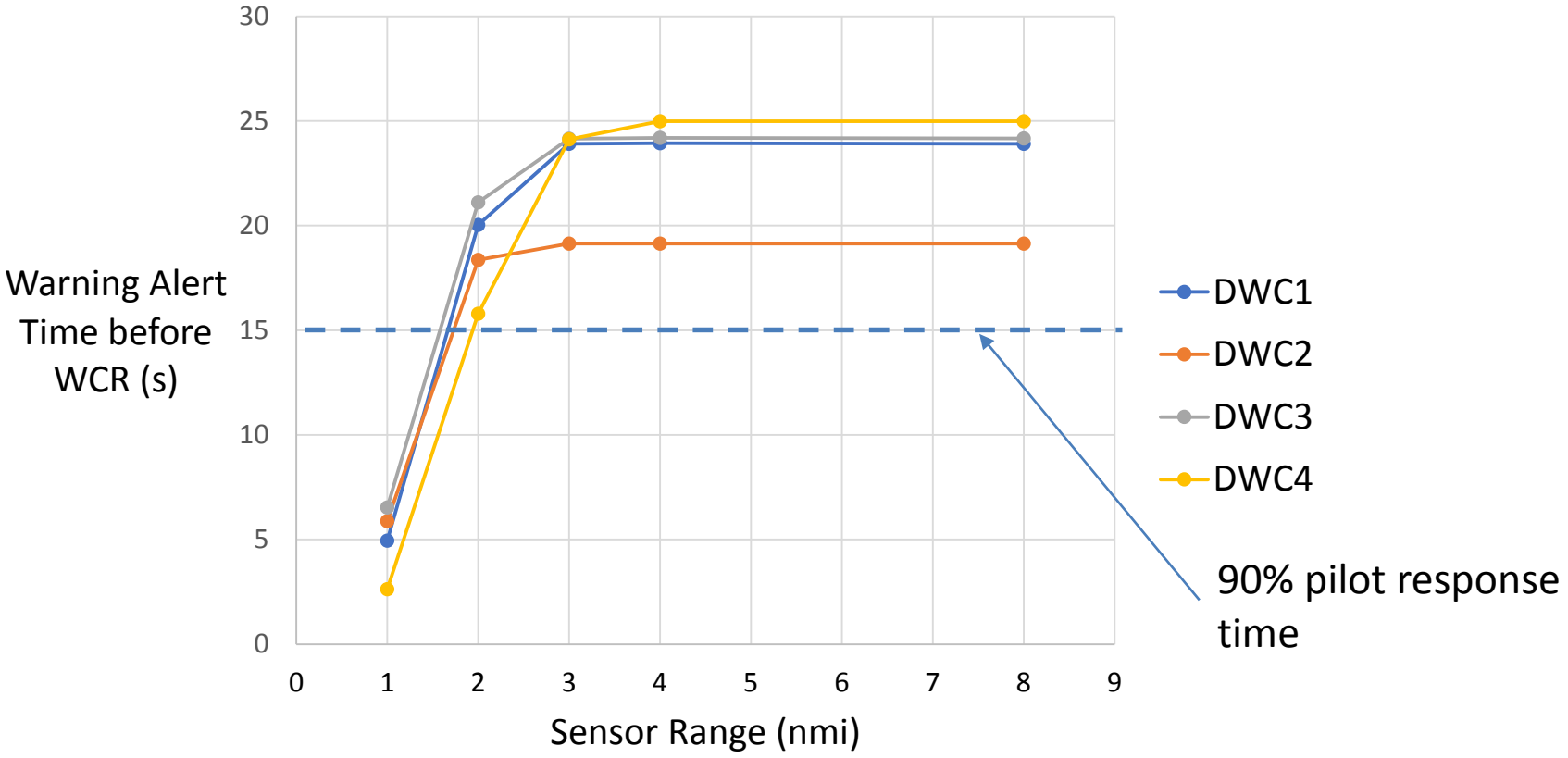
C21 in FAA SRMD Document

- Description
  - Warning alert without Corrective alert

- Comments
  - The PIC should perform a maneuver to stay well clear after receiving a Warning alert. If the system fails to issue a Corrective alert, the PIC will likely not have sufficient time to contact ATC.

- Rationale/Frequency per flight hour
  - 0.2516
  - This probability was updated from MITRE Study 5 results.

Average Warning Alert Time before WCR



	DWC1	DWC2	DWC3	DWC4
HMD*	2000 ft	2200 ft	1500 ft	2500 ft
τ_{mod}*	15 s	0 s	15 s	25 s

NASA Mitigated Well Clear Analysis: Low C-SWaP UAS

Matt Edwards
Christine Chen

Approach

- **Objective:** assess mitigated DAA performance under NASA's candidate DWC definitions based on safety and operational suitability metrics
  - Lincoln Laboratory focus is low-SWAP UAS
  - CAL Analytics focus is Phase 1 UAS
- **Approach**: simulate 1 million uncorrelated encounters with DAIDALUS to evaluate mitigated performance against noncooperative intruders
  - Lincoln encounters: low-SWAP UAS against VFR intruder aircraft
  - CAL encounters: all UAS (low-SWAP and high-performance) against VFR intruder
  - 2 runs for each DWC: nominal/unmitigated and mitigated
  - Use ADS-B surveillance initially here as ideal surveillance
- Analysis plan presented to SC-228 WG-1 at 29 May teleconference

DWC Candidates

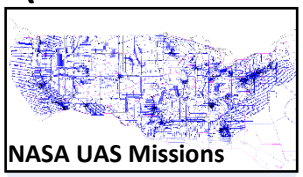
	NASA DWC1	NASA DWC2	NASA DWC3	NASA DWC4	Phase 1 (CAL Only)
HMD*	2000 ft	2200 ft	1500 ft	2500 ft	4000 ft
ModTau	15 s	0 s	15 s	25 s	35 s

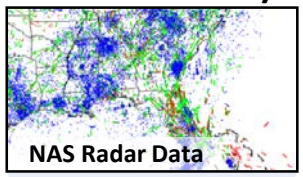
*A scale factor of 1.519 was used for DAIDALUS to inflate the horizontal dimension of well clear to be consistent with the (4000ft --> 1 nmi) adjustment used in Phase 1

** Time to co-altitude threshold = 0s, altitude threshold = 450 ft

Encounter Model DWC Analysis Approach

Synthetic Encounter Generation (Uncorrelated Encounter Model)





NASA UAS Track Database

VFR Model

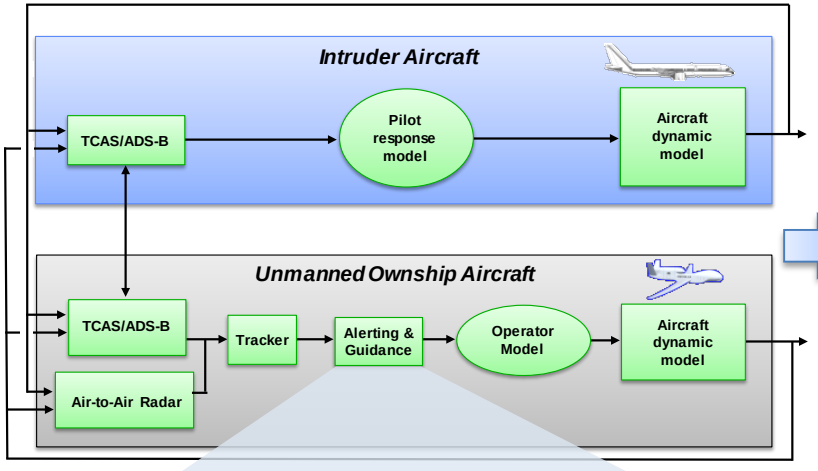
UAS Trajectory

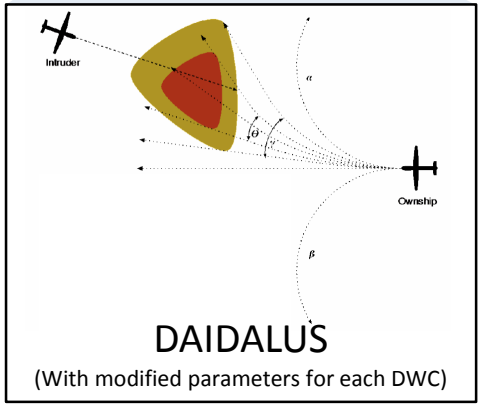
Intruder Trajectory

Initialize aircraft geometry

Encounter Situations (1 Million)

Fast-Time Encounter Simulation

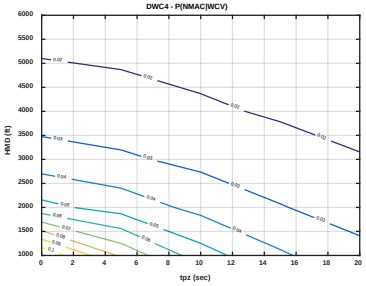


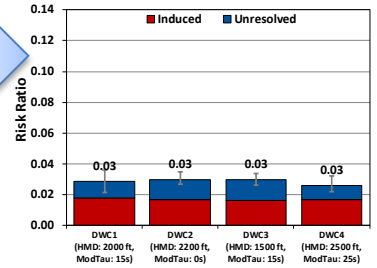


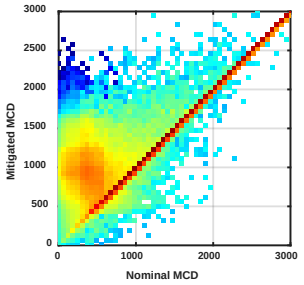
DAIDALUS

(With modified parameters for each DWC)

Metrics







Metrics

Safety metrics

- Risk ratio and loss of well clear ratios: $\frac{\mathbf{P(NMAC\ or\ LoWC|encounter,\ with\ mitigation)}}{\mathbf{P(NMAC\ or\ LoWC|encounter,\ without\ mitigation)}}$
- Minimum cylindrical distance: $\mathbf{min}_{\mathbf{encounter\ time}}\mathbf{[max(rh/5;\ rv)]}$
  - where rh is horizontal range and rv is vertical range
  - MCD is the smallest penetrated cylinder, with relative dimensions equal to NMAC
  - Surrogate for SLoWC due to different candidate DWC definitions
- Mitigated P(NMAC | LoWC): desire to match value from Phase 1

Operational suitability metrics

- Alert ratio: $\frac{\mathbf{P(Alert|encounter,\ with\ mitigation)}}{\mathbf{P(NMAC|encounter,\ without\ mitigation)}}$
- Horizontal flight path deviation
  - Max distance between current and nominal positions during an encounter

DAIDALUS alerting performance metrics

- Alerting time and range relative to CPA
  - CPA defined as minimum horizontal range

Encounter Set Parameters

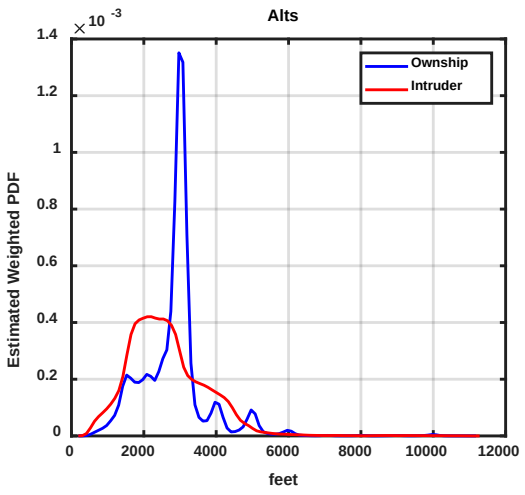
Encounter characteristics

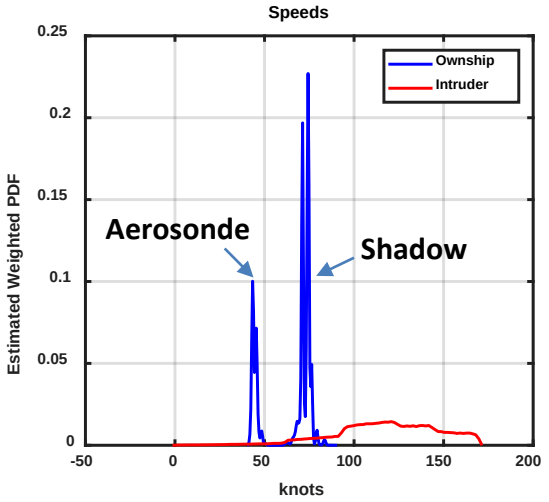
- Minimum Separation at Encounter Start: 800 ft (vertically) or 1.5 NM (horizontally)
- Max HMD: 3 NM
- Max VMD: 1500 ft
- Closest Approach: 150 sec
- Encounter duration: 180 sec
  - Extended up to 300 sec if necessary to satisfy initial minimum separation
- Airspace classes: E/G

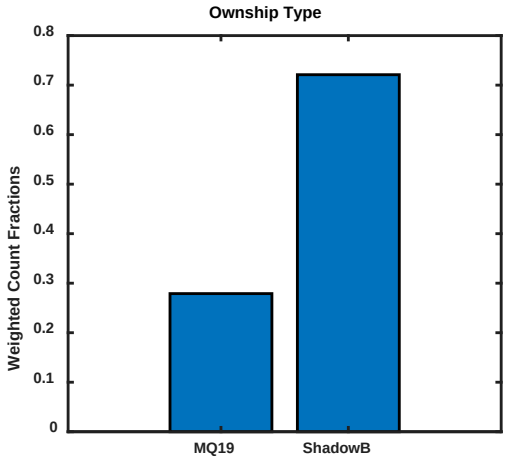
Aircraft characteristics

- Ownship speed: 40-100 kts (Lincoln), 40-250 kts (CAL)
- Intruder speed: 0-170 kts
- Ownship/intruder altitude: 500 AGL-10000 ft MSL

Low-SWAP Encounter Characteristics







MQ-19: AAI Aerosonde

Pilot Response Model

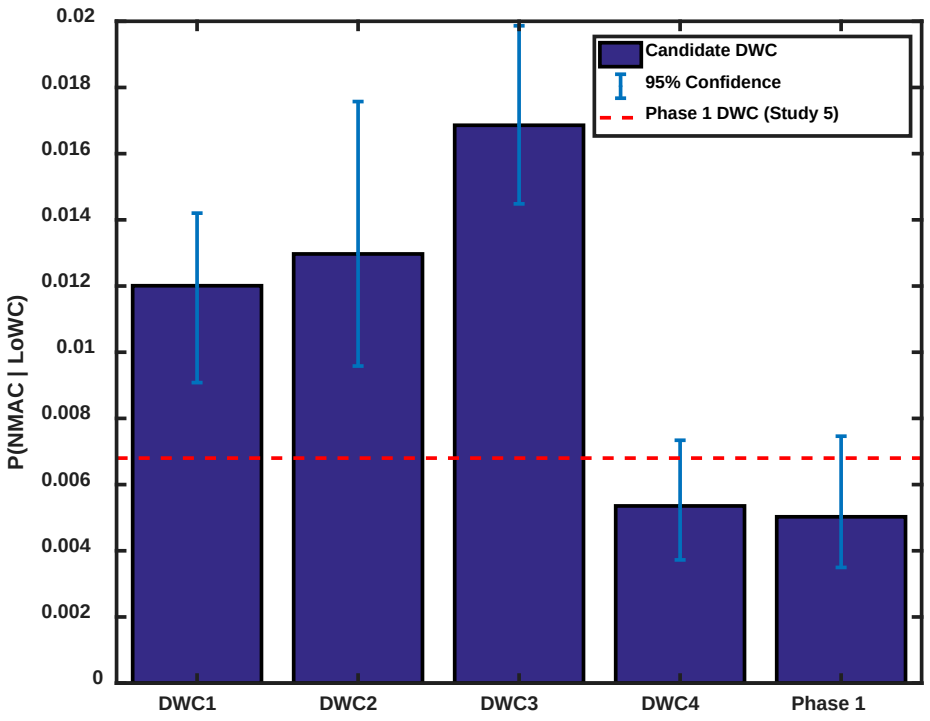
- **Use SC-228 pilot model created by Lincoln Laboratory**
  - Executed in deterministic mode
    - Always maneuvers horizontally in the direction of the minimum suggested maneuver; turns left if minimum suggestion is inconclusive
    - Follow guidance bands without buffer
  - Timing:
    - Decision updated according to alert state
    - Execution delay after decision: 3 sec
- **Analyze horizontal maneuvers only**
  - Low-SWAP turn rate: 7 deg/sec
    - Suitable for UAS speeds from 40 to 100 kts
  - High-performance UAS turn rate: 3 deg/sec

Alert State	Decision Update Period (s)
No Alert	12
Proximate Traffic	12
Preventive Alert	9
Corrective Alert	6
Warning Alert	6
Loss of Well Clear	0

Results

Mitigated P(NMAC | LoWC)

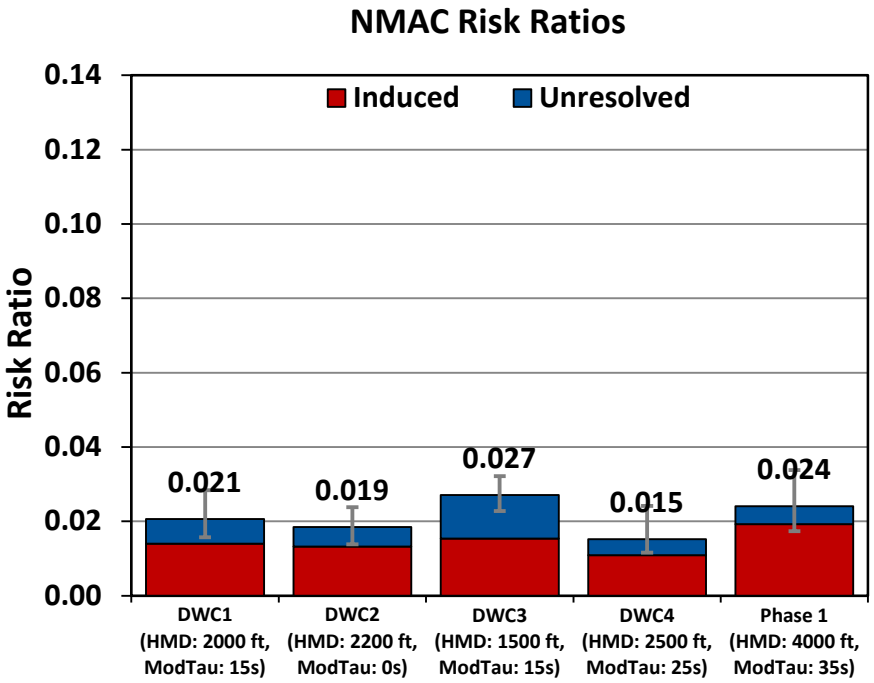
- May be desired that mitigated P(NMAC | LoWC) for Low-SWAP DWC be on-par to that from Phase 1
  - In Study 5, the mitigated P(NMAC | LoWC) was estimated to be 0.68%
- HMD appears to drive the mitigated probability more than ModTau (DWC1 to DWC3)*
- Mitigated P(NMAC | LoWC) increase compared to Phase 1 is similar to the unmitigated risk increase
- DWC4 is closest to Phase 1 mitigated P(NMAC | LoWC)
- Increase in unmitigated and mitigated risk for low-SWAP/noncooperative intruders may be acceptable given unmitigated risk reduction in Phase 1 to accommodate TCAS RA considerations (5% to 2.2%)

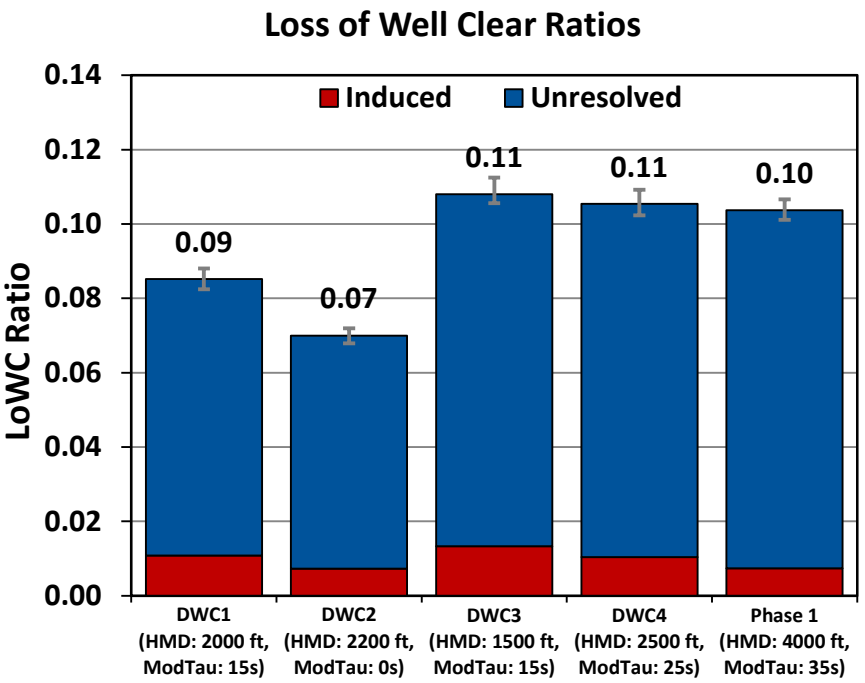


	DWC1	DWC2	DWC3	DWC4	Phase 1
HMD*	2000 ft	2200 ft	1500 ft	2500 ft	4000 ft
ModTau	15 s	0 s	15 s	25 s	35 s

*DWC1/3 different: HMD likely drives metric
DWC1/2 different: ModTau likely drives metric

Safety Ratios

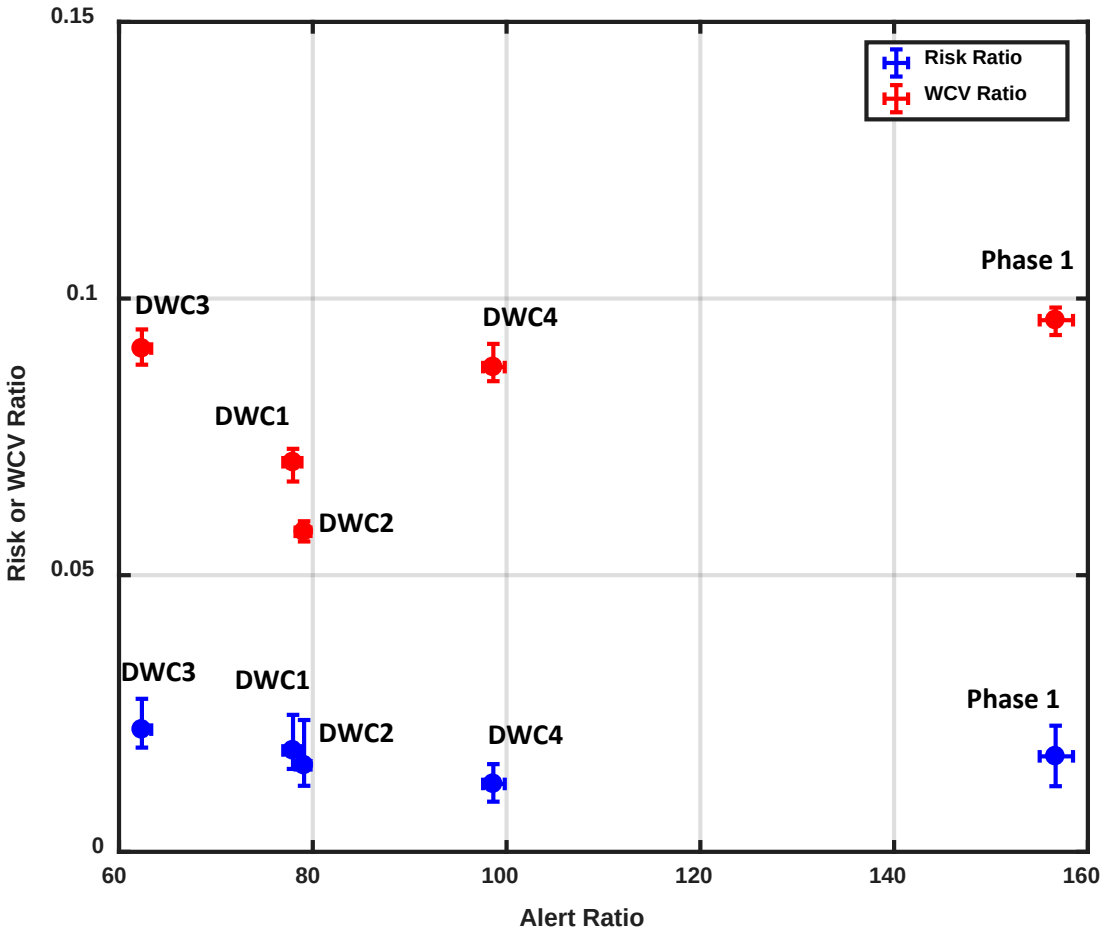




- Risk ratios are comparable among the DWC candidates
  - No statistically significant difference for risk ratios
- DWC1 and DWC2 have the lowest loss of well clear ratios

Risk ratios largely independent of DWC definition

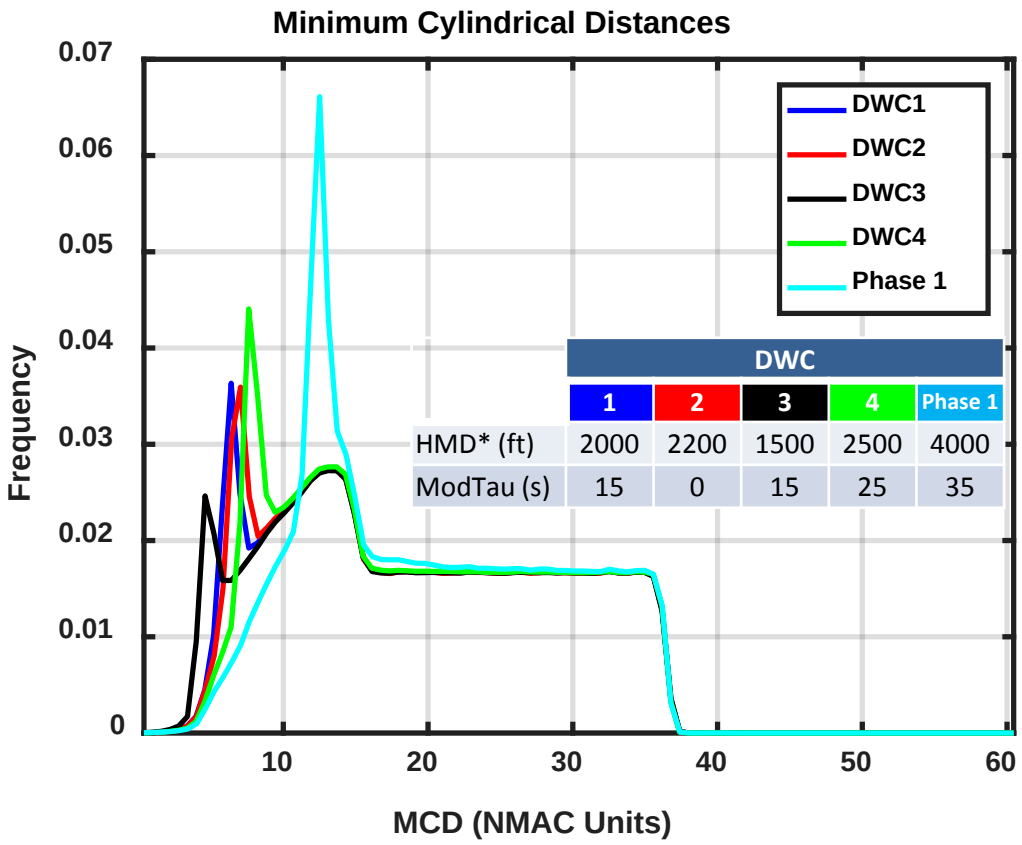
System Operating Characteristic



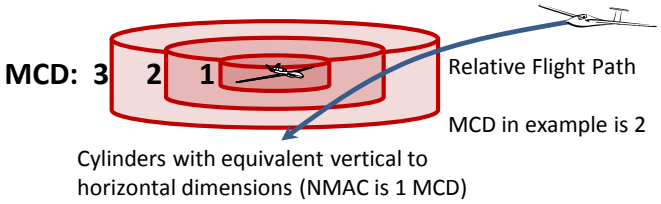
	DWC1	DWC2	DWC3	DWC4	Phase 1
HMD*	2000 ft	2200 ft	1500 ft	2500 ft	4000 ft
ModTau	15 s	0 s	15 s	25 s	35 s

- SOC allows simultaneous evaluation of safety and operational suitability
- Alert ratio measures the alert frequency relative to the nominal NMAC frequency, so it is encounter definition independent
- HMD appears to have the largest effect on alert ratio
  - DWC1 and DWC3 have the same modTau, but DWC1 alerts more frequently

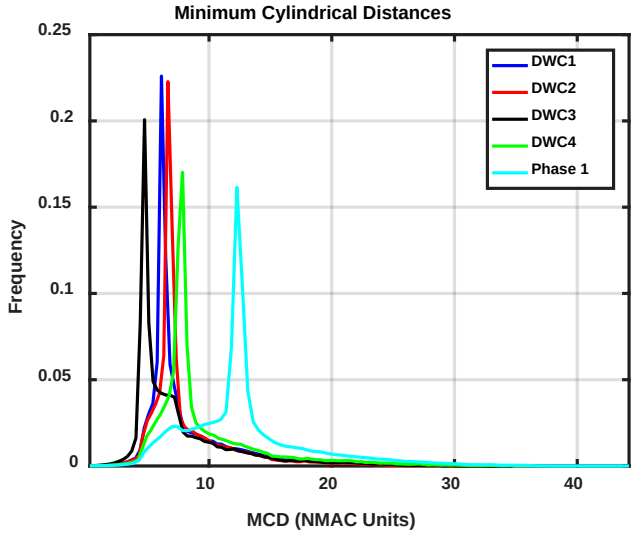
Minimum Cylindrical Distance



MCD Description & Example

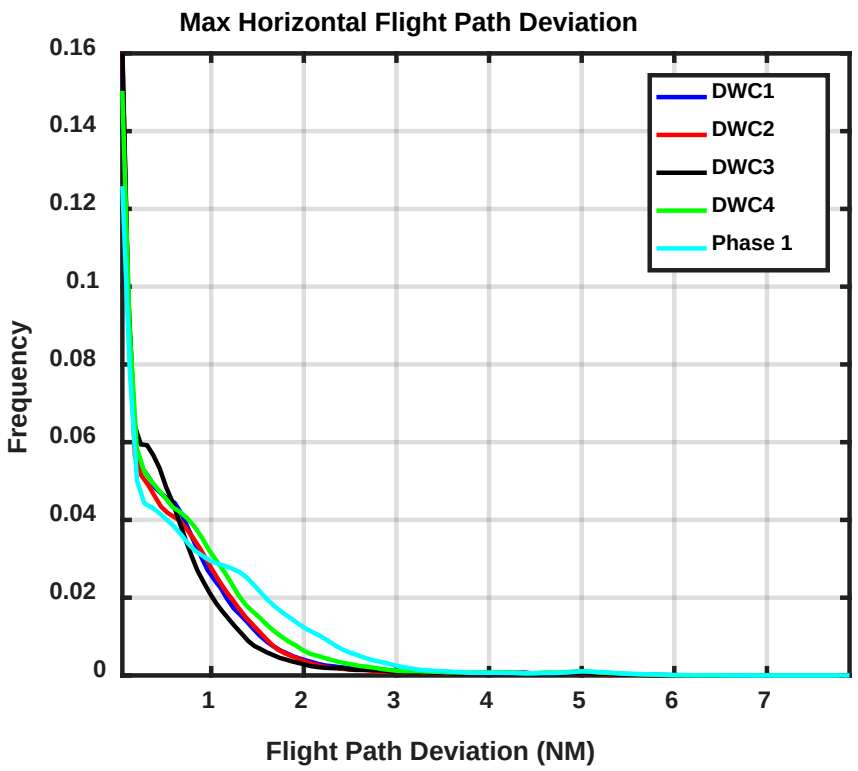


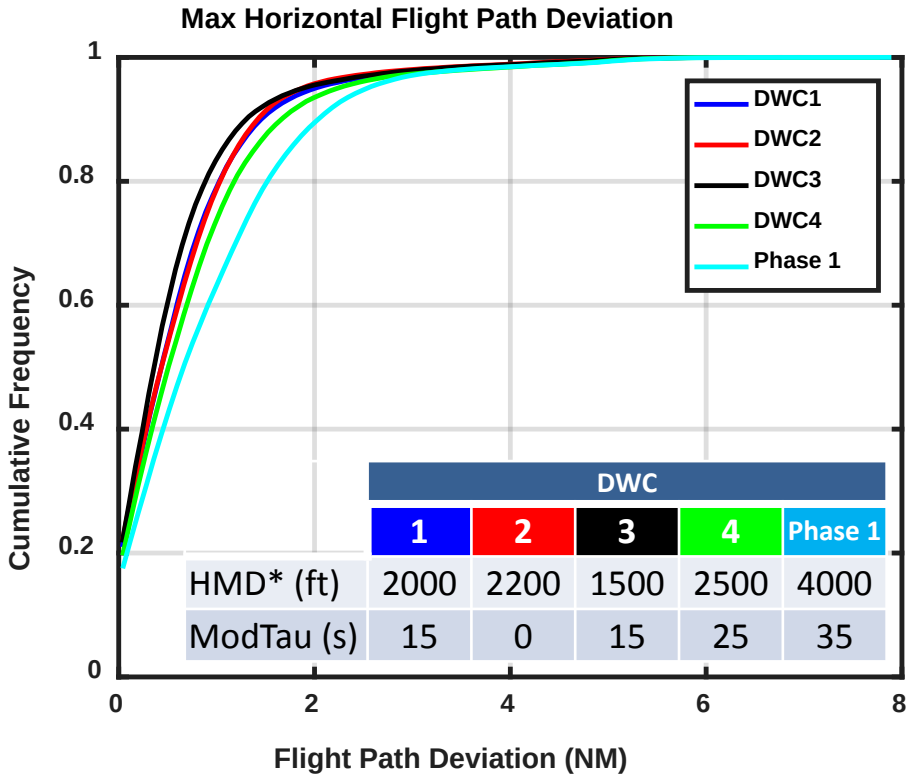
Only Encounters with an Alert



- Minimum cylindrical distance (MCD) is used as a measure of encounter severity
  - SLoWC depends on the underlying DWC, so would not be a common metric to compare DWCs
  - MCD is the smallest penetrated cylinder with dimensions equivalent to NMAC: e.g., MCD of 2 NMAC would indicate that the aircraft came no closer than a cylinder of 200 ft above/below and 1000 ft radius
- Distributions for all DWCs have same basic shape
- First peak in each distribution occurs at MCD = HMD*1.5/500; rest of distribution due to encounter geometrics of encounters where the ownship does not maneuver off of an alert

Flight Path Deviation





- Deviation is the maximum orthogonal and temporal (defined in DO-365) throughout entire encounter: nominal encounter extends to 30 s after CPA
  - Only computed for encounters where a maneuver occurred
- As expected, more deviation with larger DWCs

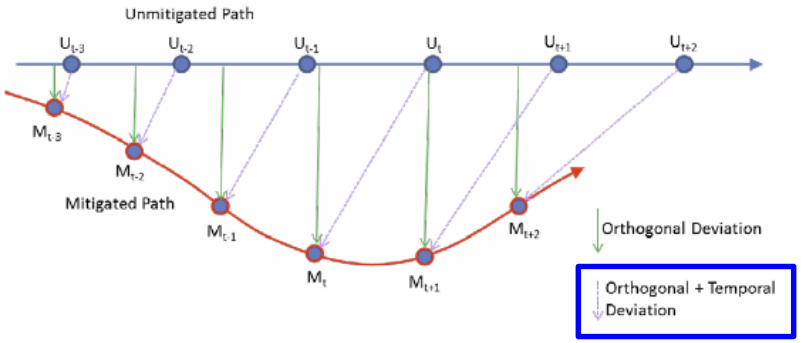
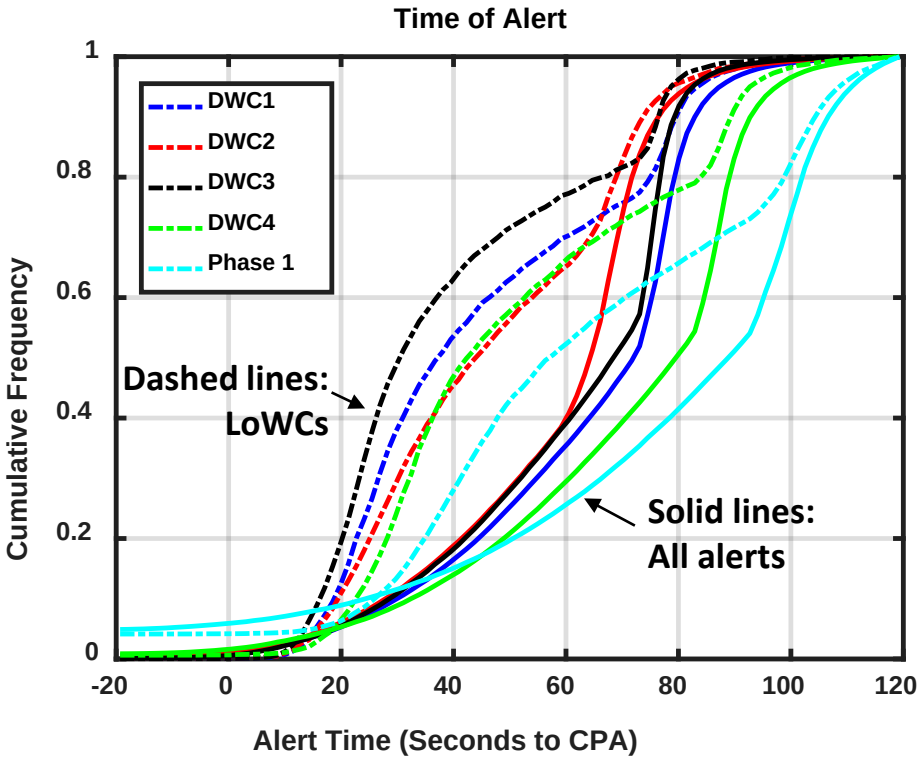
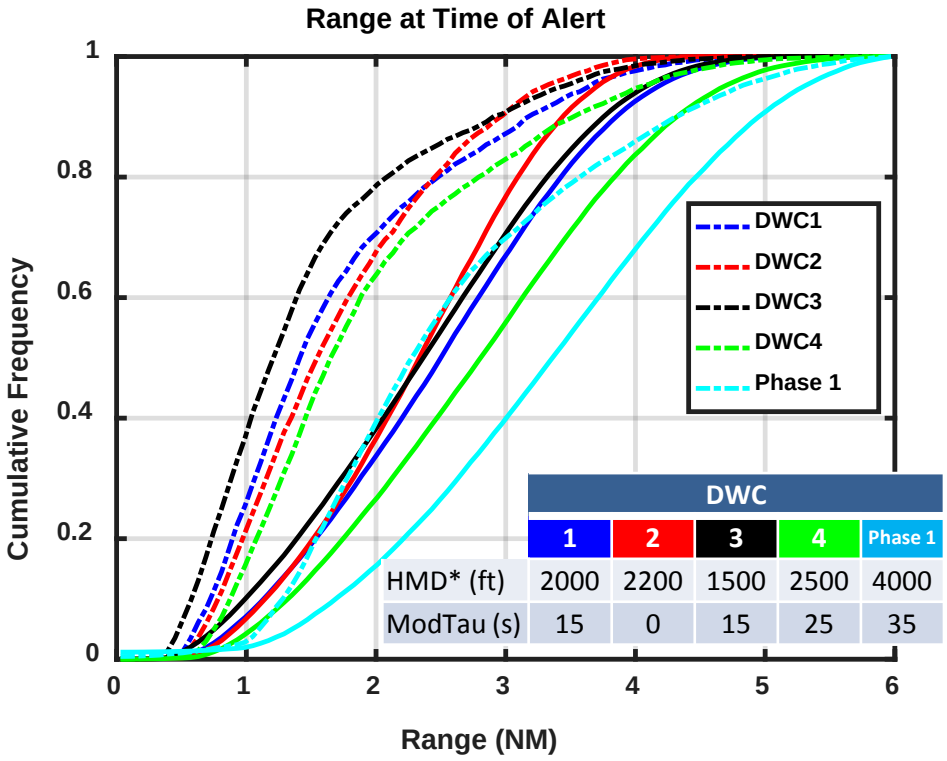


Figure L-7 Deviation Diagram

Alerting Time and Range

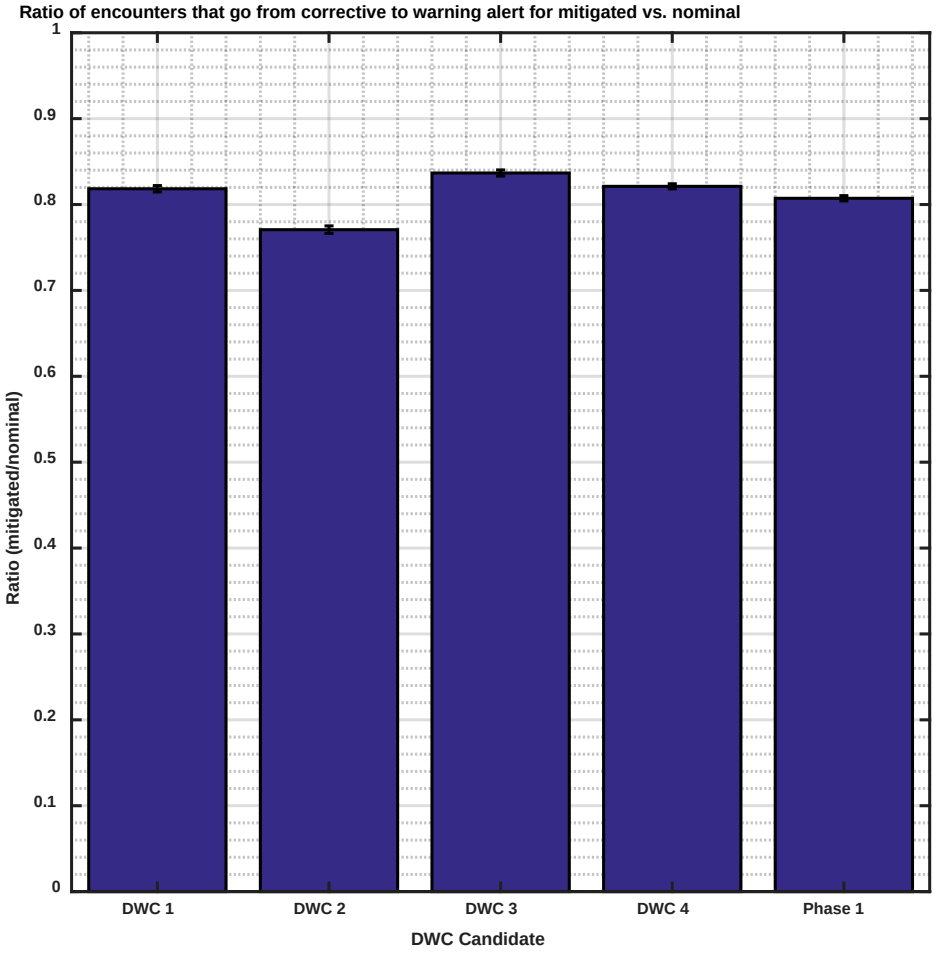




- Time and range of alert are for any alert level
- Time of alert is the projected time to CPA when the alert occurs (to prevent DAA maneuvering from affecting the metric)
- Alerting time and range driven more by tau than HMD (DWC 1/2 difference)
- LoWCs have later alert times and ranges: indicates that LoWCs may be caused by late nominal (non-DAA) maneuvers

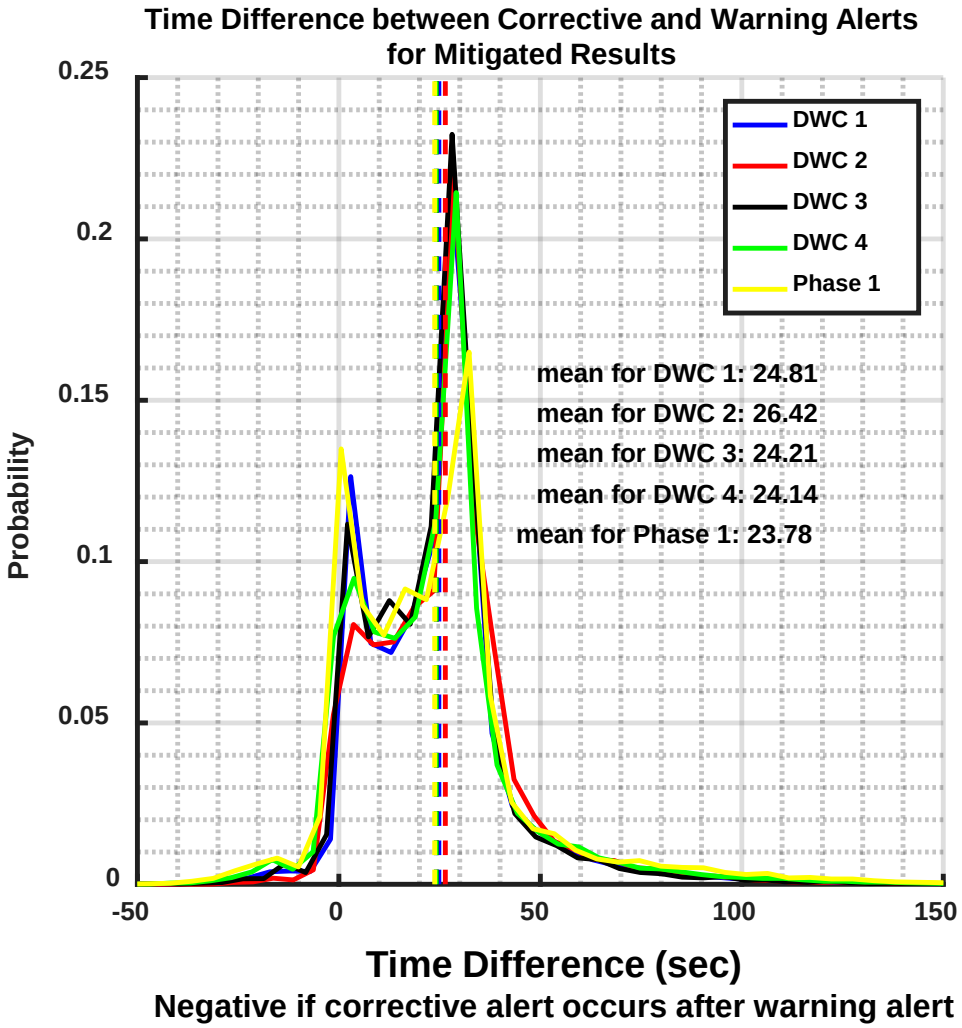
Corrective/Warning Alert Analysis

- The number of encounters where corrective alerts turn into warning alerts is compared between mitigated and nominal results
- Purpose is to asses utility of corrective alerts
  - High ratio would indicate many corrective alerts still transition to warning alerts when mitigated
  - Low ratio would indicate corrective alerts effectively mitigate the situation so that warning alerts are not needed
- 75-85% of encounters with a corrective alert still upgrade to warning alerts for the mitigated DWC candidates
- DWC 2 has the lowest ratio of corrective to warning alert ratio

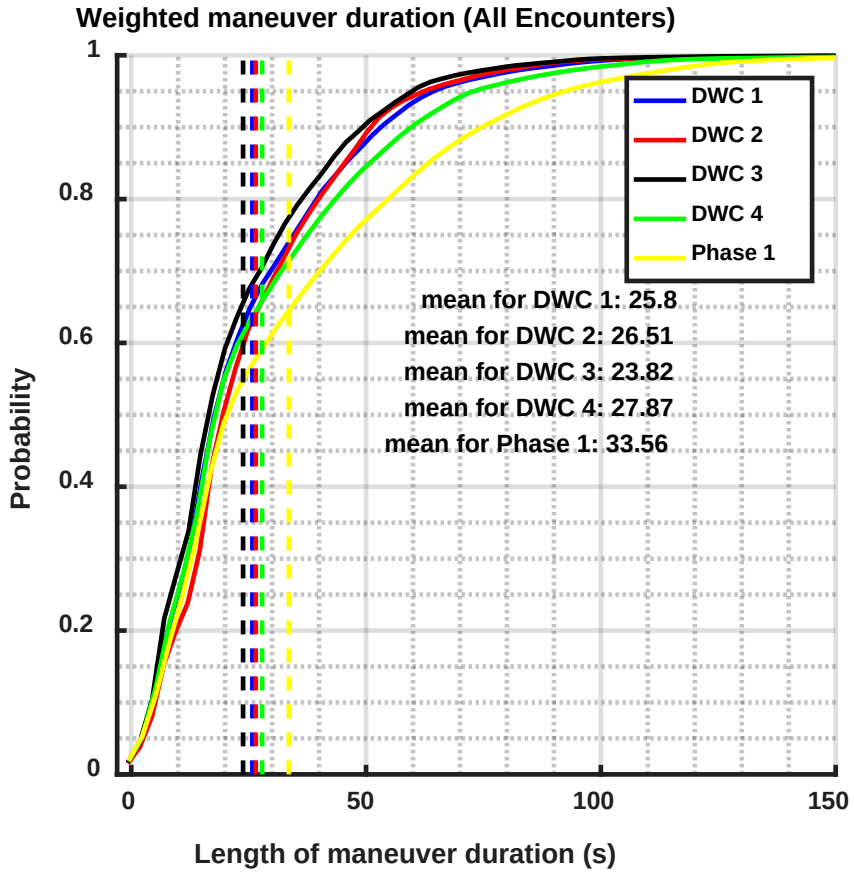


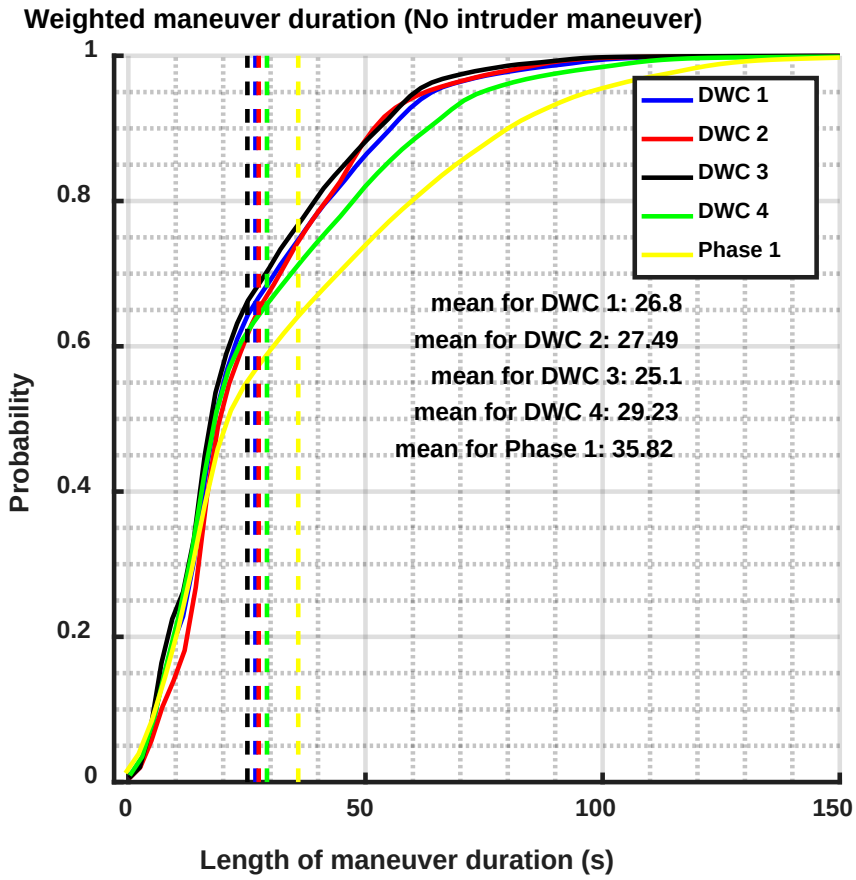
Corrective/Warning Alert Analysis

- The time difference between corrective and warning alerts is consistent across all of the DWC candidates
- Purpose of metric is to determine whether there is sufficient time for ATC coordination and maneuver execution prior to a warning alert
- This weighted histogram shows the difference in time (negative if the corrective alert occurred after the warning alert) for mitigated encounters
- Large number of encounters where the corrective alert is within 5 seconds of the warning alert for all DWC candidates
  - Due to late maneuvers performed by the intruder
  - May also explain why so many corrective alerts transition to warning



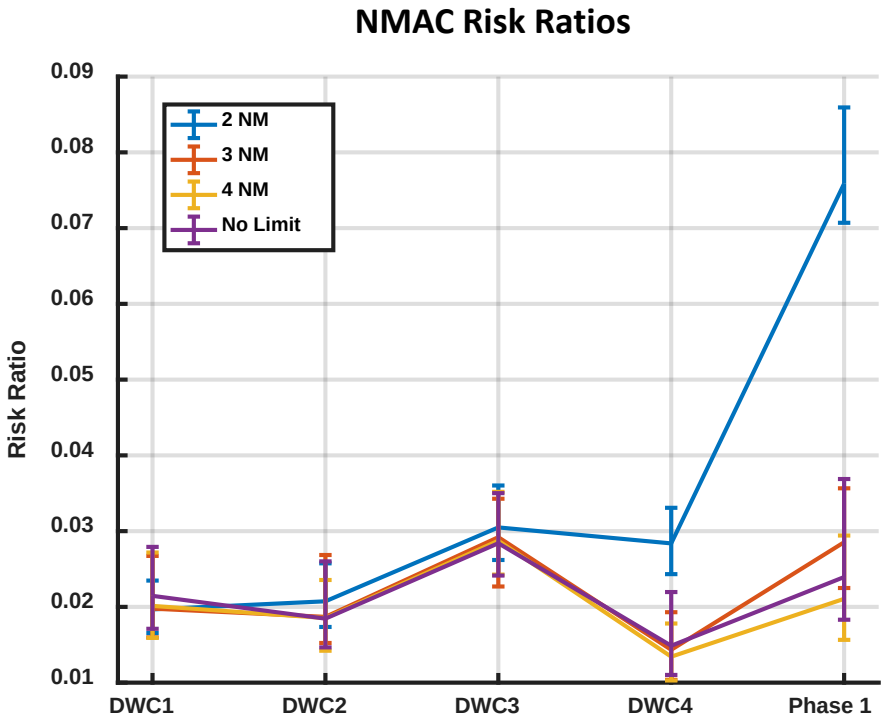
Maneuver Duration (CDF)

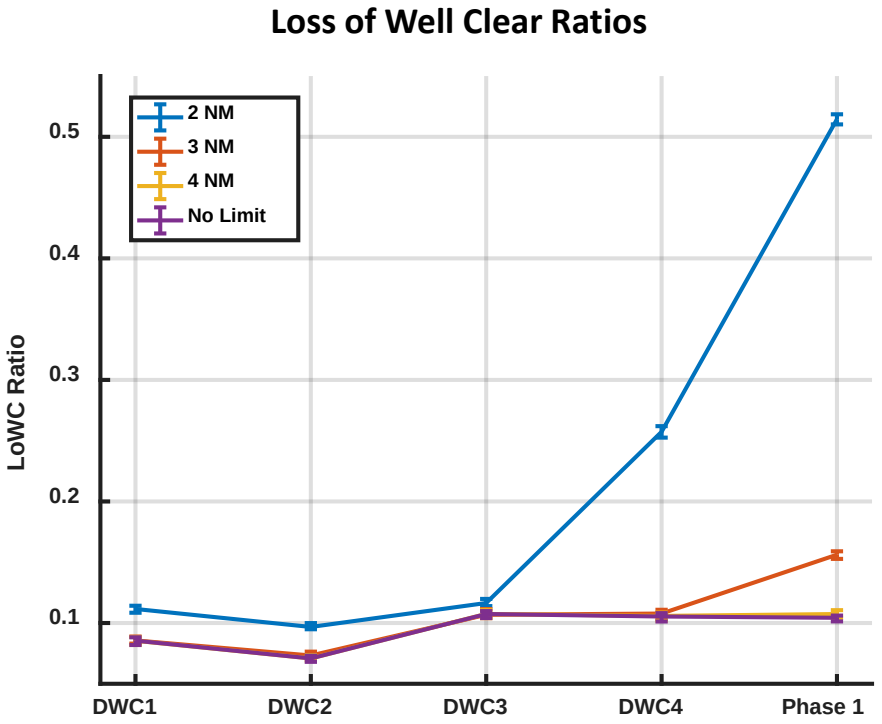




- Maneuver duration is defined as time between first maneuver and the alert being resolved
- DWC 1, 2, and 3 have similar CDF profiles while DWC 4 and Phase 1 have a higher chance of having a longer maneuver duration
- Suggests a shorter alerting timeline may be feasible for low-SWAP UAS

Safety Ratios for All Surveillance Ranges





- DWC 1, 2, 3 are largely insensitive to reduced surveillance ranges
- DWC 4 and Phase 1 experience large increases in risk ratio and loss of well clear ratio when surveillance range is reduced (see 2 NM blue line)

NASA Mitigated Well Clear Analysis: Phase 1-Like UAS

Samantha Smearcheck
Sean Calhoun, Ph.D.
Tony Adami

Overview

Objective:

Assess mitigated DAA performance under NASA's candidate DWC definitions based on safety and operational suitability metrics, focusing on Phase 1 UAS

	Default	NASA DWC1	NASA DWC2	NASA DWC3	NASA DWC4	DWC5 (TAO)
HMD*	4000 ft	2000 ft	2200 ft	1500 ft	2500 ft	1500 ft
ModTau	35 s	15 s	0 s	15 s	25 s	0 s

*A scale factor of 1.519 was used for DAIDALUS to inflate the horizontal dimension of well clear to be consistent with the (4000ft --> 1 nmi) adjustment used in Phase 1

** altitude threshold = 450 ft

High-Level Approach:

- Analysis based on 1 million encounters simulated by MIT
  - One projected UAS trajectory generated by NASA's ACES fast-time simulation paired with one intruder trajectory sampled from MIT Lincoln Laboratory's Uncorrelated Encounter Model
  - Encompass low-SWaP and high-performance aircraft against VFR intruder
- Leverage NASA's DAIDALUS algorithm
  - Configured for each volume of interest
- Leverage the MIT pilot response model
  - Deterministic mode

Description of Results

Preliminary Results: Preliminary results were presented at the September SC-228 Face-to-Face meeting based on 50,000 of the total 1 million encounters

- Two volumes were evaluated initially:
  - Phase 1 (default)
  - NASA DWC1

Baseline Results: The baseline results were based on the total 1 million encounters, and encompass all 5 volumes of interest

Re-Run Results: The results presented in this briefing are "re-runs" of the baseline analysis which address the following:

- Fix the pilot response model issue discovered by MIT
  - When subsequent decisions are made during a Warning level alert, they are not acknowledged/followed
- Calculate vertical rate using a finite difference in vertical position rather than using the provided vertical rate directly
  - MIT discovered an issue with their encounter vertical rates
- Use updated encounter weighting information provided by MIT
  - Due to vertical rate and heading issues, the previously provided weighting was incorrect
- Remove the pilot response model buffer in deterministic mode
  - i.e. adjust the buffer from 30.5 degrees to zero degrees to follow the minimum suggested guidance
- Constrain truth by a radar FOV
  - 8 nmi range, ±15 in elevation , ±110 degrees in azimuth
- Remove the Preventive alert (i.e. only Corrective and Warning alerts)
- Bin results based on ownship speed, as suggested at the September SC-228 face-to-face meeting
- Assessing an additional volume (TAO)
- Remove all encounters which have an alert within the first 5 seconds of the encounter

Assumptions

Ownship Performance Assumptions:

- Ownship speeds: 40-250 kts
- Turn rate of 3 deg/s
- Truth surveillance

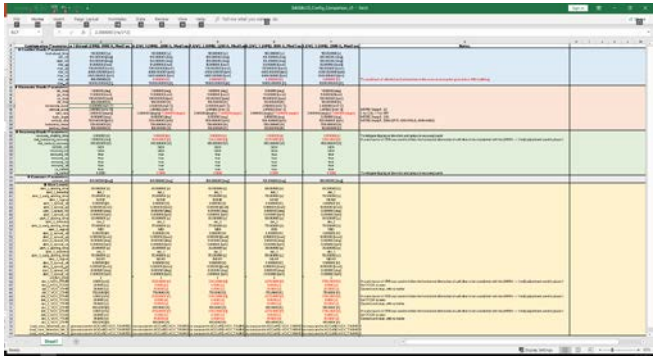
Pilot Response Model Assumptions:

- Deterministic mode
- Horizontal-only maneuvers
  - Always maneuvers horizontally in the direction of the minimum suggested maneuver; turns left if minimum suggestion is inconclusive
- Follow guidance bands determined by PRM, with no buffer on minimum suggested guidance
  - The 30.5 degree buffer in deterministic mode was removed
- Decisions updated according to alert state
- 11 second ATC delay for Corrective
- 3 second execution delay after a decision

State	Decision Update Period (s)
No Alert	12
~~Proximate Traffic~~	~~12~~
~~Preventive Alert~~	~~9~~
Corrective Alert	6
Warning Alert	6
Loss of Well Clear	0

DAIDALUS Configurations

- DAIDALUS was selected because:
  - It is the SC-228 reference
  - It is easily configurable
  - It aligns with the MIT PRM
- Configuration modification approach:
  - Began with SC-228 Phase 1 default configuration (WC_SC_228_nom_b.txt):
    - Modified as needed:
      - Adjusted size of well-clear volume to align with study volumes of interests
      - Adjust turn rate assumption for Low SWaP UAS runs (MIT)
    - Aligned where appropriate:
      - Inflated the horizontal component of each study volume of interest by the same scale factor used in Phase 1 (4000 ft to 1 nmi → 1.519) to account for some degree of dynamic uncertainty
      - Used same alerting time assumptions
- CAL generated DAIDALUS configuration files for both the Phase 1 UAS and Low SWaP UAS version of this effort



Metrics

Safety metrics

- Risk ratio and loss of well clear ratios: $\frac{\mathbf{P(NMAC\ or\ LoWC|encounter,\ with\ mitigation)}}{\mathbf{P(NMAC\ or\ LoWC|encounter,\ without\ mitigation)}}$
  - Indicates the systems ability to reduce risk (NMAC or LoWC)
- Minimum cylindrical distance: $\mathbf{min_{encounter\ time}[max(rh/5; rv)]}$
  - where rh is horizontal range and rv is vertical range
  - MCD is the smallest penetrated cylinder, with relative dimensions equal to NMAC
  - Surrogate for SLoWC due to different candidate DWC definitions
- Mitigated P(NMAC | LoWC): desire to match value from Phase 1
  - Indicates the systems ability to mitigate the risk of an NMAC given the LoWC volume

Operational suitability metrics

- Alert ratio: $\frac{\mathbf{P(Alert|encounter,\ with\ mitigation)}}{\mathbf{P(NMAC|encounter,\ without\ mitigation)}}$
  - Alert ratio measures the alert frequency relative to the nominal NMAC frequency, so it is encounter definition independent
- Horizontal flight path deviation
  - Max orthogonal + temporal deviation (as defined in Figure L-7, DO-365)
- Maneuver duration
  - Defined as the time from when a maneuver begins to when all alerts have cleared

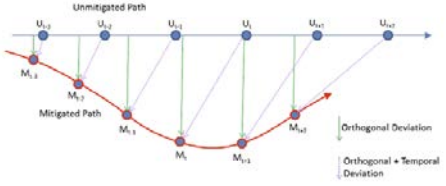
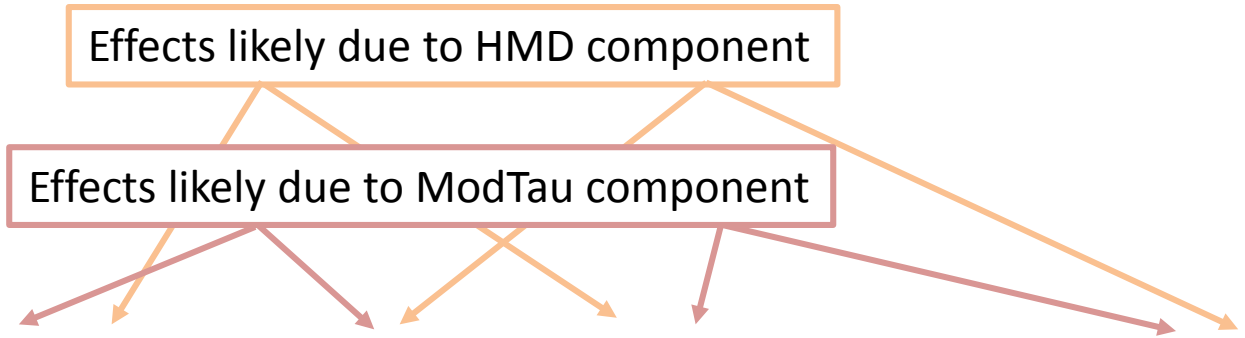


Figure L-7 Deviation Diagram

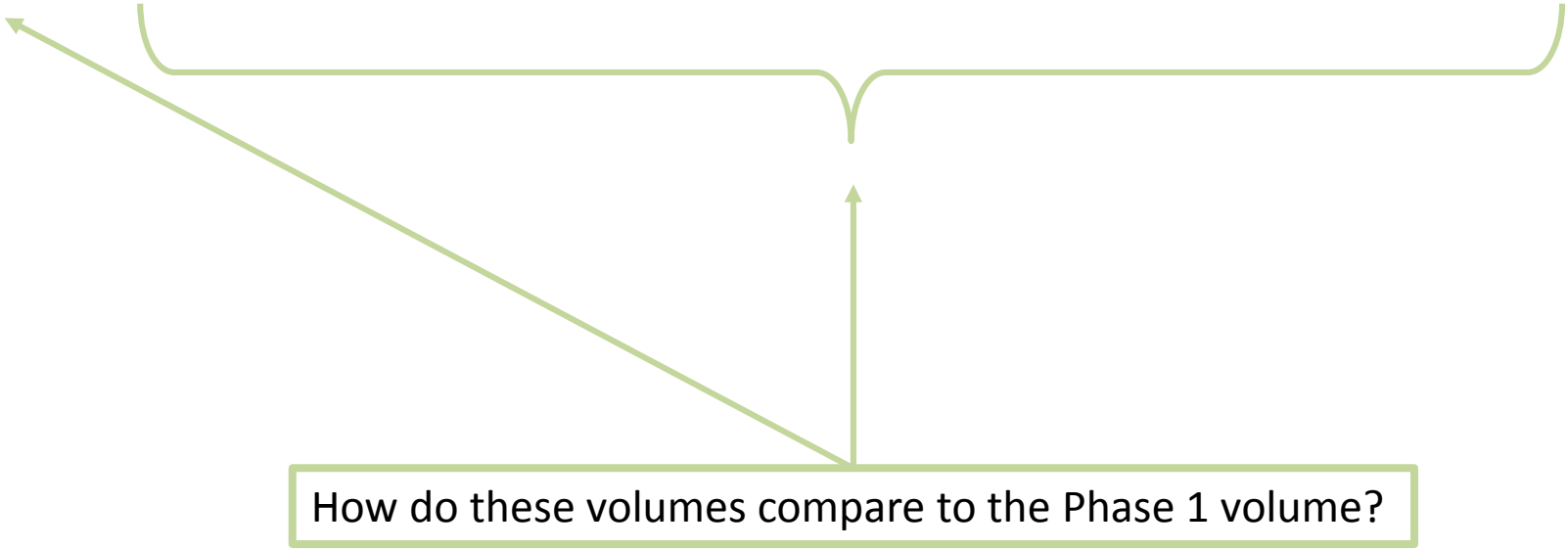
DAIDALUS alerting performance metrics

- Alerting time relative to CPA
  - CPA defined as minimum horizontal range
- Aircraft separation at time of alert
- Maximum alert level
- Alert jitter
  - Number of increasing alert transitions
- Alerting time separation between Corrective and Warning
- Benefit of the Corrective alert
  - Look at the number of unmitigated encounters where a Corrective is followed by a Warning and compare that to the number of encounters in the mitigated sense

Helpful Comparisons



	Default	NASA DWC1	NASA DWC2	NASA DWC3	NASA DWC4	DWC5 (TAO)
HMD*	4000 ft	2000 ft	2200 ft	1500 ft	2500 ft	1500 ft
ModTau	35 s	15 s	0 s	15 s	25 s	0 s

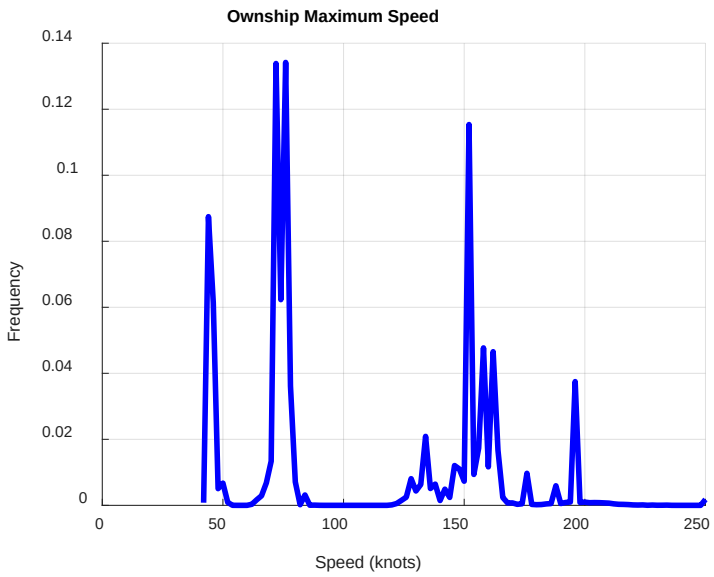


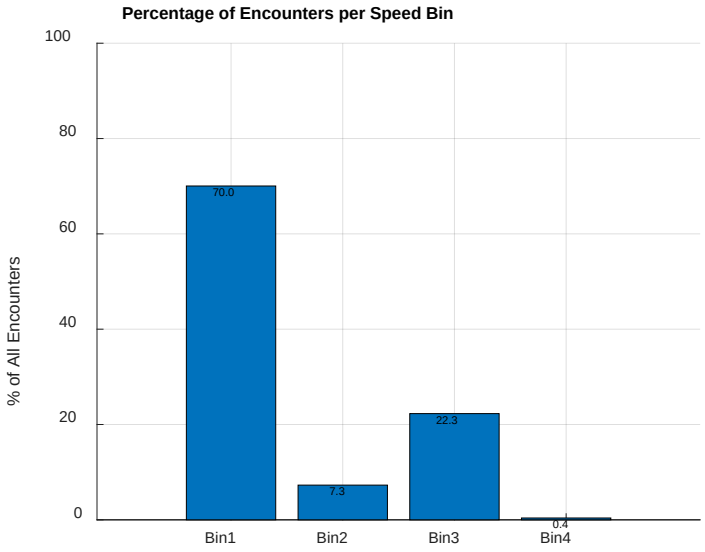
RESULTS BINNED BY OWNSHIP SPEED

Results will be presented using one figure per speed bin, showing the trends across each volume of interest

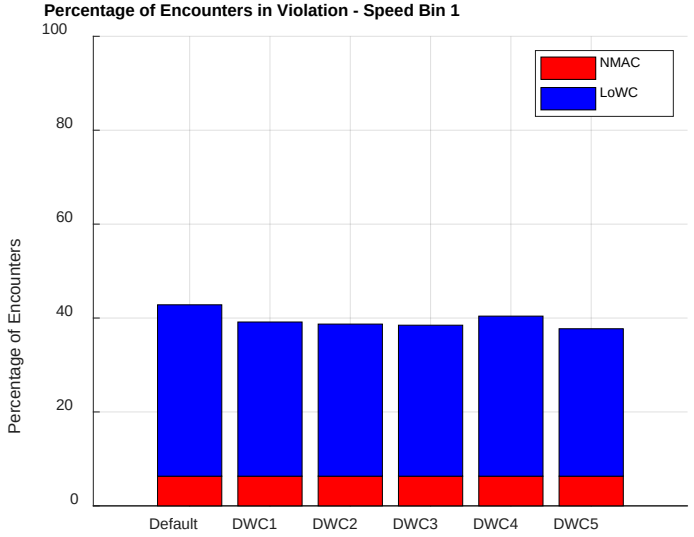
Ownship Speed Bins

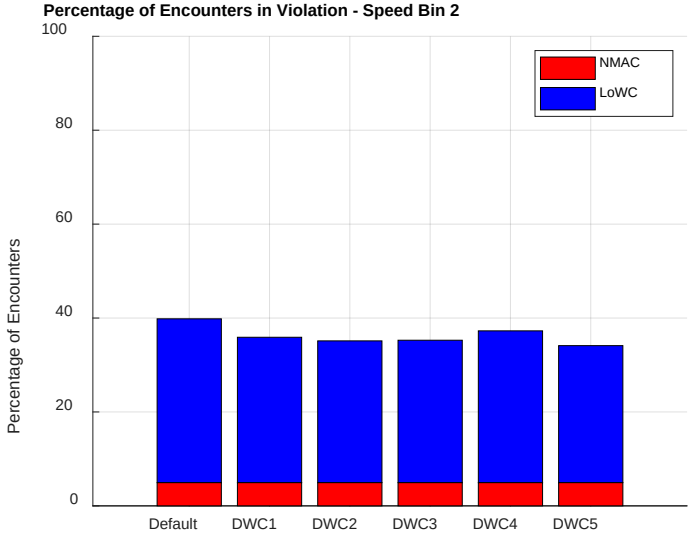
- In the following slides, results were binned by maximum ownship speed, within the unmitigated encounter, as follows:
  - Bin 1: maximum ownship speed <= 100 knots
  - Bin 2: 100 knots < maximum ownship speed <= 150 knots
  - Bin 3: 150 knots < maximum ownship speed <= 200 knots
  - Bin 4: 200 < maximum ownship speed

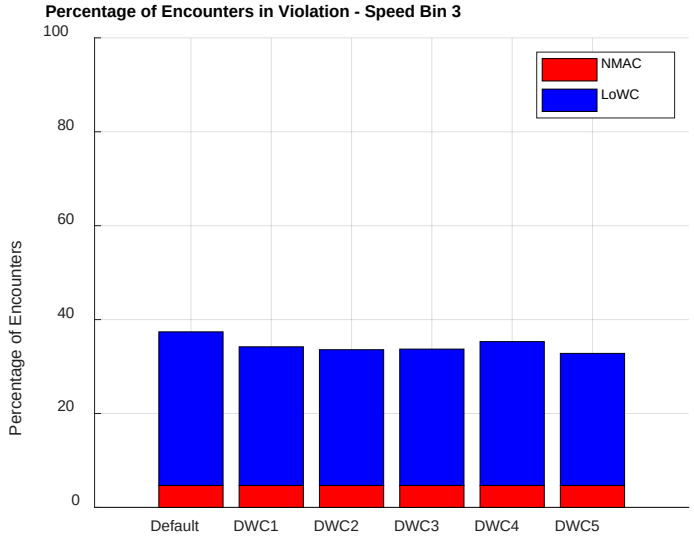


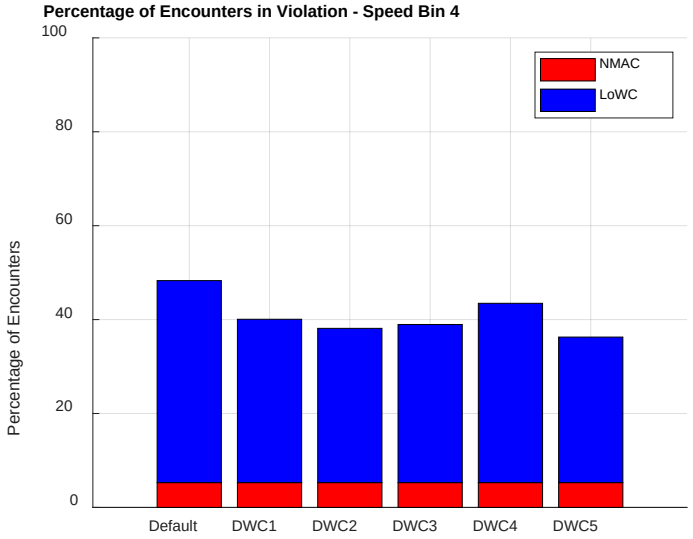


Unmitigated Violation Percentages





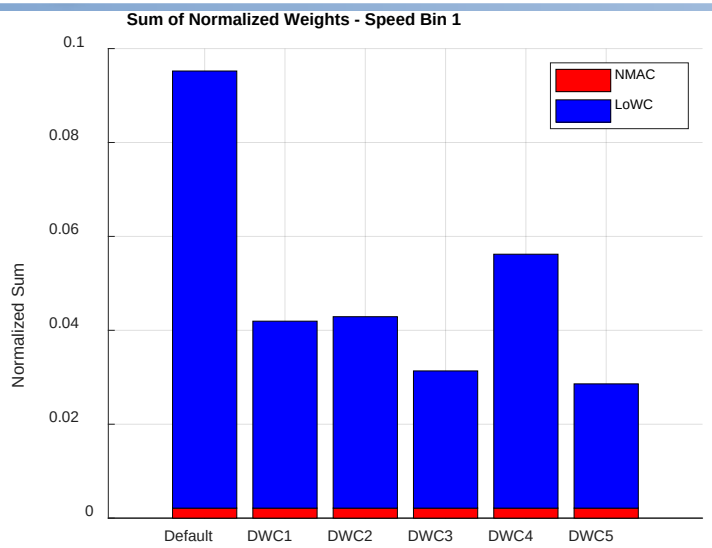


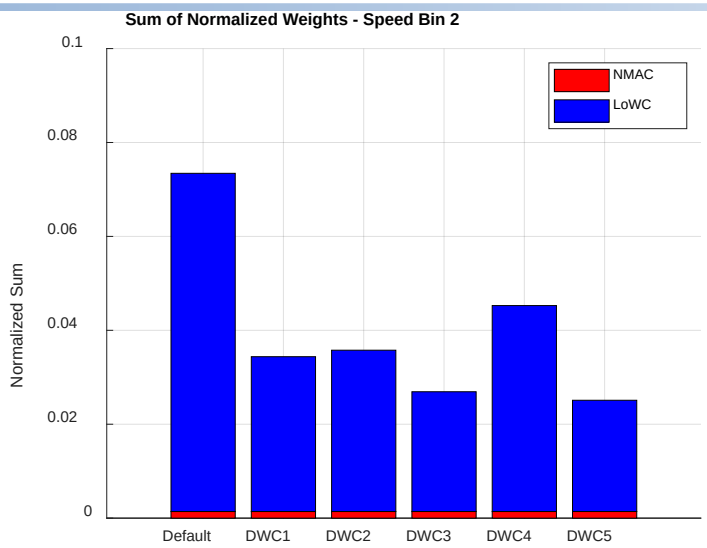


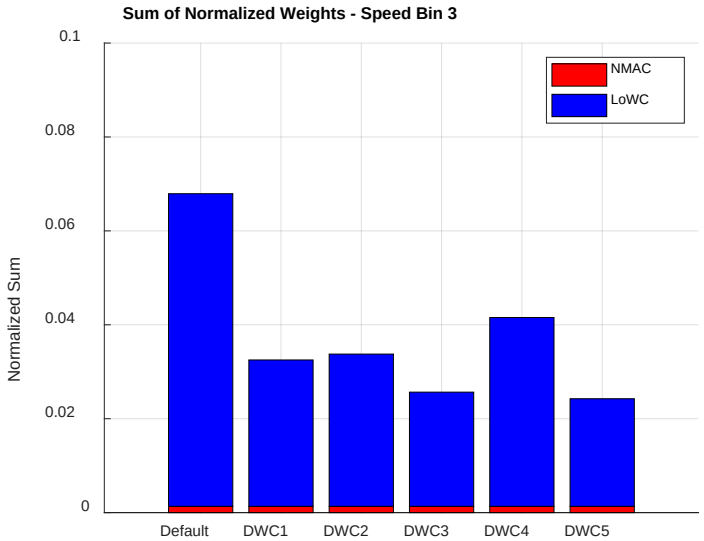
	Default	NASA DWC1	NASA DWC2	NASA DWC3	NASA DWC4	DWC5 (TAO)
HMD*	4000 ft	2000 ft	2200 ft	1500 ft	2500 ft	1500 ft
ModTau	35 s	15 s	0 s	15 s	25 s	0 s

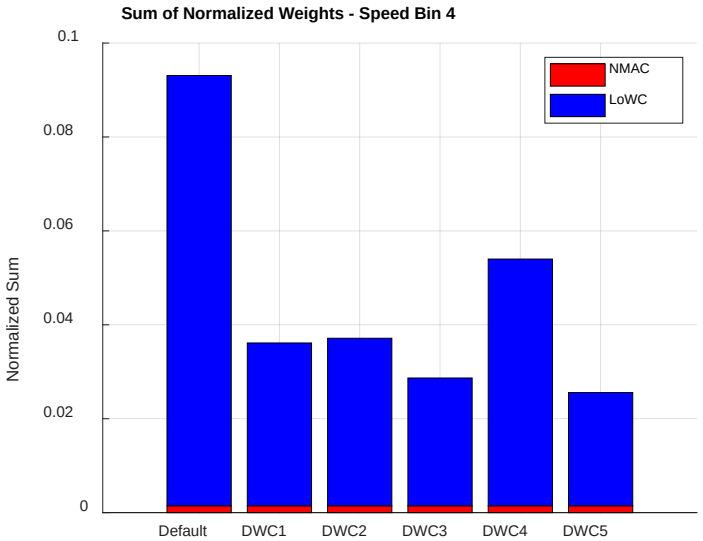
- Across the 4 speed bins, there are consistent unmitigated violation rates
- Across each speed bin, the violation rates per volume are fairly consistent

Unmitigated Violation Frequencies





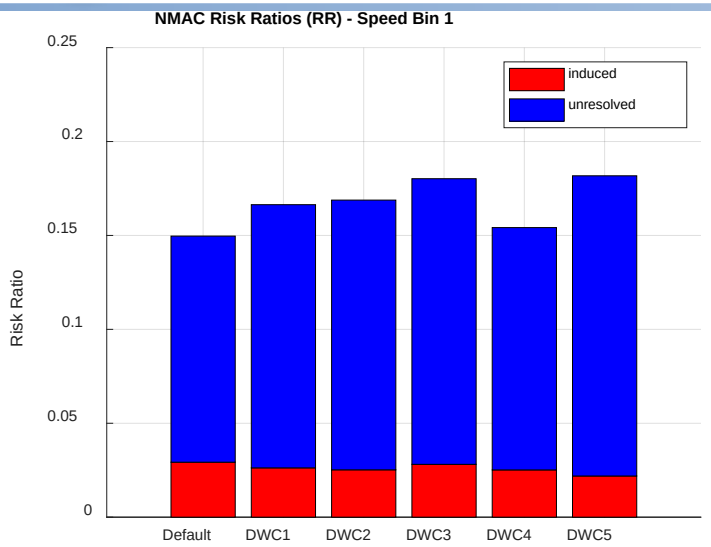


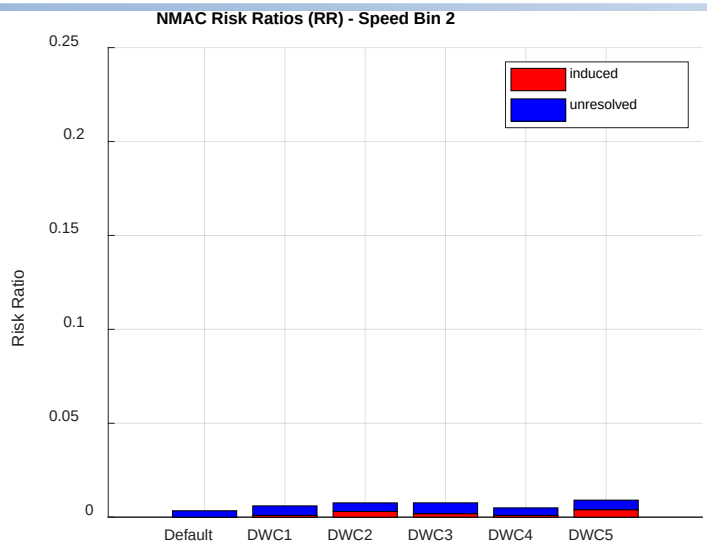


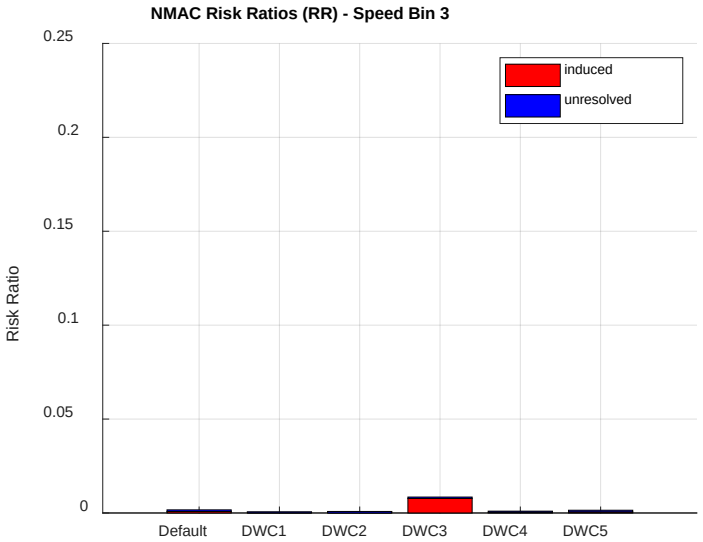
- Across the 4 speed bins, the total normalized weights are fairly consistent
  - Default consistently has the highest total normalized weight
  - DWC5 consistently has the lowest total normalized weight

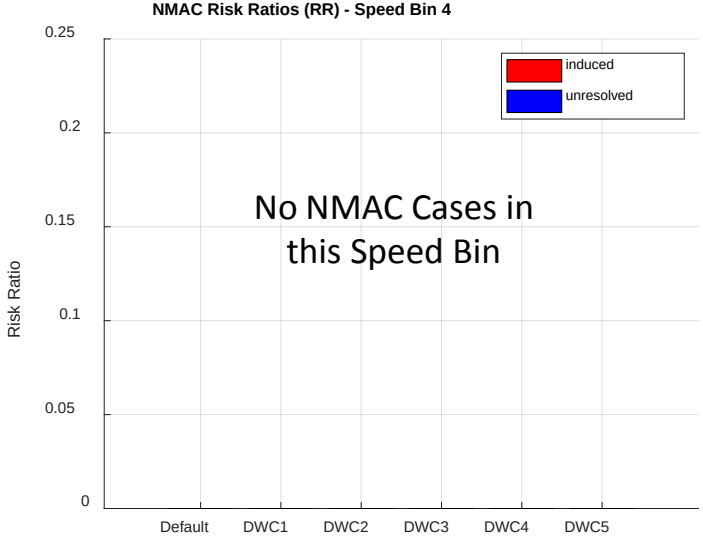
	Default	NASA DWC1	NASA DWC2	NASA DWC3	NASA DWC4	DWC5 (TAO)
HMD*	4000 ft	2000 ft	2200 ft	1500 ft	2500 ft	1500 ft
ModTau	35 s	15 s	0 s	15 s	25 s	0 s

NMAC Risk Ratios





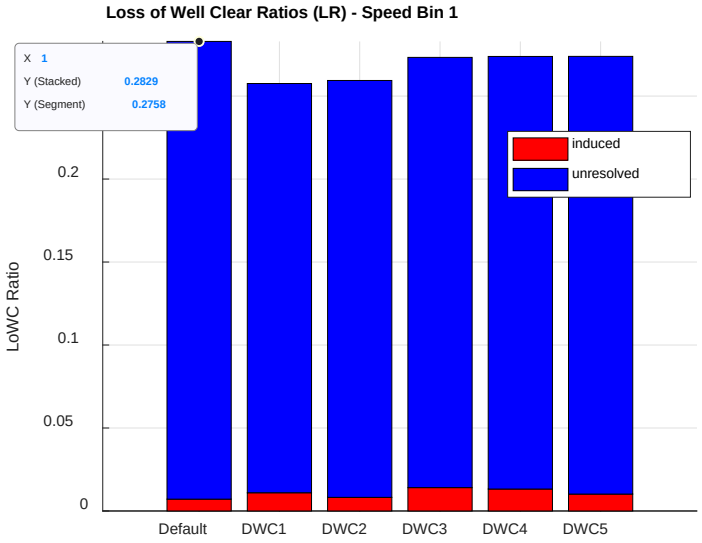


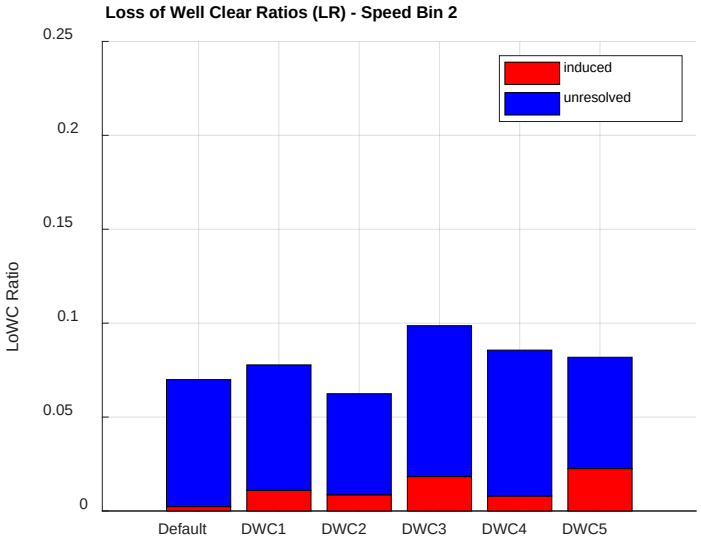


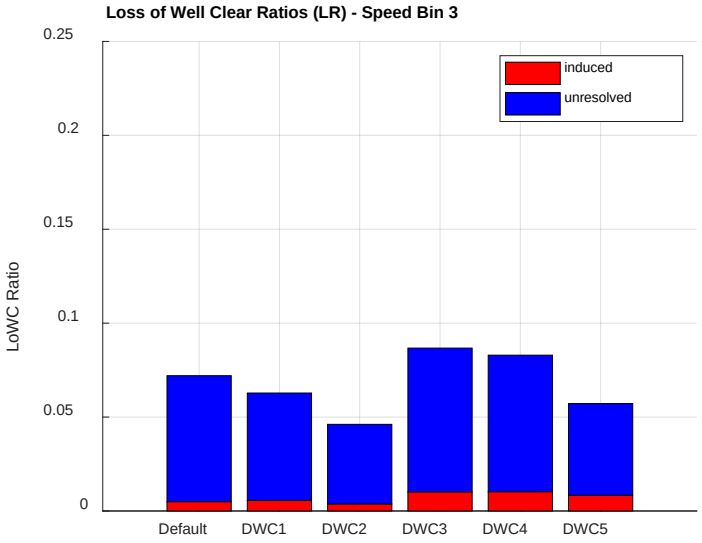
- There are no closed-loop NMACs when ownship aircraft have a maximum speed greater than 200 knots (Speed Bin 4), thus the Risk Ratios are zero
- DWC3 seems to induce NMACs for Speed Bin 3
- In general, the largest volume (Default) has the smallest NMAC Risk Ratio

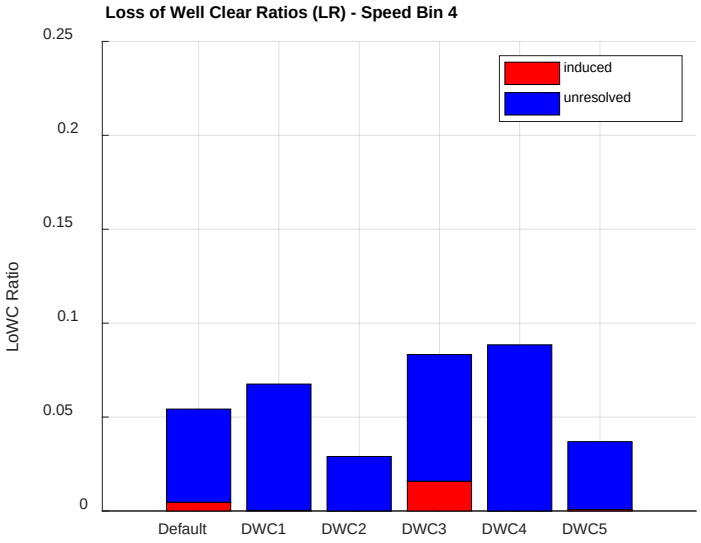
	Default	NASA DWC1	NASA DWC2	NASA DWC3	NASA DWC4	DWC5 (TAO)
HMD*	4000 ft	2000 ft	2200 ft	1500 ft	2500 ft	1500 ft
ModTau	35 s	15 s	0 s	15 s	25 s	0 s

LoWC Risk Ratios





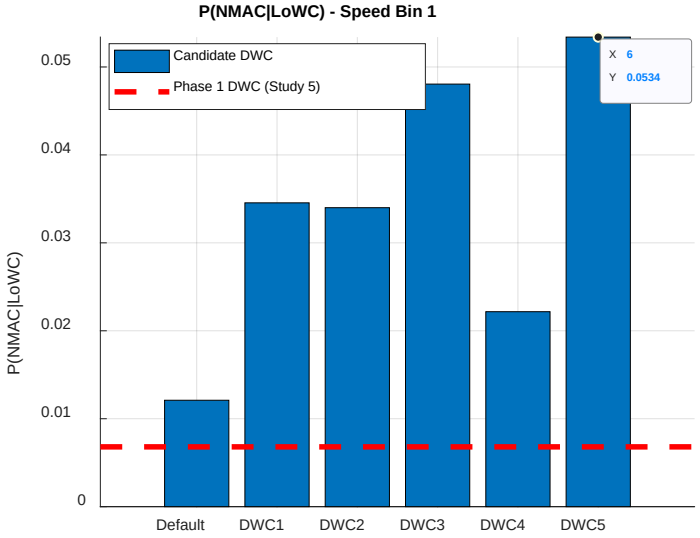


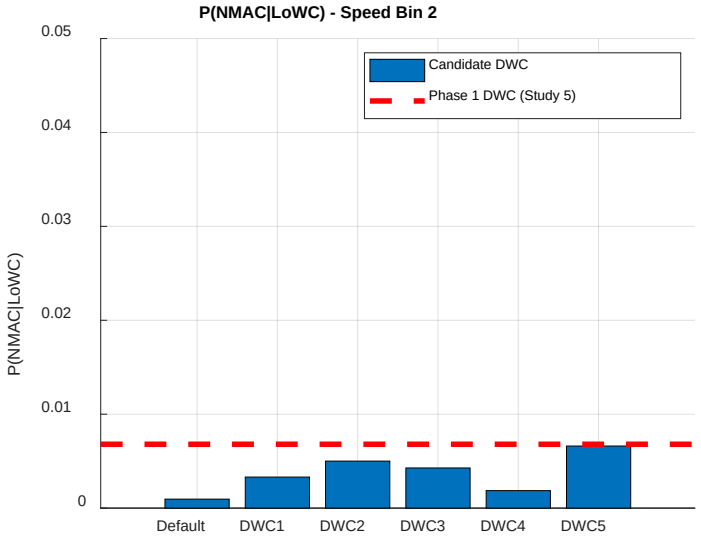


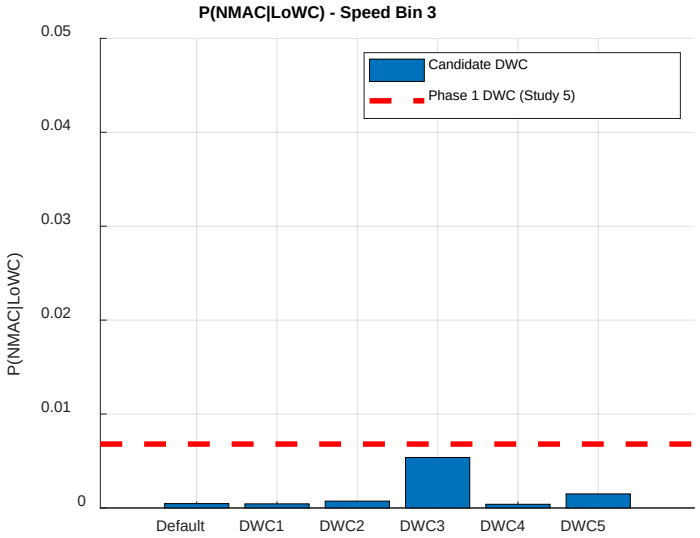
	Default	NASA DWC1	NASA DWC2	NASA DWC3	NASA DWC4	DWC5 (TAO)
HMD*	4000 ft	2000 ft	2200 ft	1500 ft	2500 ft	1500 ft
ModTau	35 s	15 s	0 s	15 s	25 s	0 s

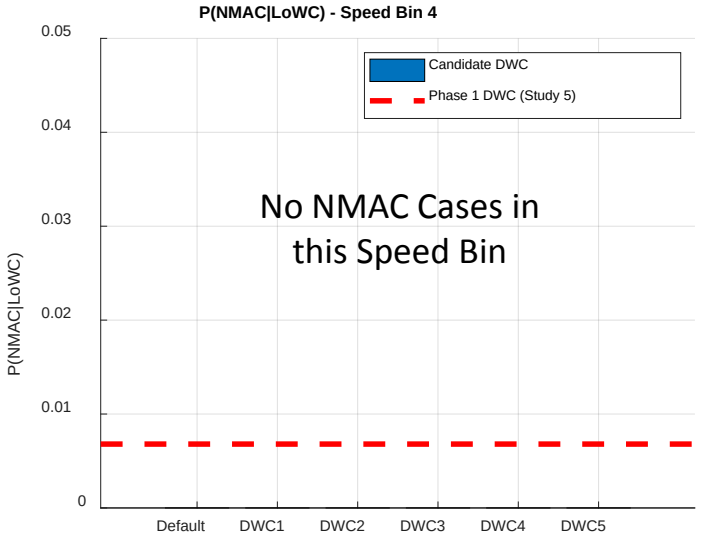
- For slower aircraft (Speed Bin 1) LR seems to be more so effected by HMD
  - Larger HMD values result in higher LR values
- For faster aircraft (Speed Bin 4) ModTau seems to have a larger effect than HMD
  - A lower ModTau leads to a lower LR

Mitigated P(NMAC | LoWC)





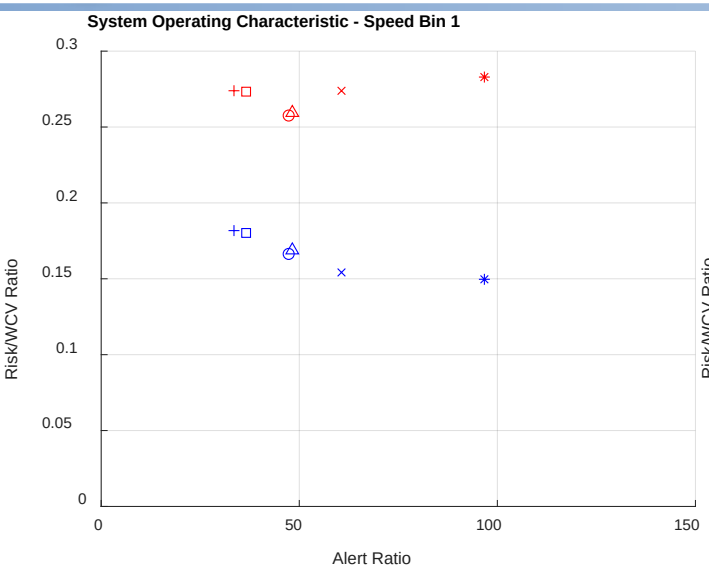


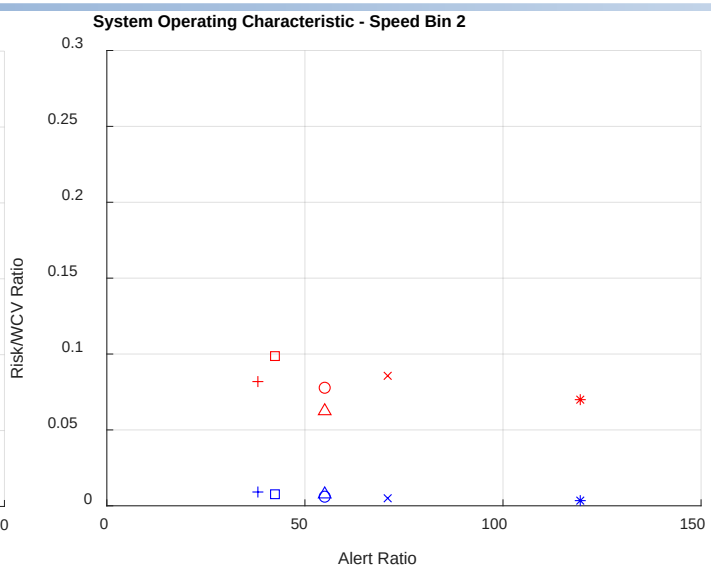


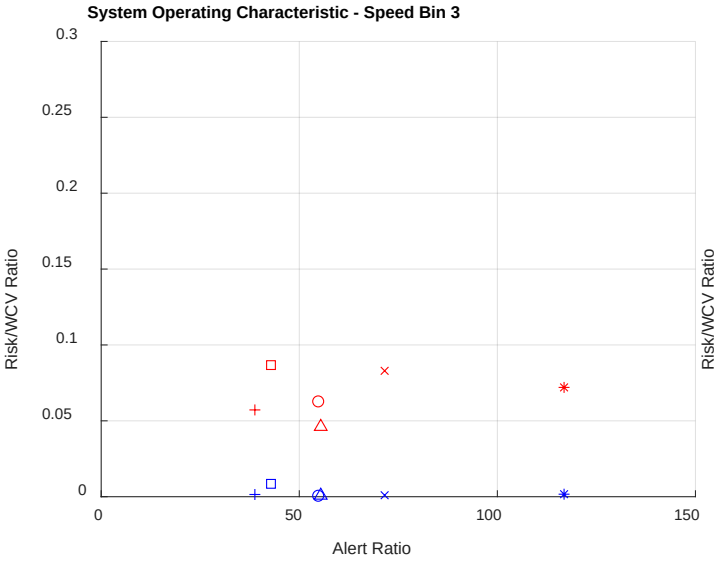
- There are no closed-loop NMACs when ownship aircraft have a maximum speed greater than 200 knots (Speed Bin 4), thus the probabilities are zero
- For slower aircraft (Speed Bin 1) P(NMAC | LoWC) seems to be more so effected by HMD
- For faster aircraft (Speed Bin 2) ModTau seems to have a larger effect than HMD
  - A lower ModTau leads to a lower LR

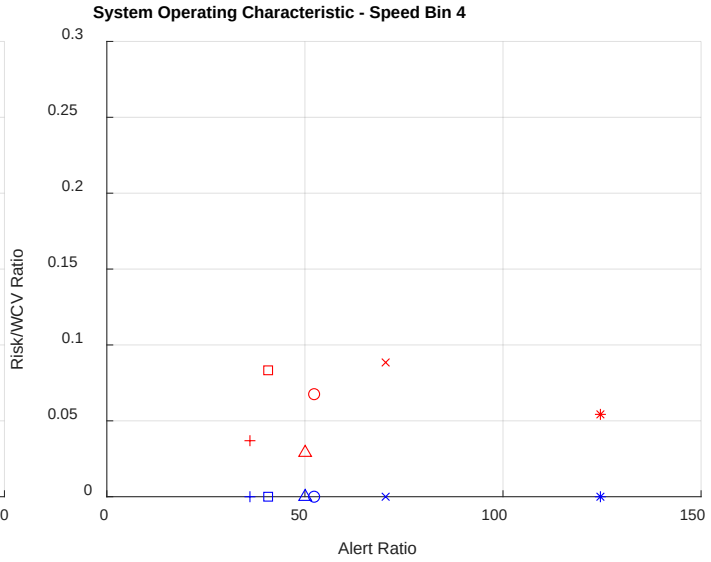
	Default	NASA DWC1	NASA DWC2	NASA DWC3	NASA DWC4	DWC5 (TAO)
HMD*	4000 ft	2000 ft	2200 ft	1500 ft	2500 ft	1500 ft
ModTau	35 s	15 s	0 s	15 s	25 s	0 s

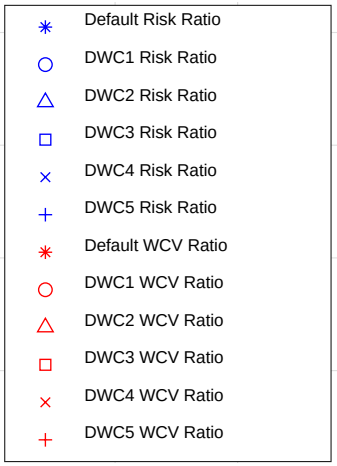
System Operating Curve







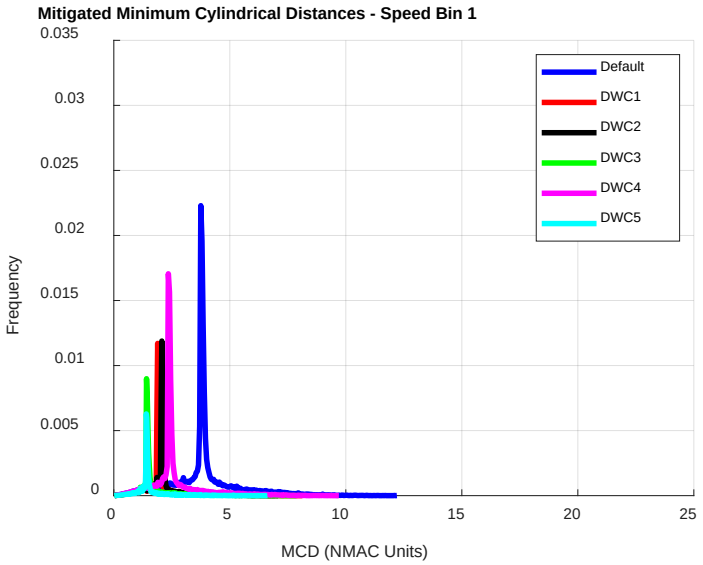


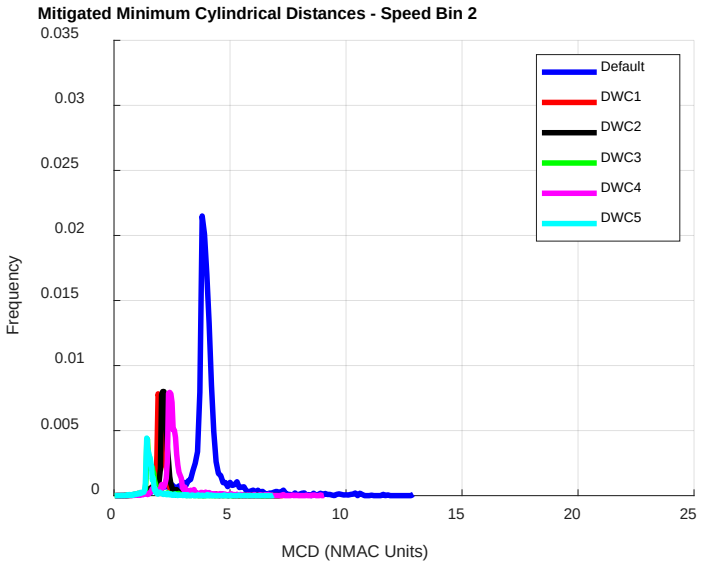


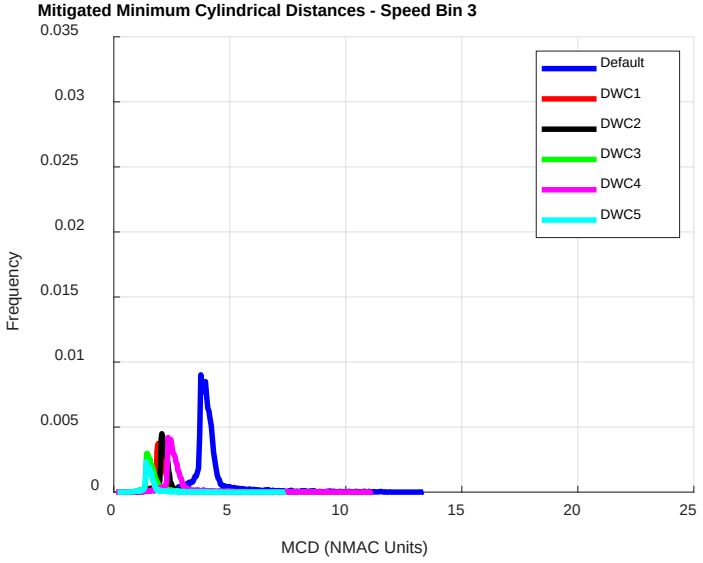
- Alert Ratio seems to be driven by HMD rather than ModTau
  - The larger the HMD, the larger the Alert Ratio
- Alert Ratio does not seem to be significantly effected by ownship speed

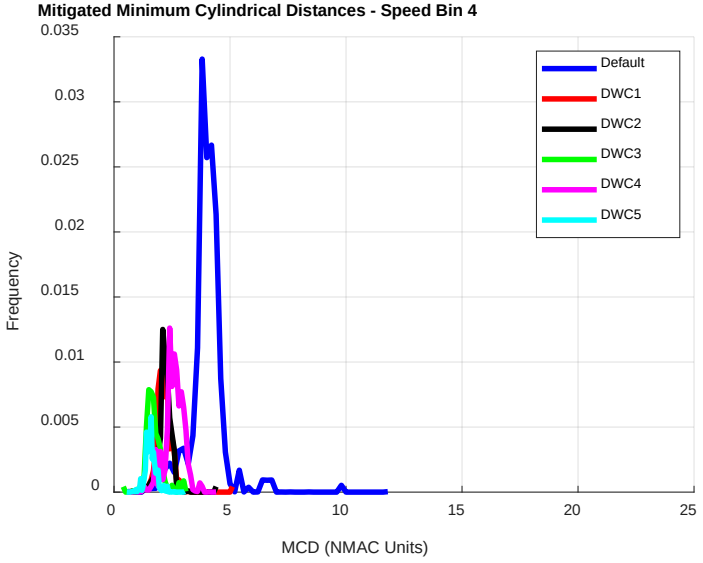
	Default	NASA DWC1	NASA DWC2	NASA DWC3	NASA DWC4	DWC5 (TAO)
HMD*	4000 ft	2000 ft	2200 ft	1500 ft	2500 ft	1500 ft
ModTau	35 s	15 s	0 s	15 s	25 s	0 s

Minimum Cylindrical Distance

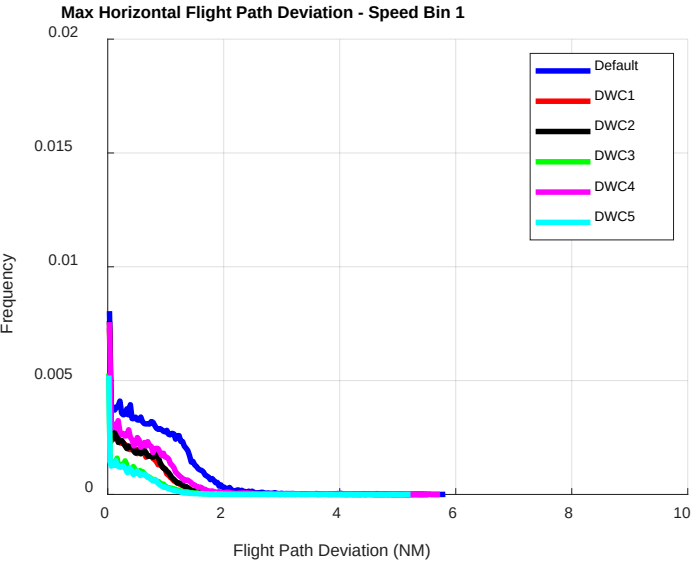


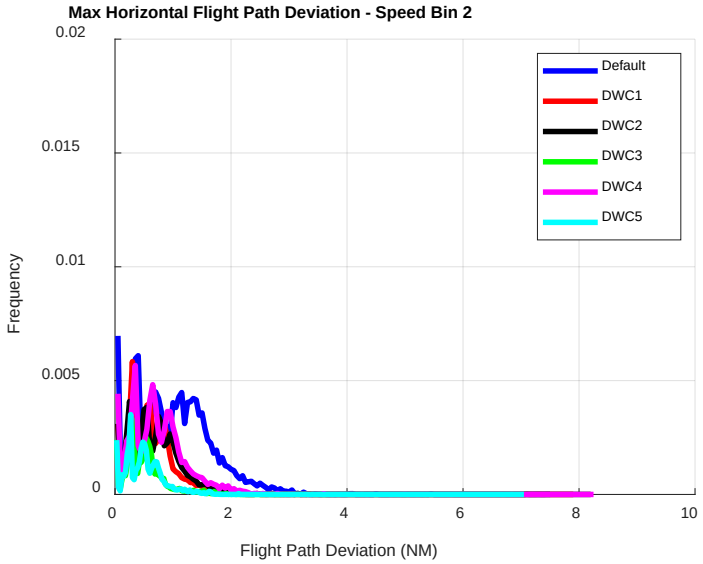


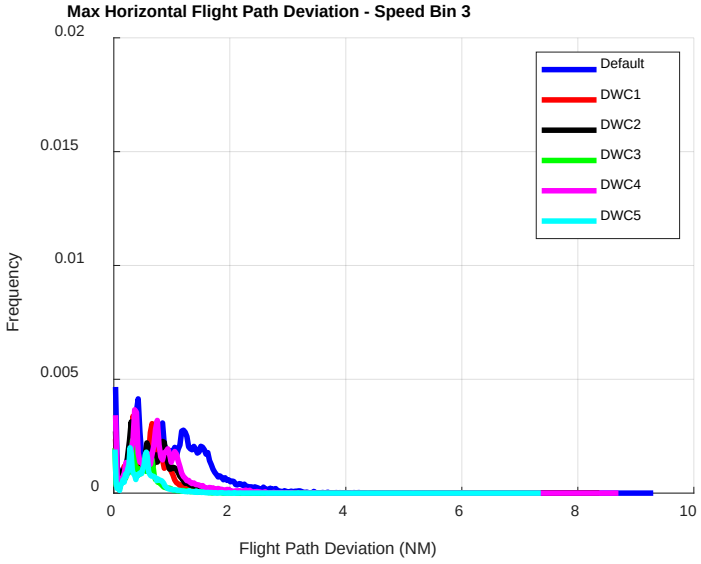


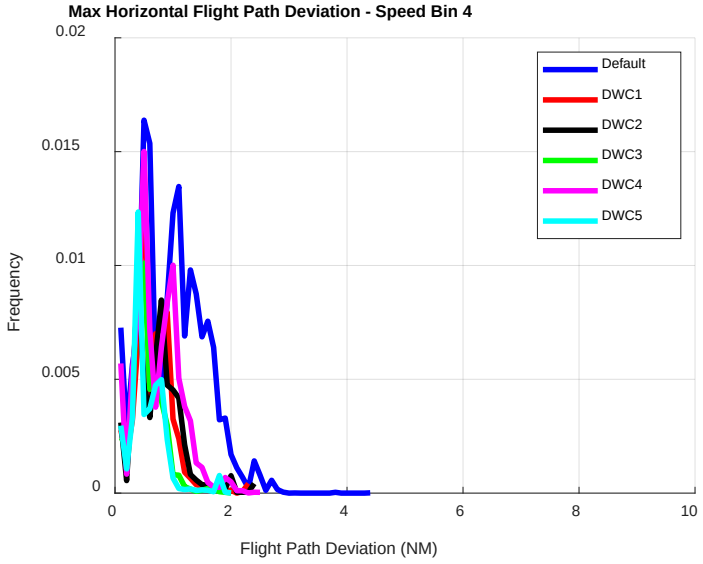


Flight Path Deviation

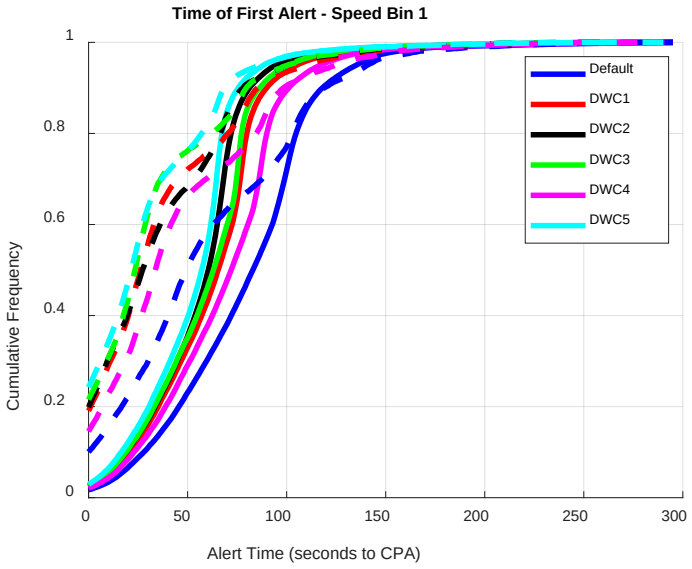


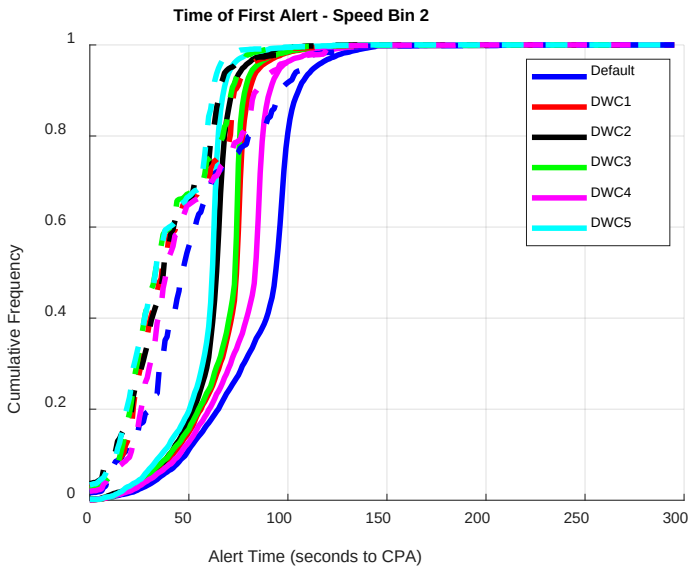


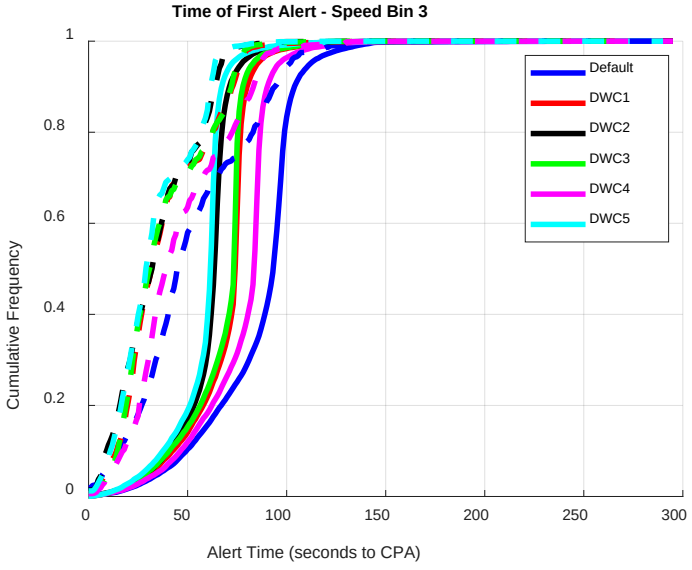


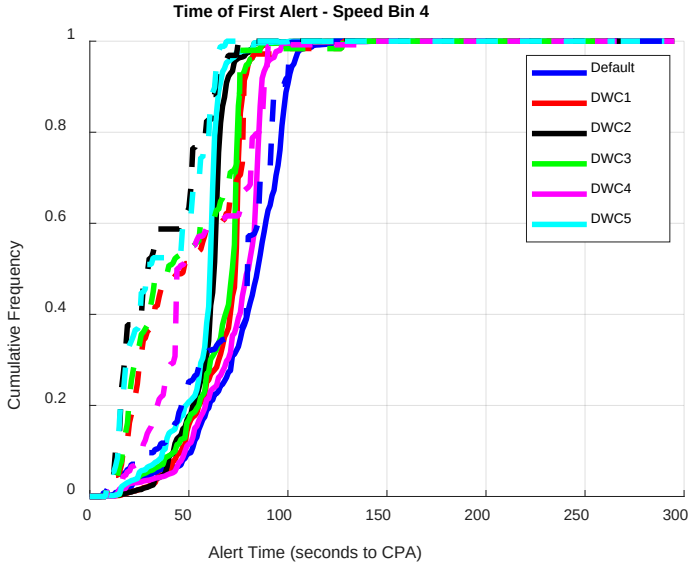


Time of First Alert

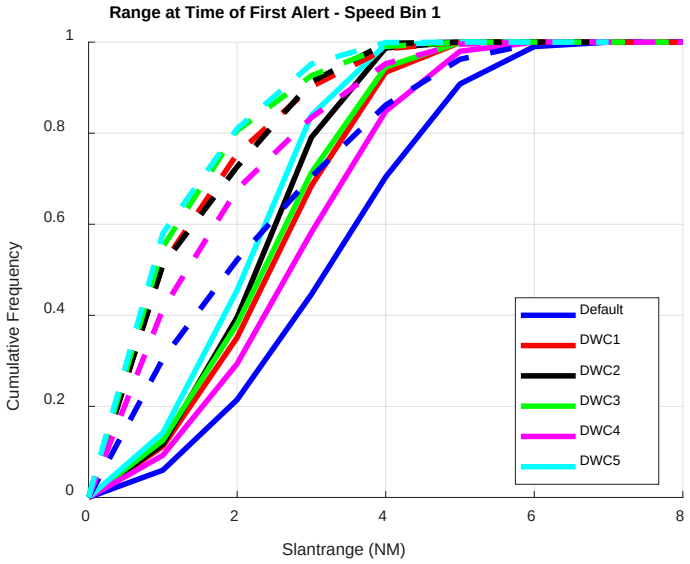


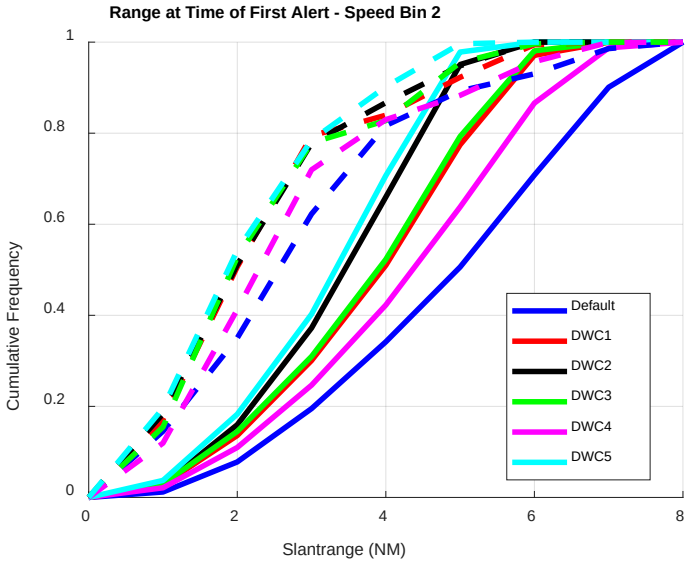


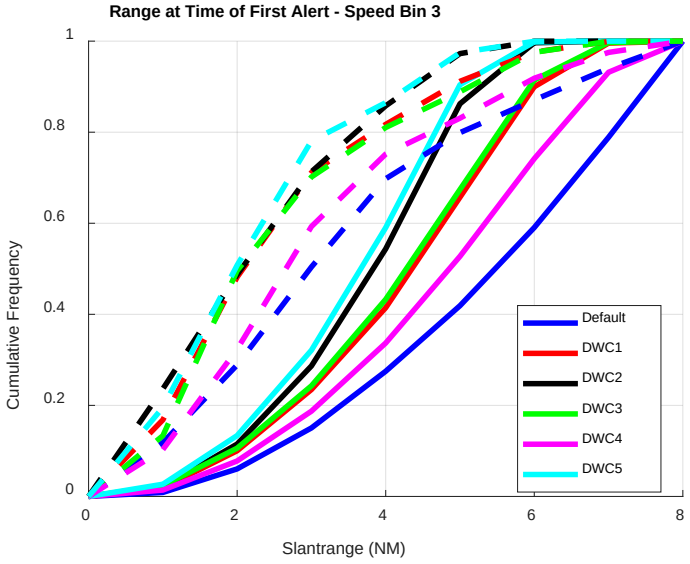


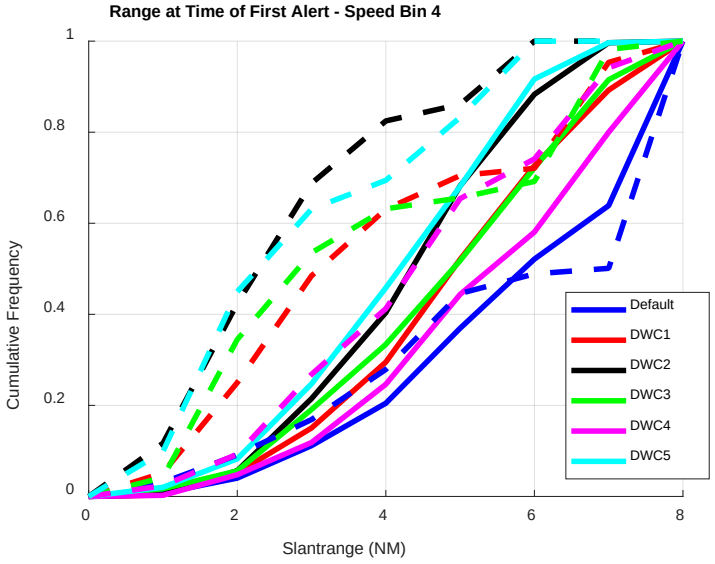


Range at First Alert









Conclusions

- The Phase 1 definition (Default) for this study falls close to that of the Study 5 value, showing consistency to the "benchmark"
  - The differences could be attributed to: Horizontal-only pilot model decisions, deterministic pilot model decisions, ownship mover modeling differences, and/or surveillance aspects
- Risk Ratio is fairly consistent across definitions
- Loss of Well Clear ratio is highest for the Phase 1 definition, which is unexpected
  - This may be due to encounter geometry/dynamics and also when encounter geometry/dynamics change relative to the various volume boundaries
- P(NMAC|LoWC) is lower for larger volumes
- There are outliers in which a Corrective Alert is issued after a Warning Alert
  - Mitigated cases exhibit this behavior more than unmitigated cases, this may be due to encounter geometry
- Both mitigated and unmitigated cases have two peaks in time separation between Corrective and Warning Alerts
  - The peak at 30s is expected given the DAIDALUS configuration
  - The peak at 5s is likely due to encounter geometry
- The Corrective Alert seems to assist in mitigating ~30% of all Warning Alerts, across all candidates
- Collective trends seem to be driven as outlined in the table to the right
- The assessed high speed encounters (Speed Bin 4) experienced no NMAC cases
- As ownship speed increases:
  - NMAC Risk Ratio seems to be driven more so by ModTau than HMD
  - LoWC Risk Ratio seems to be driven more so by ModTau than HMD
- Ownship speed seems to have little effect on Alert Ratio

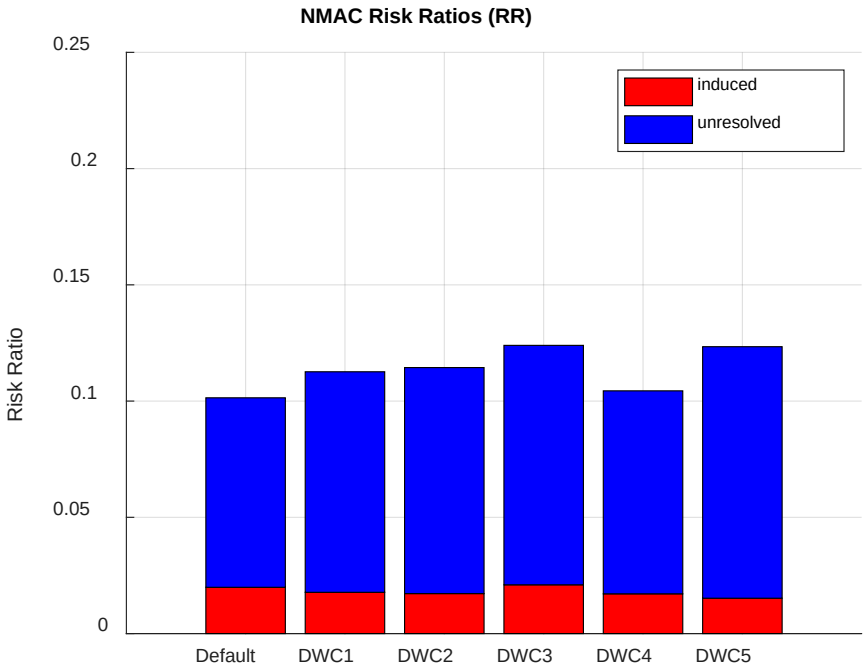
Metric	Driven by…	
	HMD	ModTau
NMAC Risk Ratio	X	
LoWC Risk Ratio	X	
P(NMAC|LoWC)	X	
Alert Ratio	X	
MCD	X	
Deviation	X	
Time of Alert prior to CPA		X
Range at Time of Alert		X
Maneuver Duration	X	

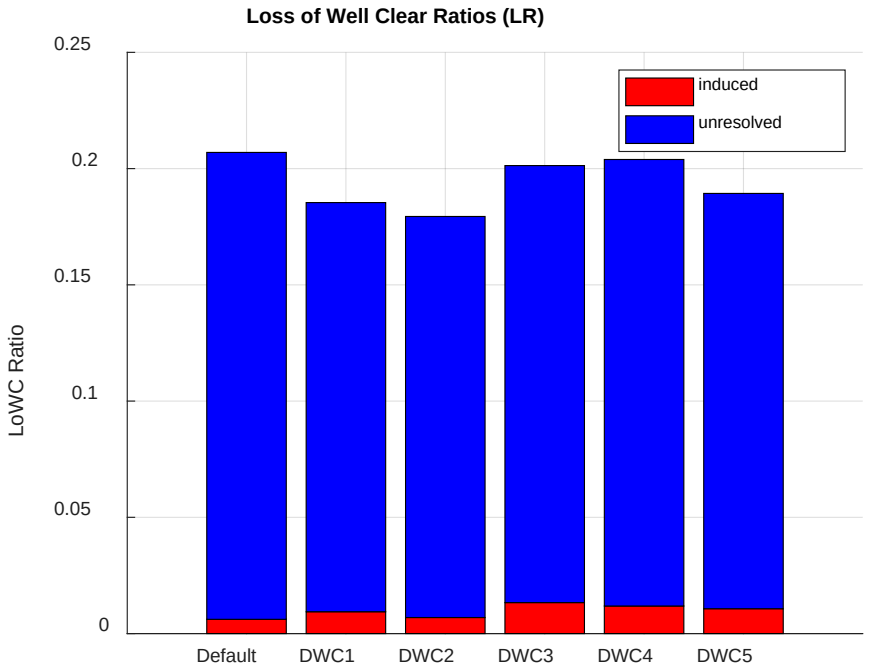
- In general, there seems to be a bigger tradeoff between the examined volumes form a operational suitability perspective versus a safety perspective
  - A smaller ModTau seems to provide operational suitability benefits, while having little effect on safety at low speeds and also reducing RR and LR high speeds

BACKUP

RESULTS COMBINING ALL SPEEDS

Safety Ratios



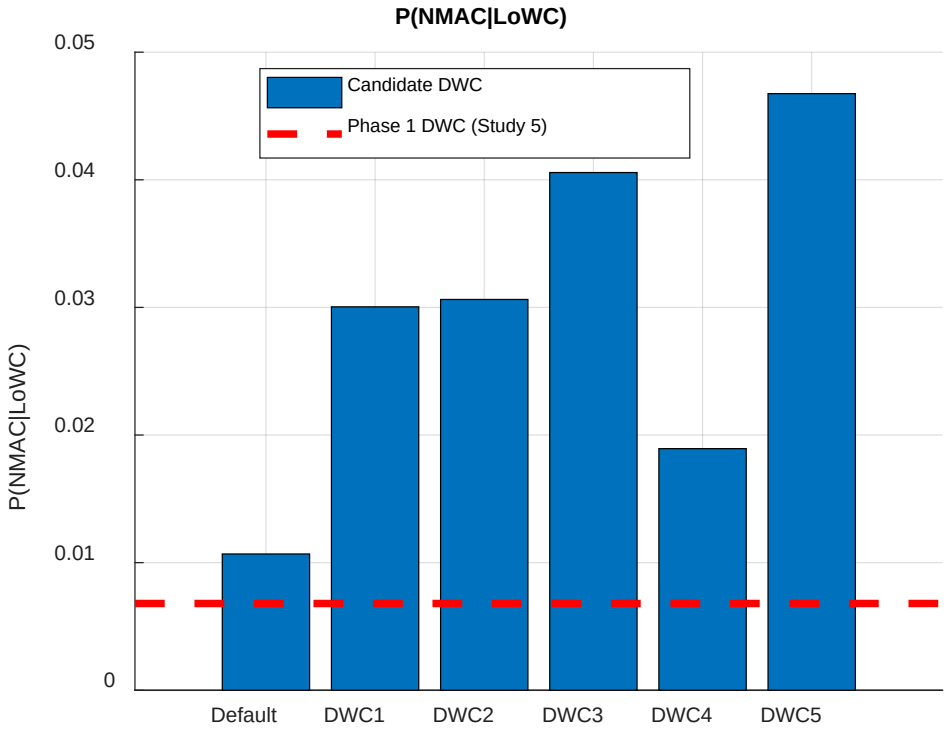


	Default	NASA DWC1	NASA DWC2	NASA DWC3	NASA DWC4	DWC5 (TAO)
HMD*	4000 ft	2000 ft	2200 ft	1500 ft	2500 ft	1500 ft
ModTau	35 s	15 s	0 s	15 s	25 s	0 s

- Risk ratios are comparable between candidates
  - HMD appears to have a larger impact on RR than ModTau
- The largest (Phase 1) definition results in the highest Loss of Well Clear Ratio, which is unexpected
  - This may be due to encounter geometry/dynamics and also when encounter geometry/dynamics change relative to the various volume boundaries
    - For example, dynamics/geometry may more often be changing when the aircraft are more largely separated, which would have a larger effect on the larger definitions

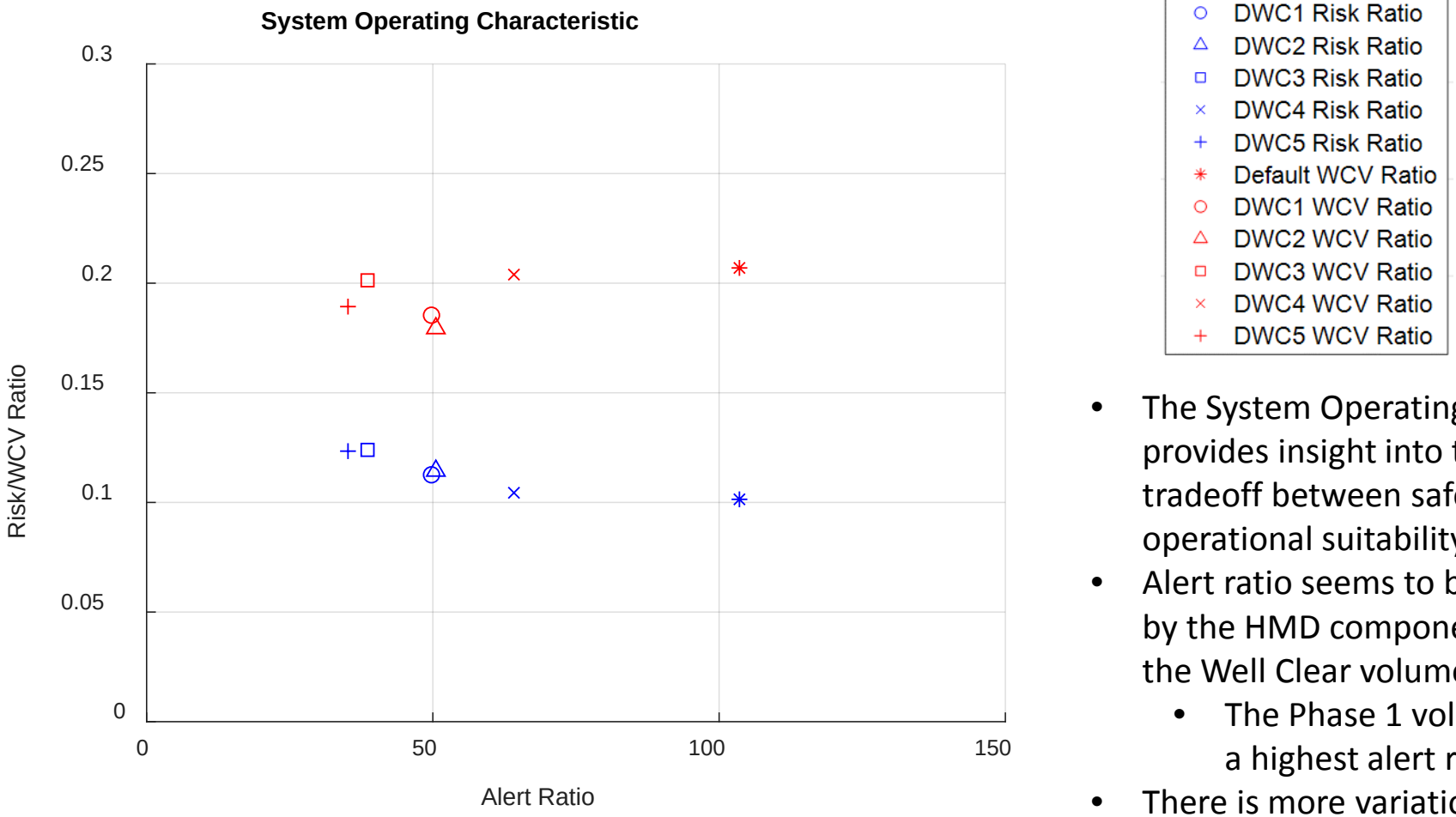
Mitigated P(NMAC | LoWC)

- May be desired that mitigated P(NMAC | LoWC) for Low-SWAP DWC be on-par to that from Phase 1
  - In Study 5, the mitigated P(NMAC | LoWC) was estimated to be 0.68%
- The Phase 1 definition (Default) for this study falls close to the Study 5 value
  - The differences could be attributed to:
    - Horizontal-only pilot model decisions
    - Deterministic pilot model decisions
    - Ownship mover modeling differences
    - Truth surveillance, constrained by radar FOV
- HMD appears to drive the mitigated probability more so than ModTau
  - A larger difference is seen between DWC2 and DWC5 than between DWC1 and DWC3, and both differences are larger than between DWC 1 and DWC2 and also DWC3 and DWC5



	Default	NASA DWC1	NASA DWC2	NASA DWC3	NASA DWC4	DWC5 (TAO)
HMD*	4000 ft	2000 ft	2200 ft	1500 ft	2500 ft	1500 ft
ModTau	35 s	15 s	0 s	15 s	25 s	0 s

System Operating Characteristic

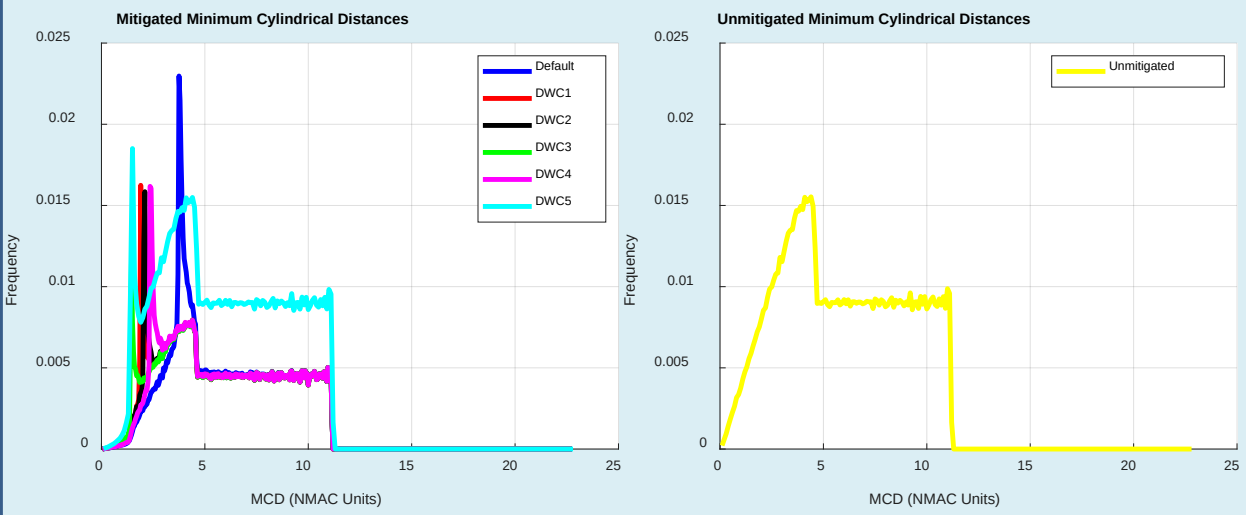


	Default	NASA DWC1	NASA DWC2	NASA DWC3	NASA DWC4	DWC5 (TAO)
HMD*	4000 ft	2000 ft	2200 ft	1500 ft	2500 ft	1500 ft
ModTau	35 s	15 s	0 s	15 s	25 s	0 s

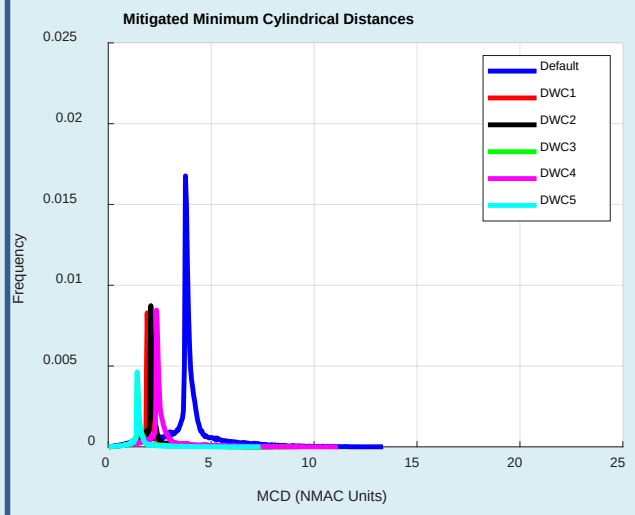
- The System Operating Curve provides insight into the tradeoff between safety and operational suitability
- Alert ratio seems to be driven by the HMD component of the Well Clear volume
  - The Phase 1 volume has a highest alert ratio
- There is more variation in alert ratio than Risk or WCV ratio between the candidates

Minimum Cylindrical Distance

All Encounters



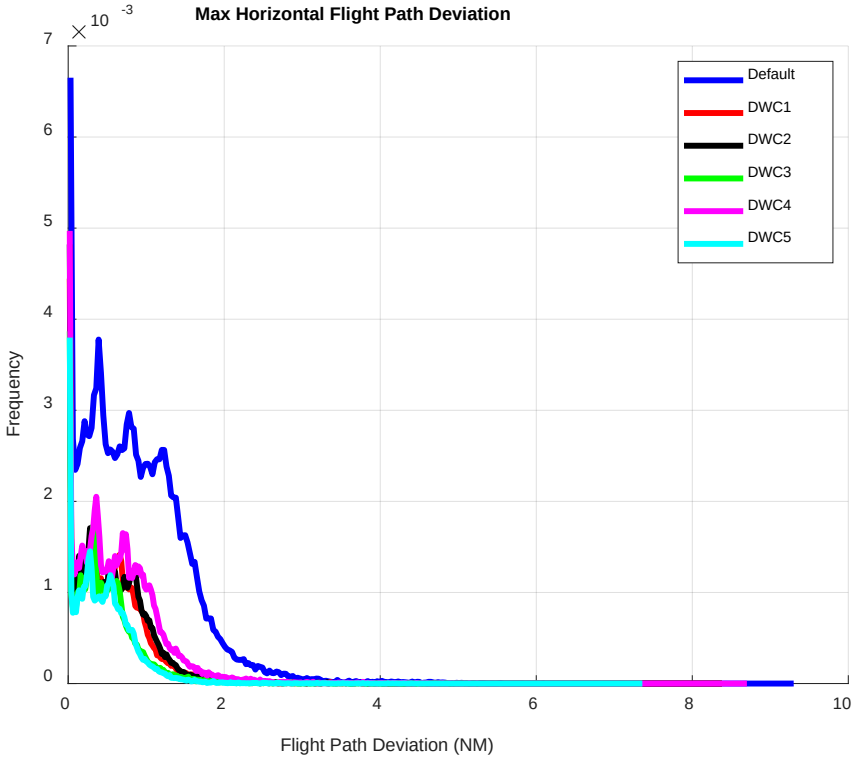
Only Encs. Which Mitigated

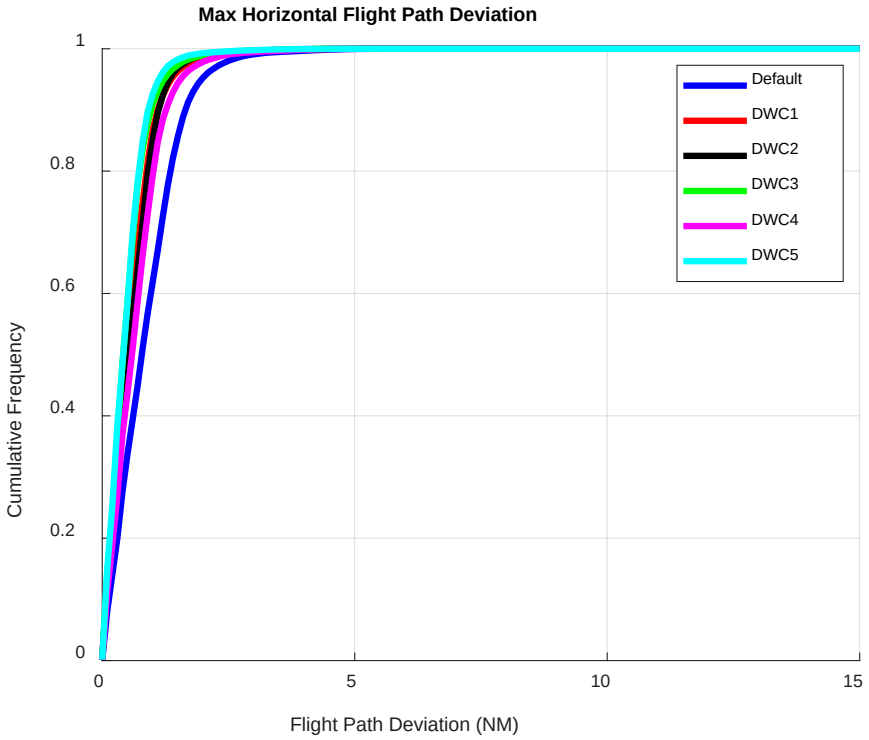


	Default	NASA DWC1	NASA DWC2	NASA DWC3	NASA DWC4	DWC5 (TAO)
HMD*	4000 ft	2000 ft	2200 ft	1500 ft	2500 ft	1500 ft
ModTau	35 s	15 s	0 s	15 s	25 s	0 s

- Distributions for all volumes have similar basic shape
- DWC5 most closely aligns with the MCD exhibited in the unmitigated case
- Looking only at the cases where maneuvering/mitigation occurred, it is clear to see that:
  - DWC5 exhibits the smallest MCD
  - The Phase 1 definition (Default) exhibits the largest MCD

Flight Path Deviation

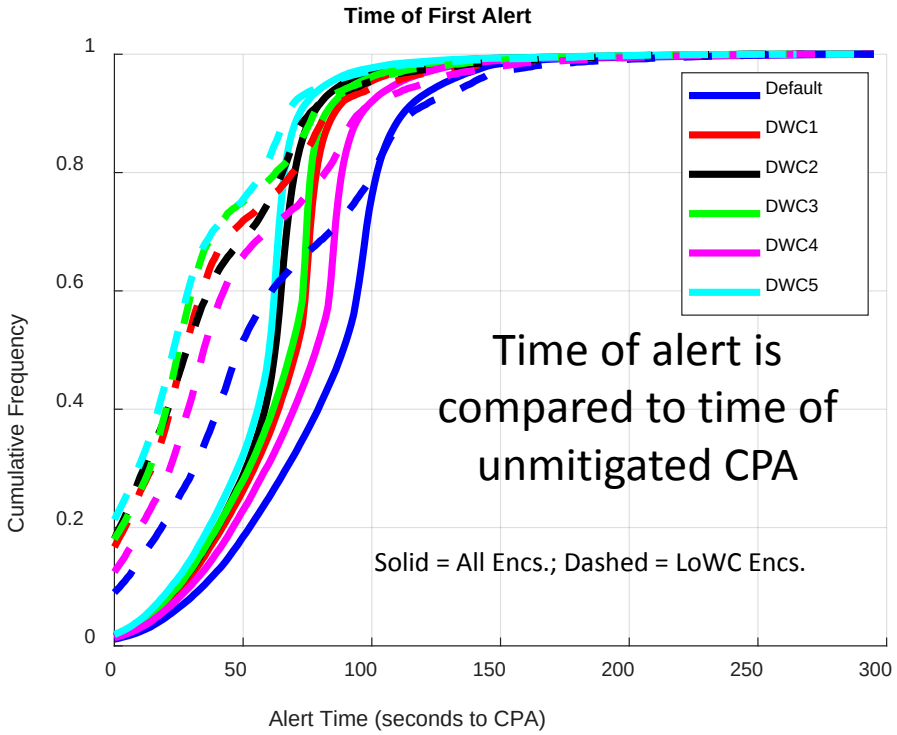


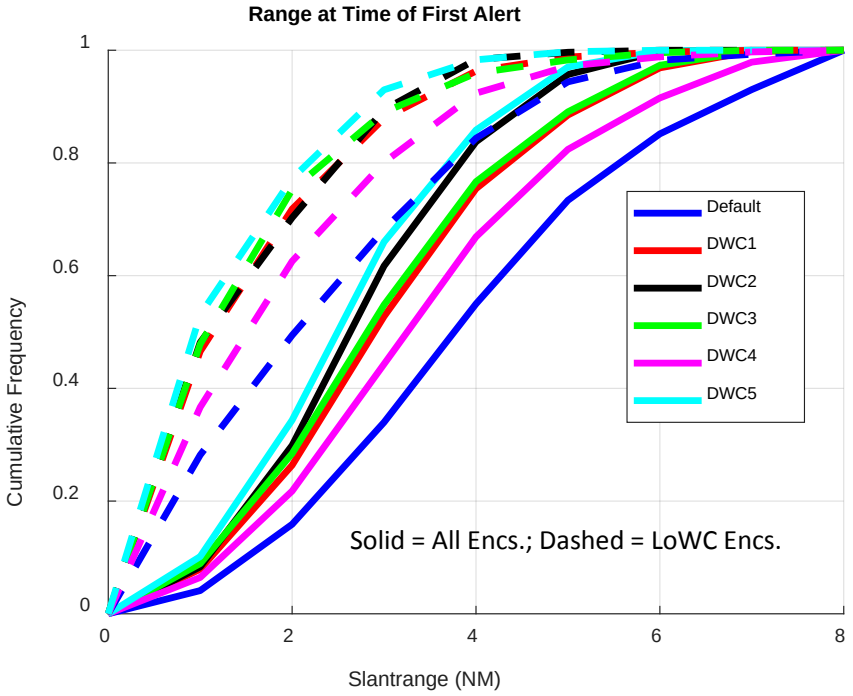


	Default	NASA DWC1	NASA DWC2	NASA DWC3	NASA DWC4	DWC5 (TAO)
HMD*	4000 ft	2000 ft	2200 ft	1500 ft	2500 ft	1500 ft
ModTau	35 s	15 s	0 s	15 s	25 s	0 s

- The Phase 1 definition causes the largest horizontal deviations
- The deviations are fairly consistent across the remaining definitions

Alerting Time and Range

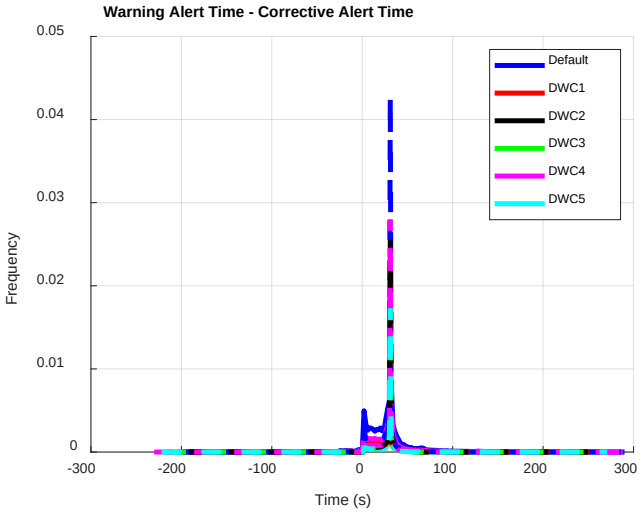


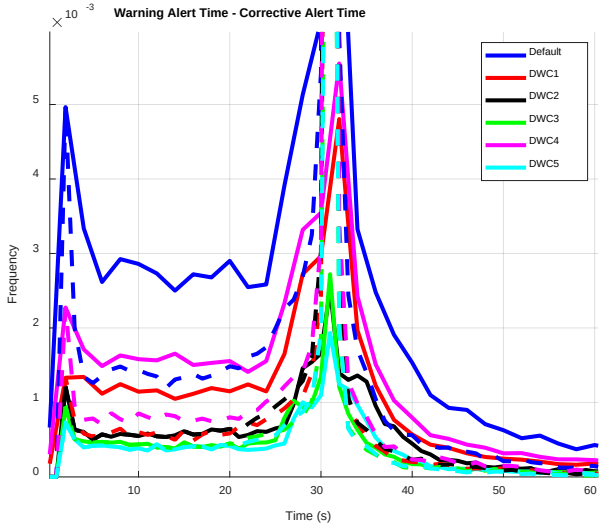


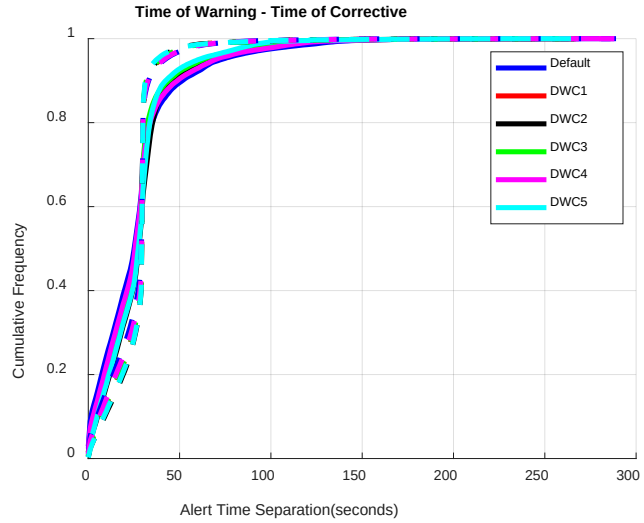
	Default	NASA DWC1	NASA DWC2	NASA DWC3	NASA DWC4	DWC5 (TAO)
HMD*	4000 ft	2000 ft	2200 ft	1500 ft	2500 ft	1500 ft
ModTau	35 s	15 s	0 s	15 s	25 s	0 s

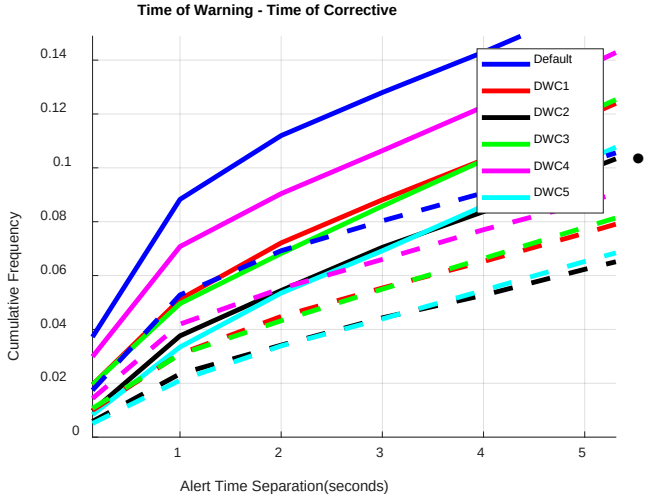
- As expected, alerting time and range are larger for the larger definitions
- Alerting time and range are driven more so by ModTau than HMD
- LoWC cases provide less time to CPA and less separation at time of alert, which may indicate that encounter geometry / maneuvering intruders may be the cause of violation

Alerting Time Separation





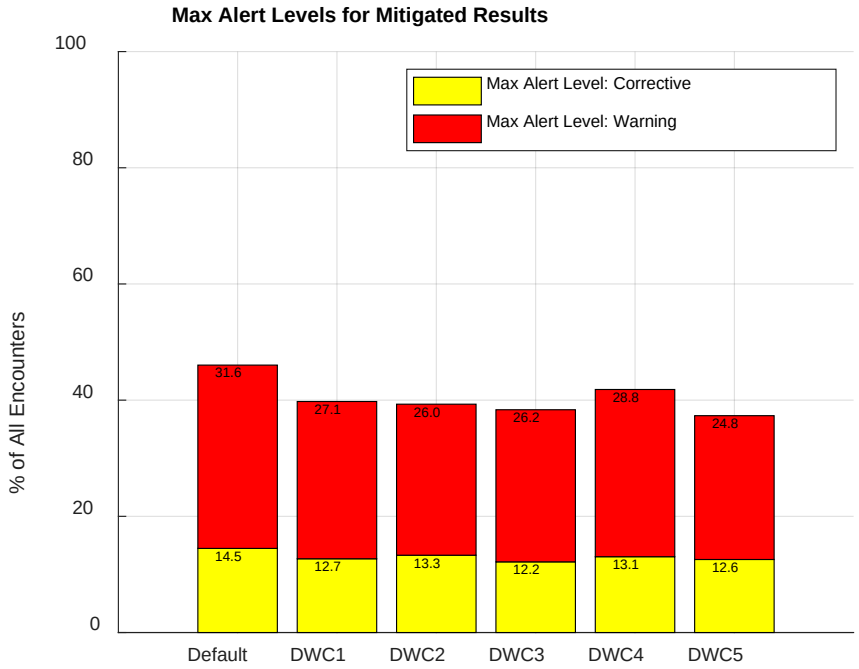


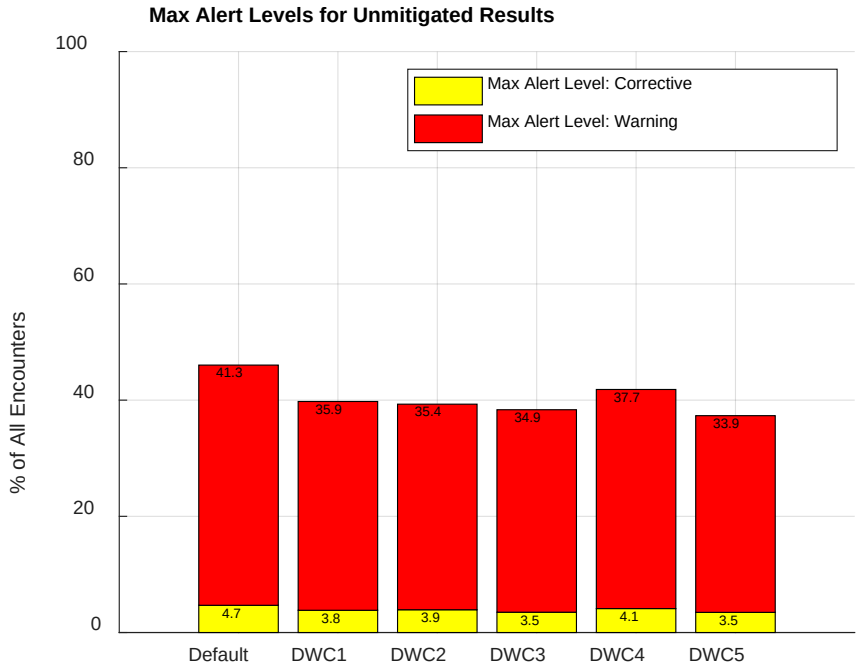


- There are some outliers, which have time separations less than zero, indicating that the Corrective happens after the Warning
  - Not surprising in the unmitigated sense, but this would be unexpected in the mitigated sense
  - Mitigated cases exhibit this behavior more than unmitigated
    - Suspected that this is due encounter geometry
- Both the mitigated and unmitigated data have dual peaks
  - A time separation around 30 s is expected give the DAIDALUS configurations
  - The first peak around 2 seconds is likely due to encounter geometry

Solid = Mitigated; Dashed = Unmitigated

Maximum Alert Level





	Default	NASA DWC1	NASA DWC2	NASA DWC3	NASA DWC4	DWC5 (TAO)
HMD*	4000 ft	2000 ft	2200 ft	1500 ft	2500 ft	1500 ft
ModTau	35 s	15 s	0 s	15 s	25 s	0 s

- The same overall percentage of encounters alert in the mitigated case as in the unmitigated case, across all volumes
- Mitigating seems to result in approximate 10% fewer Warning alerts, across all volumes
- These figures do not provide insight into cases which:
  - A Warning may precede a Corrective Alert
  - Both levels of alerts are not issued

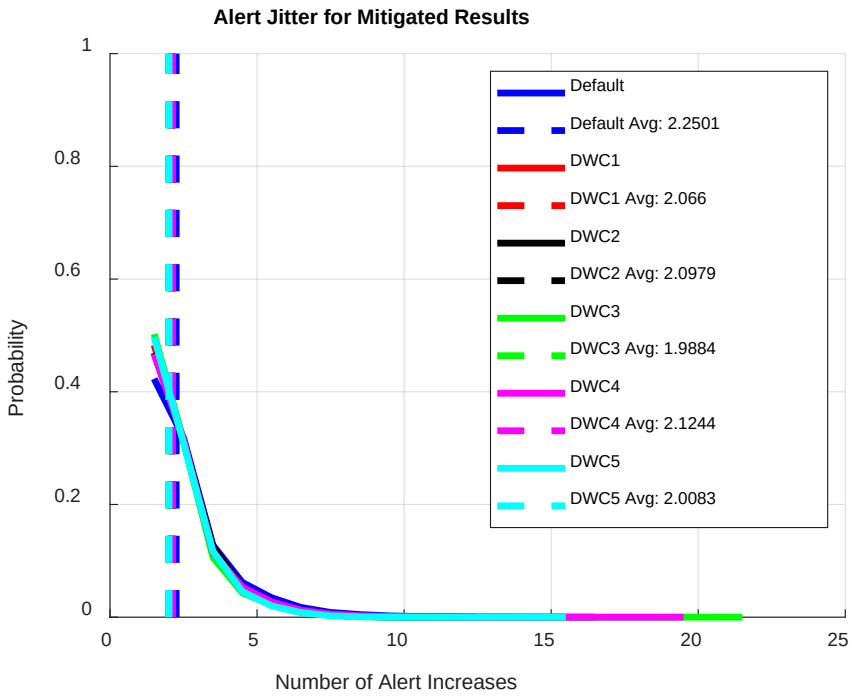
Insight into Corrective Alert Benefit

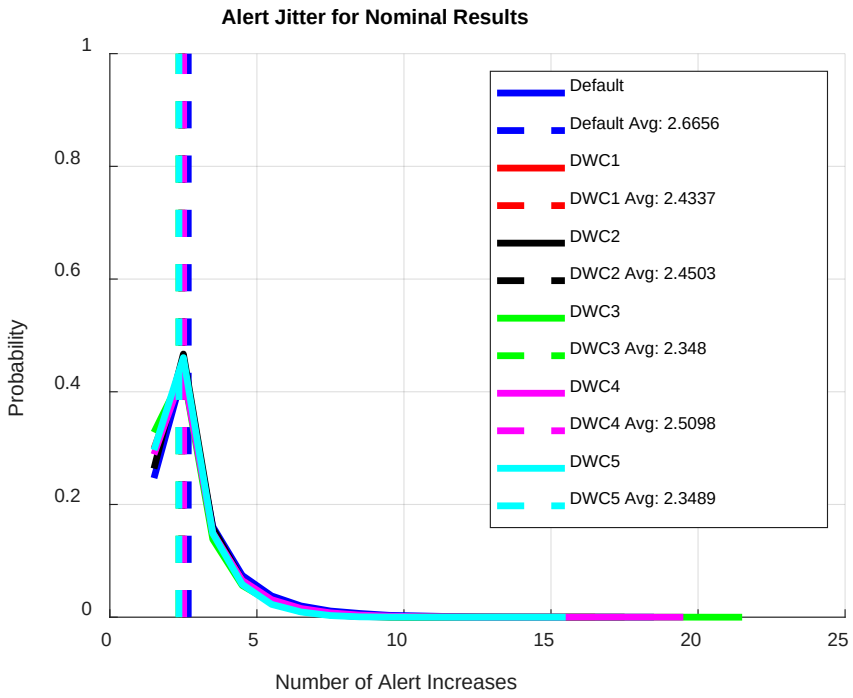
- The number of cases with a **Corrective Alert preceding a Warning Alert** was compared between unmitigated and mitigated runs to provide insight in the benefit a Corrective Alert may have in reducing Warning Alerts

Candidate	Unmitigated Count	Mitigated Count	Reduction Count	"Induced" Count
Default	321142	225499	95944 (~30%)	301 (~.1%)
DWC1	280474	193869	86927 (~31%)	322 (~.2%)
DWC2	292800	201088	92003 (~31%)	291 (~.1%)
DWC3	262562	177878	85020 (~32%)	336 (~.2%)
DWC4	289906	202701	87566 (~30%)	361 (~.2%)
DWC5 (TAO)	272302	183378	89211 (~32%)	287 (~.2%)

- The Corrective Alert seems to assist in mitigating ~30% of all Warning Alerts, across all candidates
- Some cases are "induced" meaning there was no Warning Alert issued in the unmitigated case, but one was issued in the mitigated case
  - This may be due intruder maneuvering

Alert Jitter

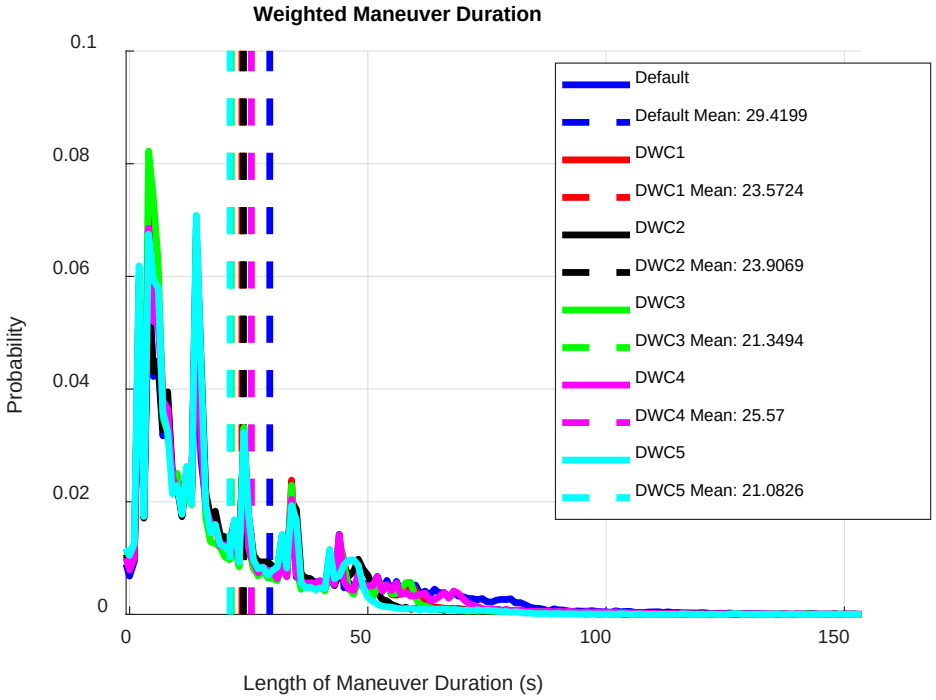


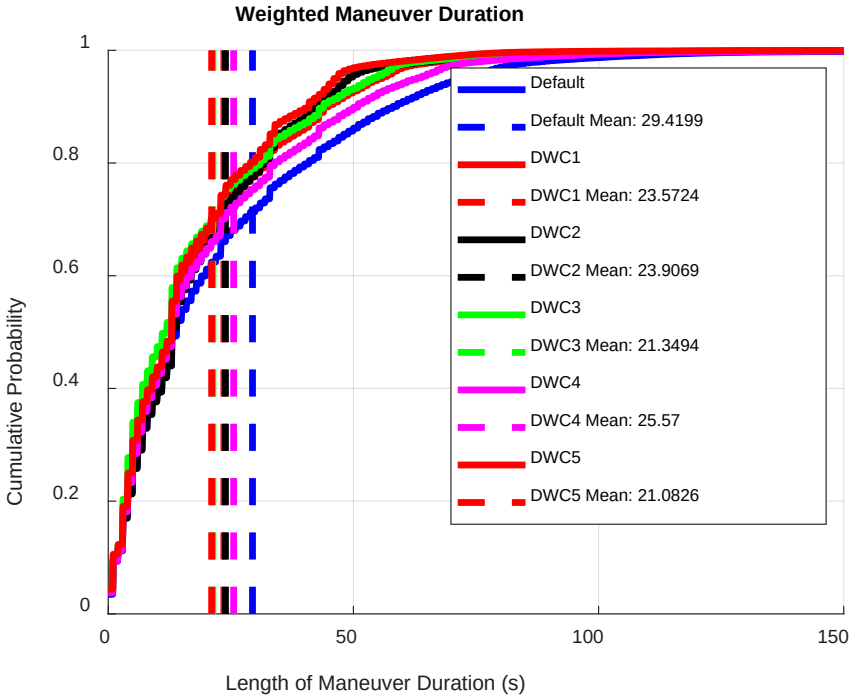


	Default	NASA DWC1	NASA DWC2	NASA DWC3	NASA DWC4	DWC5 (TAO)
HMD*	4000 ft	2000 ft	2200 ft	1500 ft	2500 ft	1500 ft
ModTau	35 s	15 s	0 s	15 s	25 s	0 s

- Mitigated cases have less alert jitter
- Jitter seems to be fairly consistent across volumes
  - DWC3 experiences the least amount of jitter, on average

Maneuver Duration





	Default	NASA DWC1	NASA DWC2	NASA DWC3	NASA DWC4	DWC5 (TAO)
HMD*	4000 ft	2000 ft	2200 ft	1500 ft	2500 ft	1500 ft
ModTau	35 s	15 s	0 s	15 s	25 s	0 s

- Maneuver duration seems to be fairly consistent across the definitions
- HMD seems to have more of an effect on maneuver duration than ModTau, with larger HMD values resulting in longer durations of maneuvering

Encounter Set Parameters

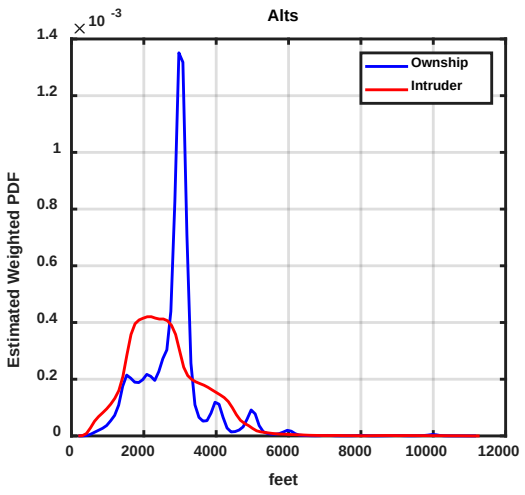
Encounter characteristics

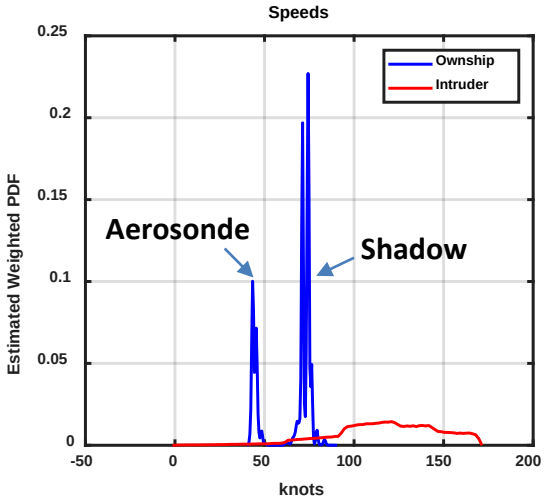
- Minimum Separation at Encounter Start: 800 ft (vertically) or 1.5 NM (horizontally)
- Max HMD: 3 NM
- Max VMD: 1500 ft
- Closest Approach: 150 sec
- Encounter duration: 180 sec
  - Extended up to 300 sec if necessary to satisfy initial minimum separation
- Airspace classes: E/G

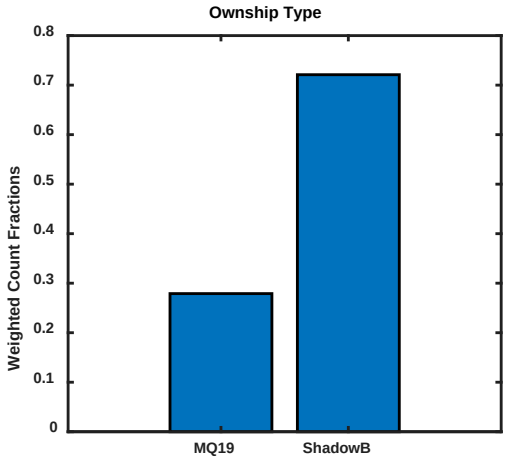
Aircraft characteristics

- Ownship speed: 40-100 kts (Lincoln), 40-250 kts (CAL)
- Intruder speed: 0-170 kts
- Ownship/intruder altitude: 500 AGL-10000 ft MSL

Low-SWAP Encounter Characteristics

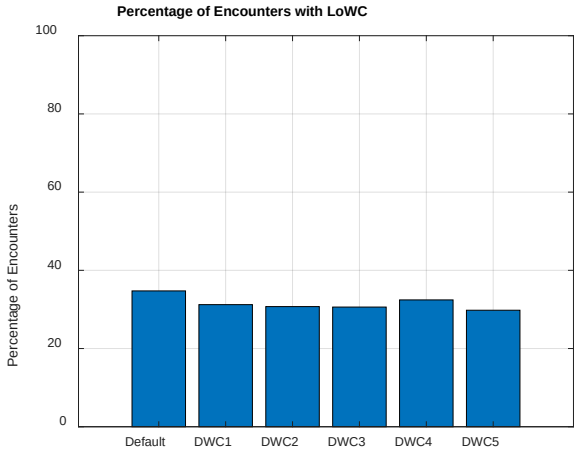


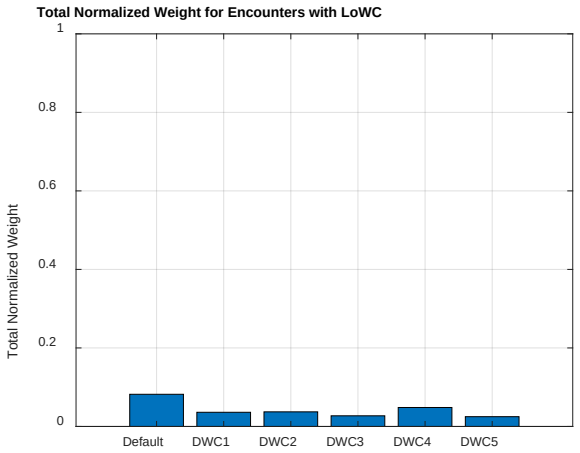


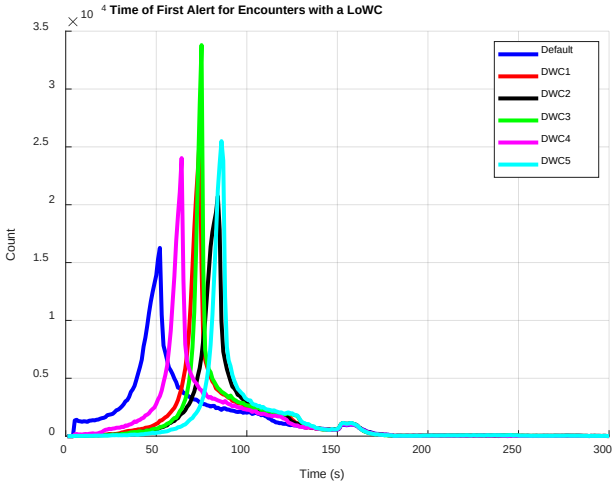


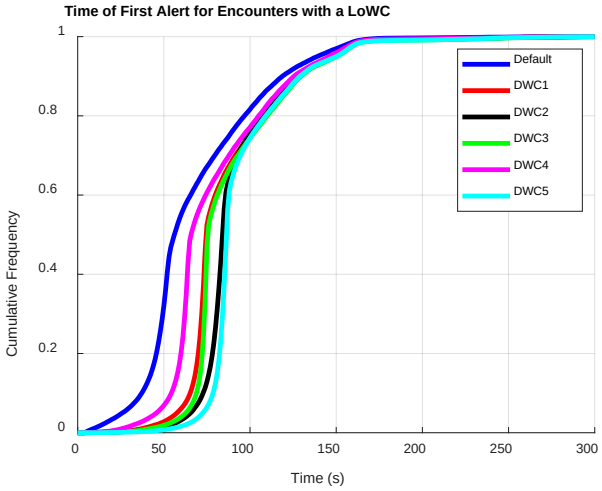
MQ-19: AAI Aerosonde

Investigation of LR Tends



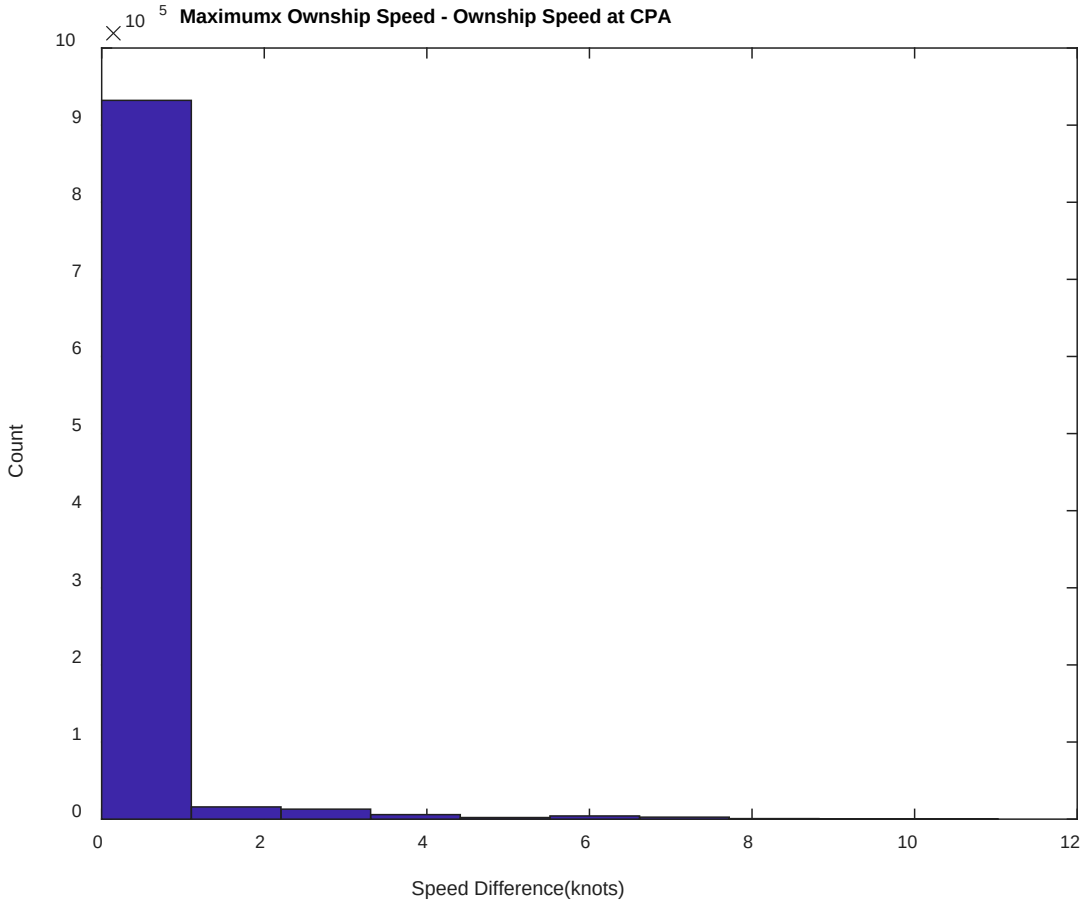




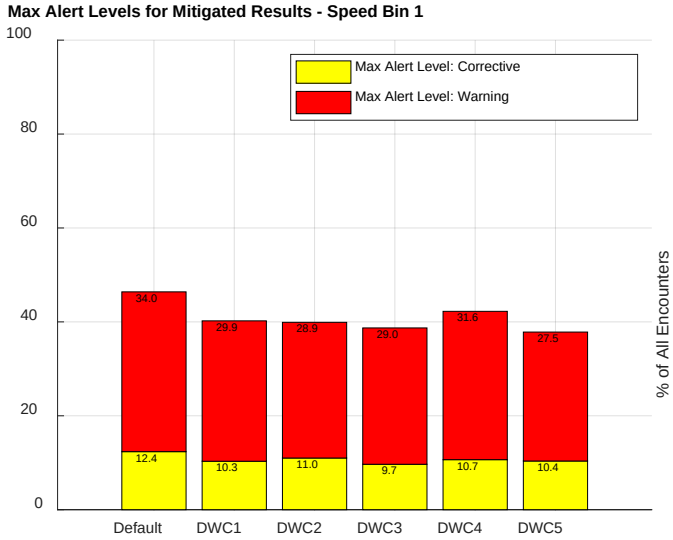


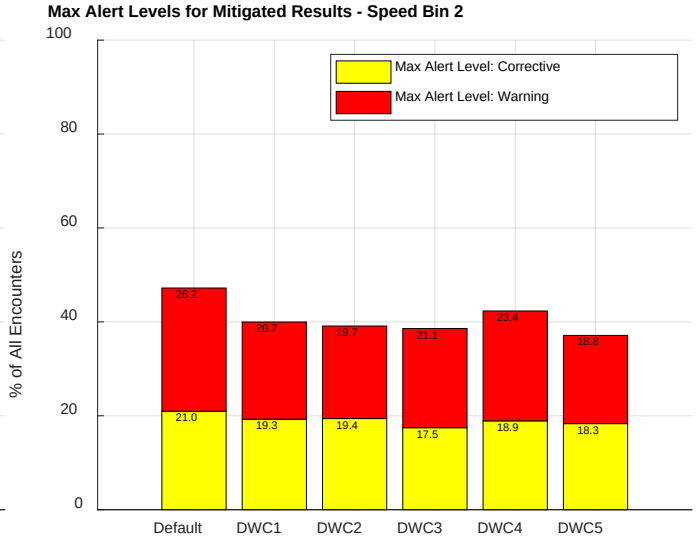
- The percentage of unmitigated encounters with a violation is fairly consistent across candidates, with the percentage of encounters violating the Phase 1 volume having the highest percentage
- Taking into consideration encounter weights, there seems to be more variation between candidates, with the Phase 1 volume having the highest total normalized weight

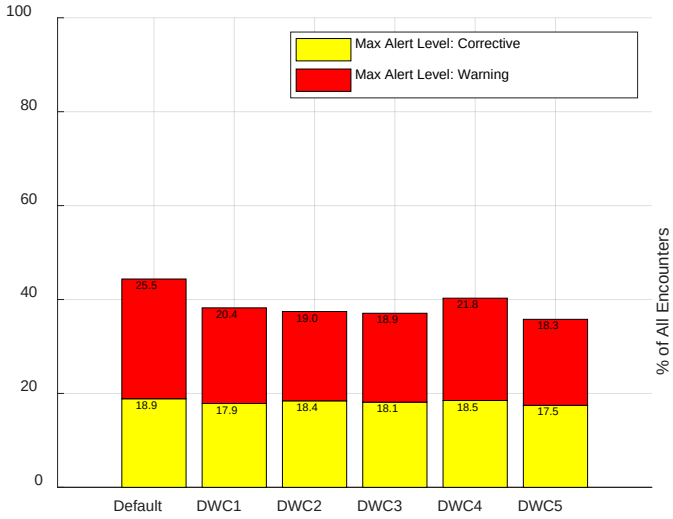
Speed Characterization

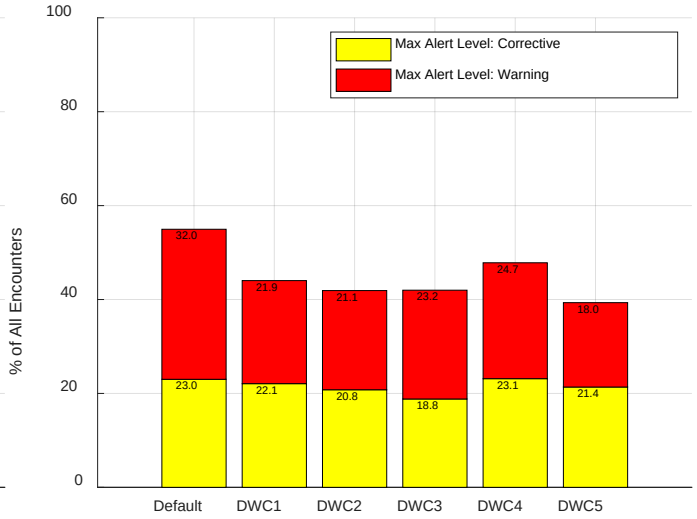


Max Mitigated Alert Level









Alert Jitter