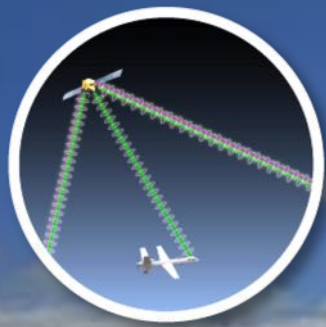




Unmanned Aircraft Systems (UAS) Integration in the National Airspace System (NAS) Project

Terminal Operations HITL 1B
Primary Results
Presented to: RTCA SC-228 WG-1





Objective

- Purpose: leverage the lessons learned from the Foundational Terminal Operations human-in-the-loop (HITL) simulation to test a DAA system better suited to the terminal environment
- Objectives:
 - Implement two candidates for a terminal area DAA well clear (DWC) definition
 - Further investigate the efficacy of the DAA Corrective alert in the terminal area
 - Compare pilot and system performance to previous studies



TOPS 1 Results Summary

- Phase 1 DWC definition resulted in an exceedingly high number of alerts in the terminal area
 - As a result pilots had a hard time judging when a maneuver was necessary to avoid high-severity LoDWC
 - **17** > 50% SLoWC & **6** > 70% SLoWC
 - No SLoWC above 30% in PT6
- The DAA Corrective alert was shown to be less useful in the terminal area
 - Best performance seen in configuration with DAA Warning but no Corrective
 - Pilots rarely coordinated with tower before maneuvering against intruders
 - Intruders often spent < 15sec as Corrective before transitioning to Warning
- Encounters that occurred with ownship established on final were the most likely to lead to severe losses of DWC



Experimental Design

- 2 x 2 Mixed-Factorial Design
 - DWC Candidate (Within-Subjects):

	<i>No Tau</i>	<i>Tau</i>
Horizontal Threshold*	1500ft	1500ft
Vertical Threshold	450ft	450ft
modTau	N/A	15sec

*HMD in Tau definition

- Alerting Configuration (Between-Subjects)
 - *No Corrective* = **No** DAA Corrective alert or guidance, all other alerting/guidance remains
 - *With Corrective* = Full Phase 1 MOPS DAA alerting and guidance structure (Class I)



Experimental Design

No Corrective

Symbol	Name	Time to Hazard Zone
	Warning Alert	30sec
	Preventive Alert	45sec
	Remaining Traffic	N/A

Includes Only Warning
Guidance and Regain DWC
Guidance

With Corrective

Symbol	Name	Time to Hazard Zone
	Warning Alert	30sec
	Corrective Alert	45sec
	Preventive Alert	45sec
	Guidance Traffic	N/A
	Remaining Traffic	N/A

All Remain & Regain
DWC Guidance



Alerting Criteria for DWC Candidates

Symbol	Name	Pilot Action	No Tau DWC Criteria	Tau DWC Criteria	Time to Loss of DWC	Aural Alert Verbiage
	Warning Alert	<ul style="list-style-type: none"> Notify ATC as soon as practicable after taking action 	Horz = 1500ft ZTHR = 450 ft	DMOD = 1500ft HMD = 1500ft ZTHR = 450 ft modTau = 15 sec	30 sec	"Traffic, Maneuver Now" x2
	Corrective Alert	<ul style="list-style-type: none"> Coordinate with ATC to determine an appropriate maneuver 	Horz = 1500ft ZTHR = 450 ft	DMOD = 1500ft HMD = 1500ft ZTHR = 450 ft modTau = 15 sec	45 sec	"Traffic, Avoid"
	Preventive Alert	<ul style="list-style-type: none"> On current course, corrective action should not be required 	Horz = 1500ft ZTHR = 700 ft	DMOD = 1500ft HMD = 1500ft ZTHR = 700 ft modTau = 15 sec	45 sec	"Traffic, Monitor"
	Guidance Traffic	<ul style="list-style-type: none"> Traffic generating guidance bands outside of current course 	Associated w/ bands outside current course	Associated w/ bands outside current course	X	N/A
	Remaining Traffic	<ul style="list-style-type: none"> Traffic within sensor range 	Within surveillance field of regard	Within surveillance field of regard	X	N/A

NOTES:

- Corrective alert only present in *With Corrective* alerting configuration
- No sensor uncertainty was modeled
- Alerting criteria was identical between DWC Candidates

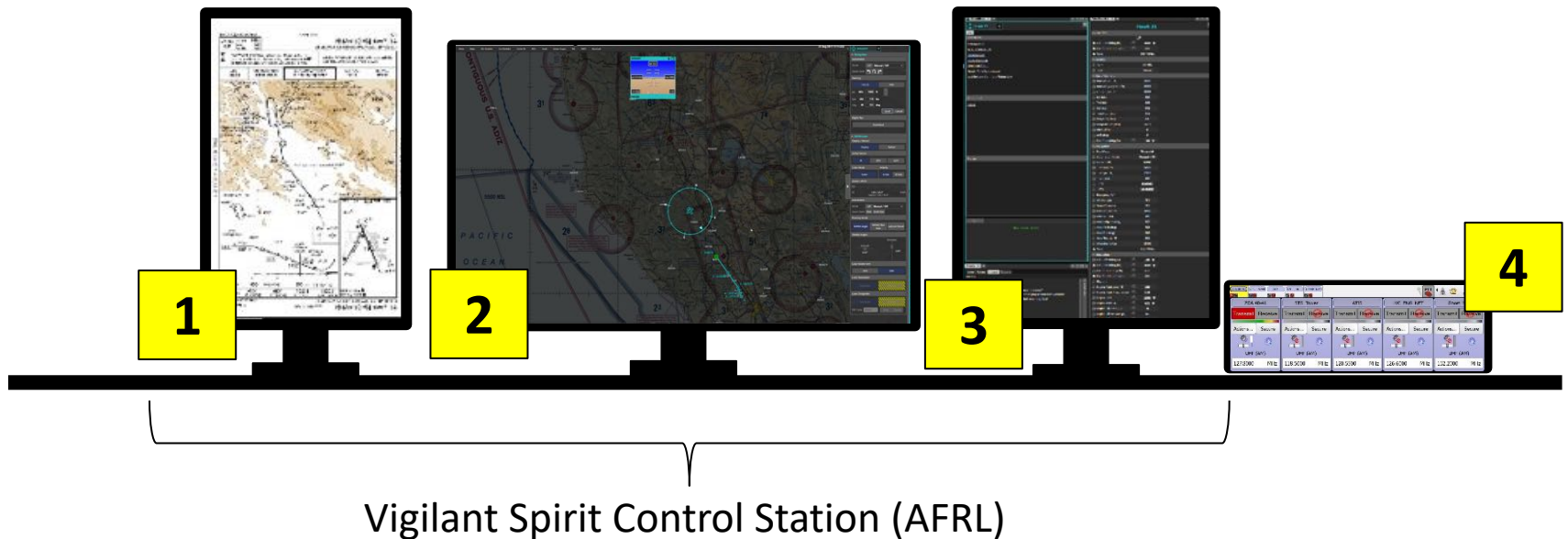


- Generic MQ-9 Reaper
 - Speed:
 - Cruise: 110 knots
 - Landing: 90-110 knots
 - Min: 70 knots
 - Default Climb/Descent Rate:
 - 1000ft/min
 - Roll:
 - Max: +/- 20°
 - Rate: 5°/sec
 - Pitch:
 - Max: +/- 10°
 - Rate: 1°/sec



Ground Control Station (GCS)

- Ground control station (GCS) contains:
 1. Viewer Tool – contains approach plate & airport facility directory (AFD)
 2. Tactical Situation Display (TSD) – DAA information and vehicle control interfaces
 3. Right Panel – landing checklist and additional info
 4. Voice communication panel – touchscreen, transmit/receive on select freqs.





Sonoma County Airport

- Primary = Rwy14
- Runway 14/32
 - Length = 6000ft x 150ft
 - RNAV (GPS)
- Elevation = 129ft
- Traffic Pattern = 1150ft
- Downwind offsets:
 - Left = ~1.5nm
 - Right = ~0.5nm
- Runway 20/02
 - Not used



Traffic Pattern Altitude = 1150ft
3NM (WP1) to RW14 (WP2) = 3nm
RW14 (WP2) to RW32 (WP3) = 1nm



Simulation Components

- Pseudo-pilots monitored and managed all manned traffic (IFR & VFR)
 - Multi-Aircraft Control System (MACS) software suite
- Air Traffic Control managed UAS and manned traffic
 - Tower controller managing Santa Rosa (KSTS)
 - Center controller managing Oakland Center (ZOA 40/41)
 - Sector traffic modeled using real sector activity and data
- All participants communicated via push-to-talk headsets
 - KSTS Tower frequency: 118.50
 - Oakland Center frequency: 127.80
 - KSTS ATIS: 120.55





Training on DAA System

- Pilots trained first on the ground control station followed by training on the DAA system
 - Trained on the meaning of each alert/guidance type in their given configuration
 - Practice en-route scenario flown with conflicts & ATC in-the-loop
- Pilots trained last on how to fly the given approach
 - 2 practice approaches flown, one with a scripted conflict
- Informed that a DAA system has been specifically developed to support terminal operations
 - Told the hazard zone was 1500ft x 450ft (did not explain tau component)
- ❖ Told to use the DAA system **to maintain DAA well clear** from traffic in the terminal environment (i.e., expected to utilize the alerts/guidance)

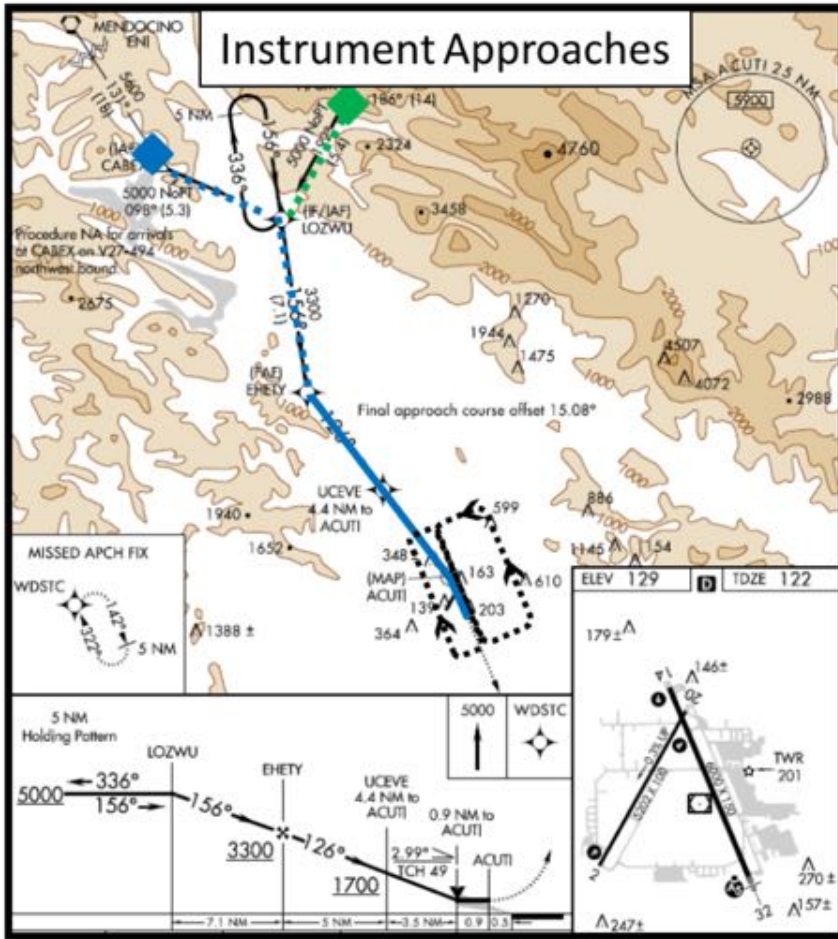


Scenario Design

- Participants flew 2 types of approaches into Santa Rosa Rwy 14 under Instrument Flight Rules (IFR)
 - Instrument (RNAV GPS) Approach
 - “Visual” Approach
- Common across scenarios:
 - Start in Vigilant Spirit’s HOLDS mode & in Oakland center airspace
 - Coordinate transfer to KSTS Tower
 - Perform checklist actions as able (e.g., check ATIS, brief approach)
 - Fly final in Vigilant Spirit’s NAV mode (enables glide slope)

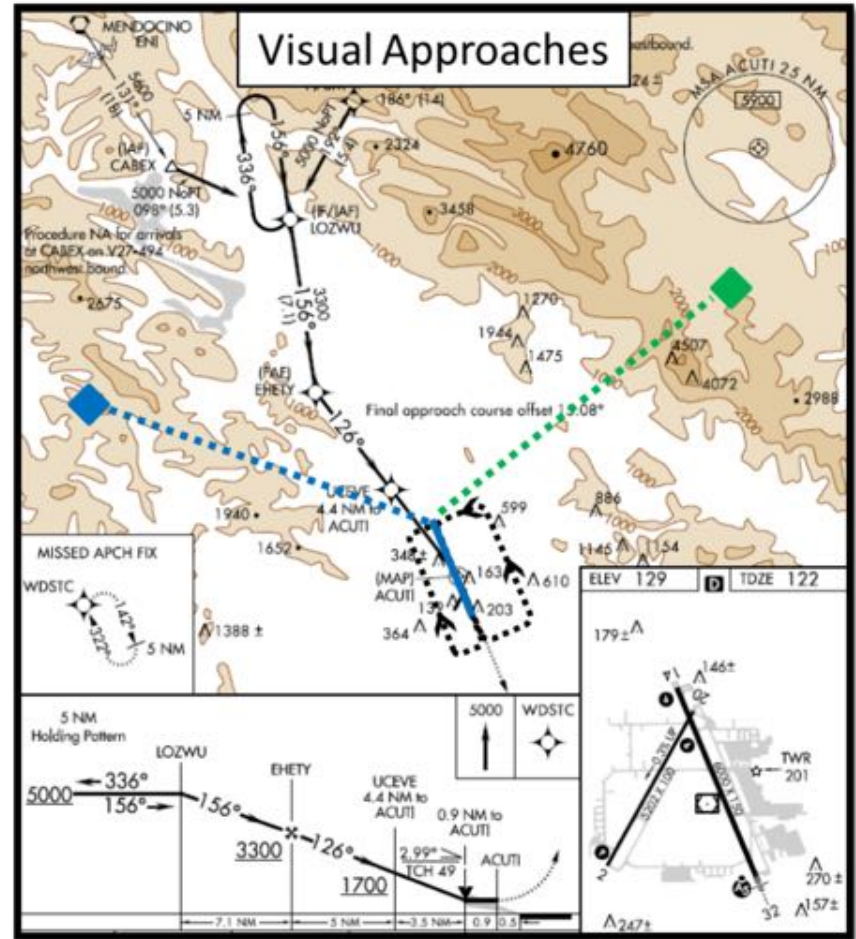


Scenario Design



Instrument Approach Notes:

- Final approach coarse offset 15°
- **Missed approach procedures** = climb to 5000ft, fly runway heading (143°)



“Visual” Approach Notes:

- Airport “in sight” 10-12nm from runway
- Line up for 3nm final stabilized approach
- Traffic pattern @ 1150ft
- **Go-around** = climb to pattern alt (1150ft)



Scenarios

- Pilots flew 4 trials per day (2 Instrument & 2 Visual)
- 4 approaches flown per trial (= ~45min per trial)
- The following encounter types occurred every trial:
 - **Turn Into** = traffic blunders into UA on final and will result in NMAC without UAS pilot response [*1 per trial*]
 - **Turn In Front** = traffic turns in front of UAS with sufficient separation (~1.5-2nm) to land safely (the turn is coordinated w/ Tower) [*1 per trial*]
 - **Unscripted** = no encounter is scripted to occur but traffic expected to be on downwind as UAS is on final [*2 per trial*]
- Encounter type breakdown:

	Blunder?	Predicted HorzSep @ CPA	Corrective or Warning Alert Desired?	Maneuver Desired?
Turn Into	Yes	~0nm	Yes	Yes
Turn In Front	No	~1.5-2nm	No	No
Unscripted	No	N/A	No	No



Participants

- Participants
 - 16 UAS pilot participants (avg. age = 33 years)
 - All IFR rated with manned & unmanned flying experience
 - Manned experience = avg. 1000 civilian flight hours, 1600 military flight hours
 - Unmanned experience = avg. 500 civilian flight hours, 700 military flight hours
 - 2 retired tower controllers served as tower controller confederates
 - 1 ATC SME served as center controller confederate
 - 4 current general aviation pilots served as manned traffic confederates





RESULTS



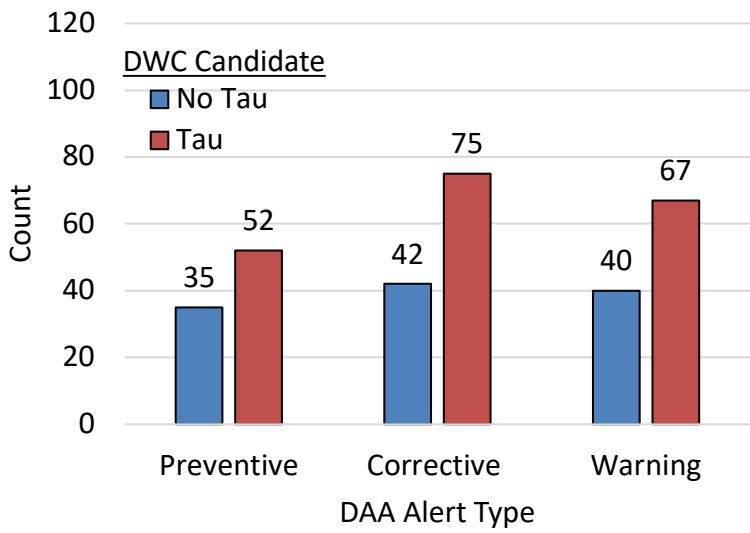
DAA ALERTING AND MEASURED RESPONSE



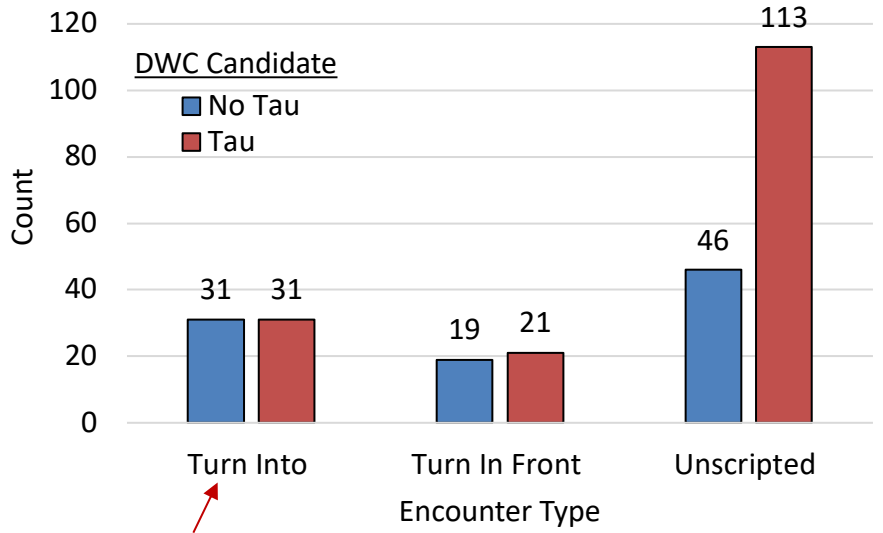
DAA Alerting Statistics

- 32 total alerts desired per DWC candidate
= 16 [pilots] * 2 [trials per pilot] * 1 [Turn Into encounter per trial]
 - There was also 1 Turn In Front encounter per trial
- 215 different intruders registered (in truth) as a DAA alert
 - “Truth” alerts = all alerts captured by the DAA system, across all trials and conditions (**ignores alert configuration variable**)
- The Tau DWC candidate alerted more frequently overall, a consequence of disproportionately alerting to Unscripted traffic

of DAA Alerts (Truth)



of Corrective or Warning DAA Alerts (Truth)



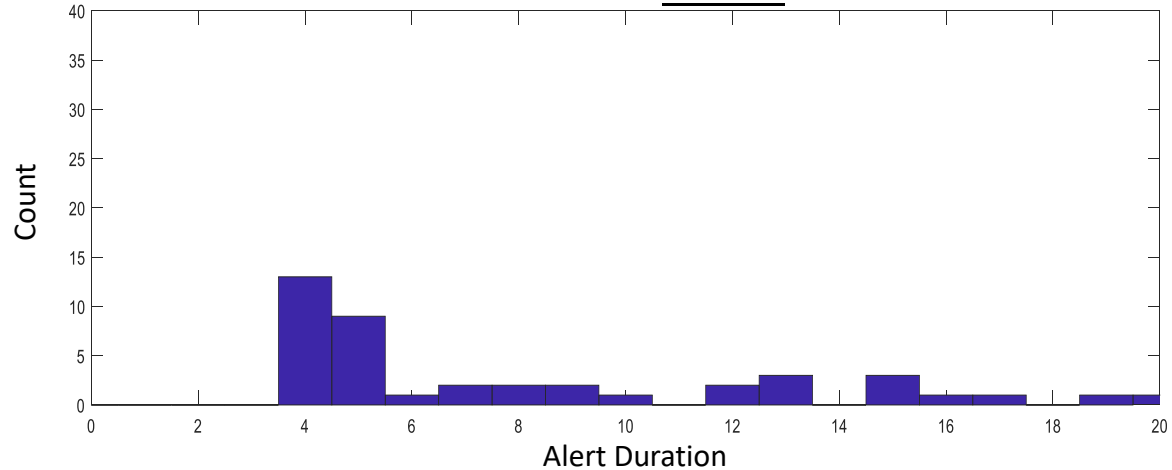
Desired alerts



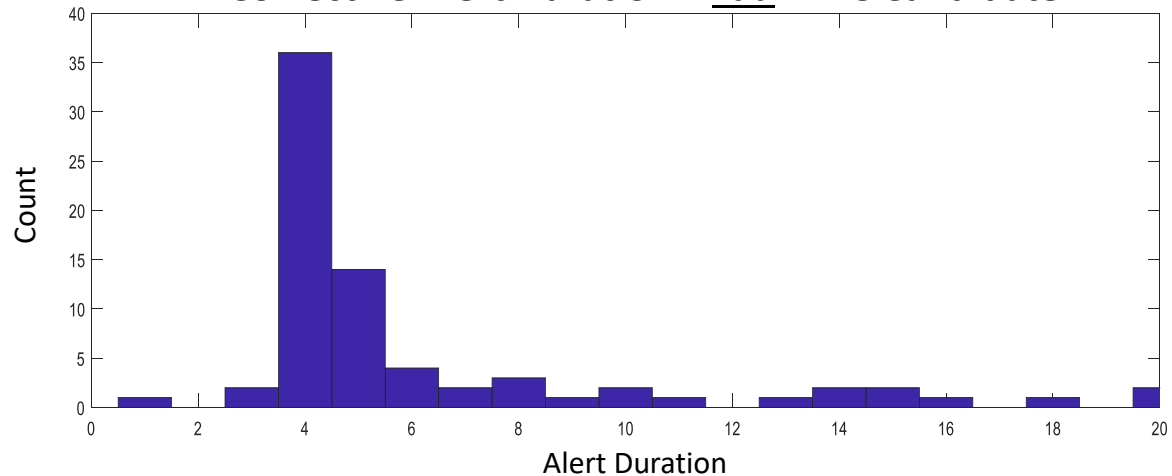
Corrective Alert Duration

- More Corrective (truth) alerts issued when Tau DWC definition used
 - No Tau = 42 total
 - Tau = 75 total
- Majority of these Corrective alerts lasted *less than 6sec*
 - NOTE: 4sec is min. alert duration
 - Most did not progress to a Warning alert
 - No Tau = 17/22 (77%)
 - Tau = 44/53 (83%)
- Avg. Corrective alert duration
 - No Tau = 6.9sec
 - Median = 5sec
 - Tau = 7.5sec
 - Median = 5sec
 - Typically allot 10-15sec for ATC coordination

Corrective Alert Duration – No Tau DWC Candidate



Corrective Alert Duration – Tau DWC Candidate

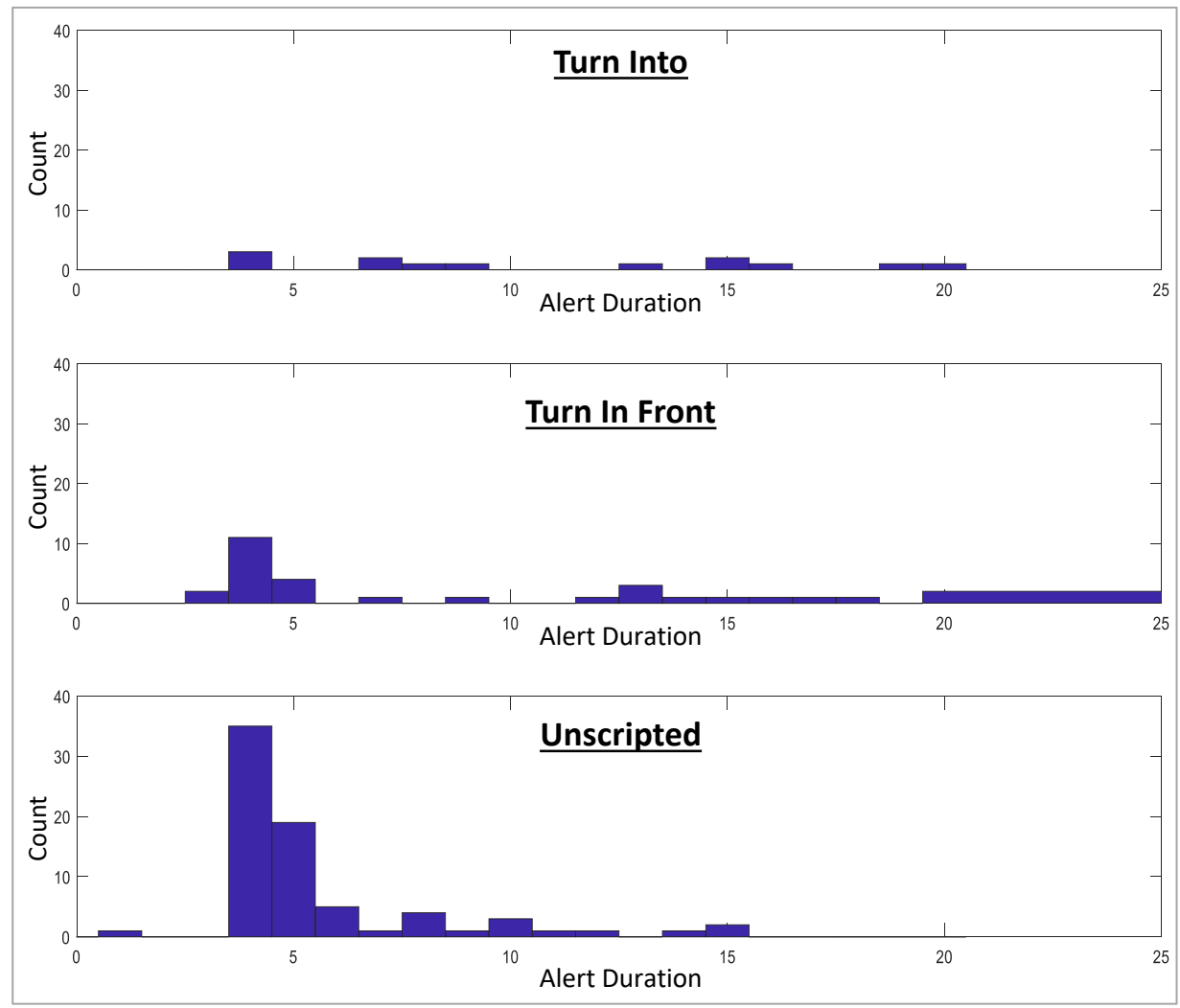




Corrective Alert Duration

- Corrective (truth) alerts *least* common during the Turn Into encounter types
 - Only **13 Corrective** alerts issued against Turn Into encounters
- Correctives more common with Turn In Front & Unscripted encounters
 - Turn In Front = 30
 - Unscripted = 74
- Avg. Corrective duration
 - Turn Into = 10.8sec
 - Median = 9sec
 - Turn In Front = 9.6sec
 - Median = 5sec
 - Unscripted = 5.5sec
 - Median = 5sec

Corrective Alert Duration by Encounter Type

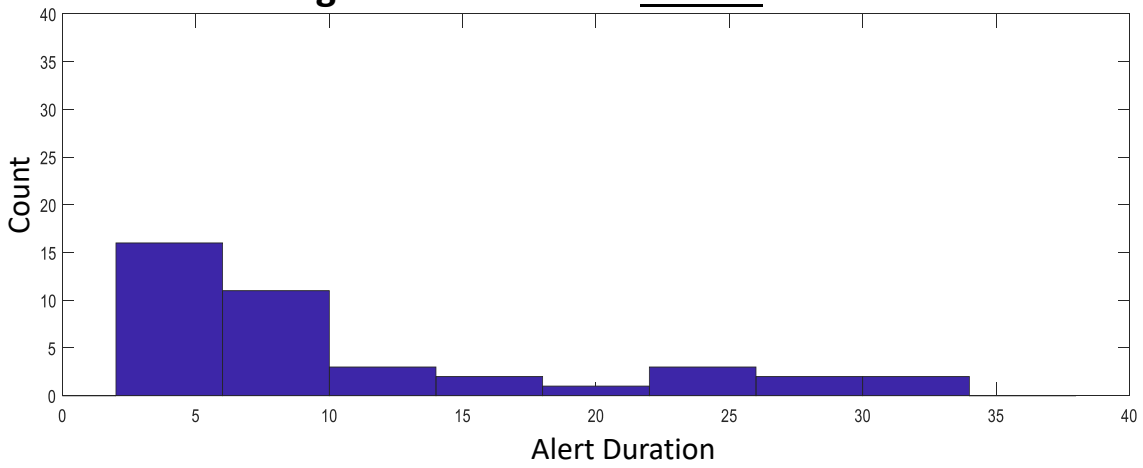




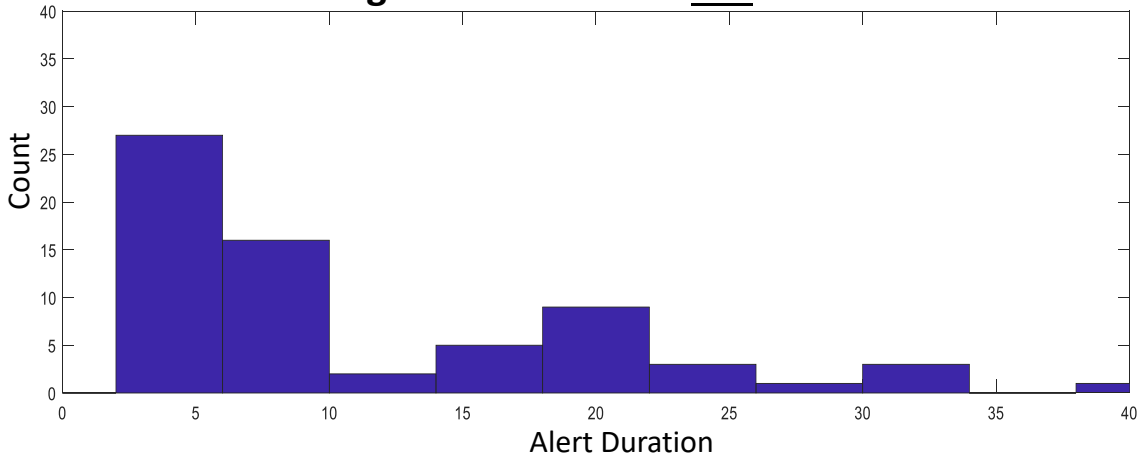
Warning Alert Duration

- More Warning (truth) alerts issued when Tau DWC definition used
 - No Tau = 40
 - Tau = 67
- Warnings typically lasted less than 10sec
 - However, Tau candidate led to more alerts w/ **20sec duration**
- Avg. Warning alert duration
 - No Tau = 10.9sec
 - Median = 8sec
 - Tau = 12.4sec
 - Median = 8sec

Warning Alert Duration – No Tau DWC Candidate



Warning Alert Duration – Tau DWC Candidate

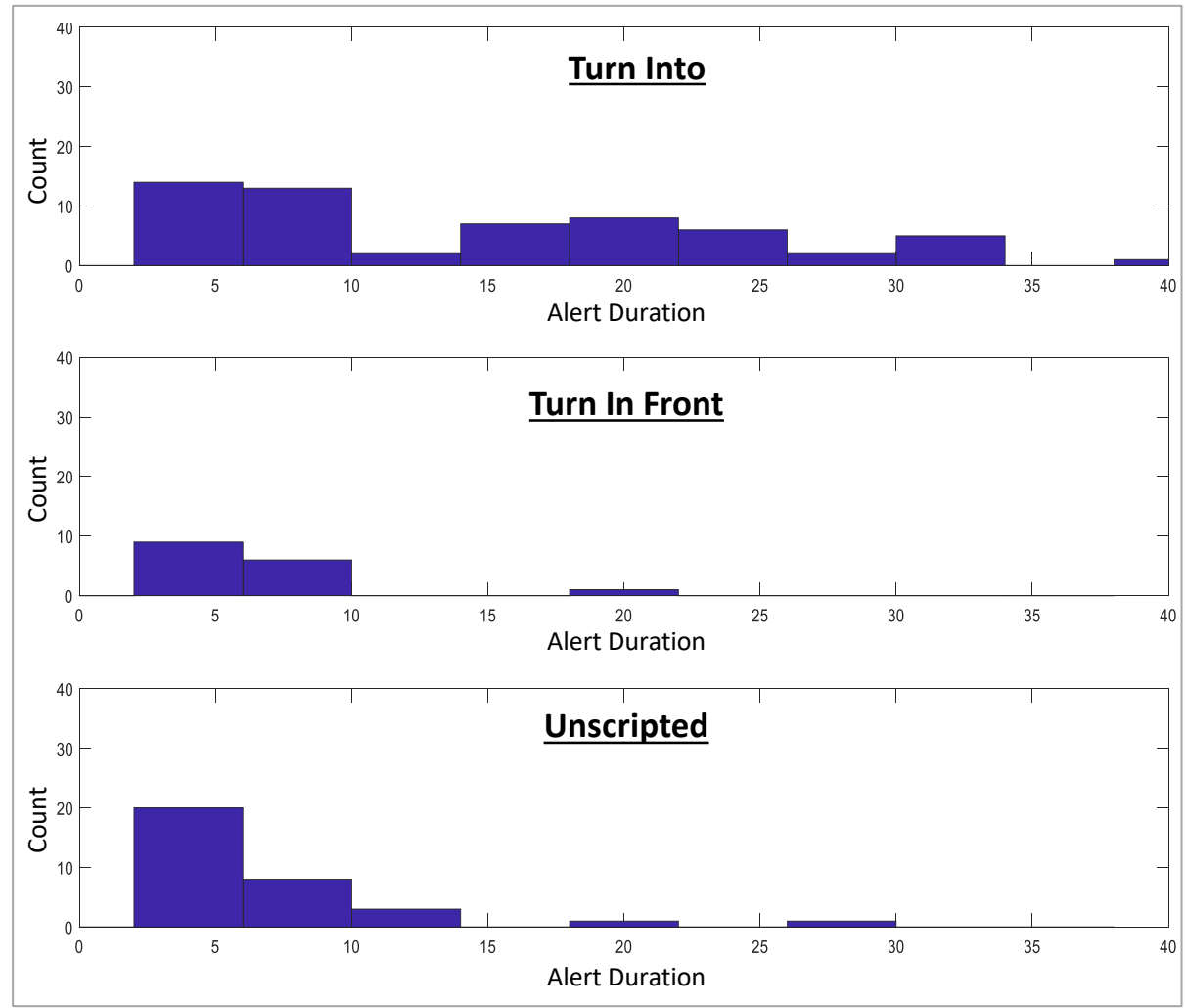




Warning Alert Duration

- Warning (truth) alerts *most* common during the Turn Into encounter types
 - **58 Warning** alerts issued against Turn Into encounters
- Warnings less common with Turn In Front & Unscripted encounters
 - Turn In Front = 16
 - Unscripted = 33
- Avg. Warning duration
 - Turn Into = 15.2sec
 - Median = 15sec
 - Turn In Front = 7.3sec
 - Median = 6sec
 - Unscripted = 7.5sec
 - Median = 6sec

Warning Alert Duration by Encounter Type

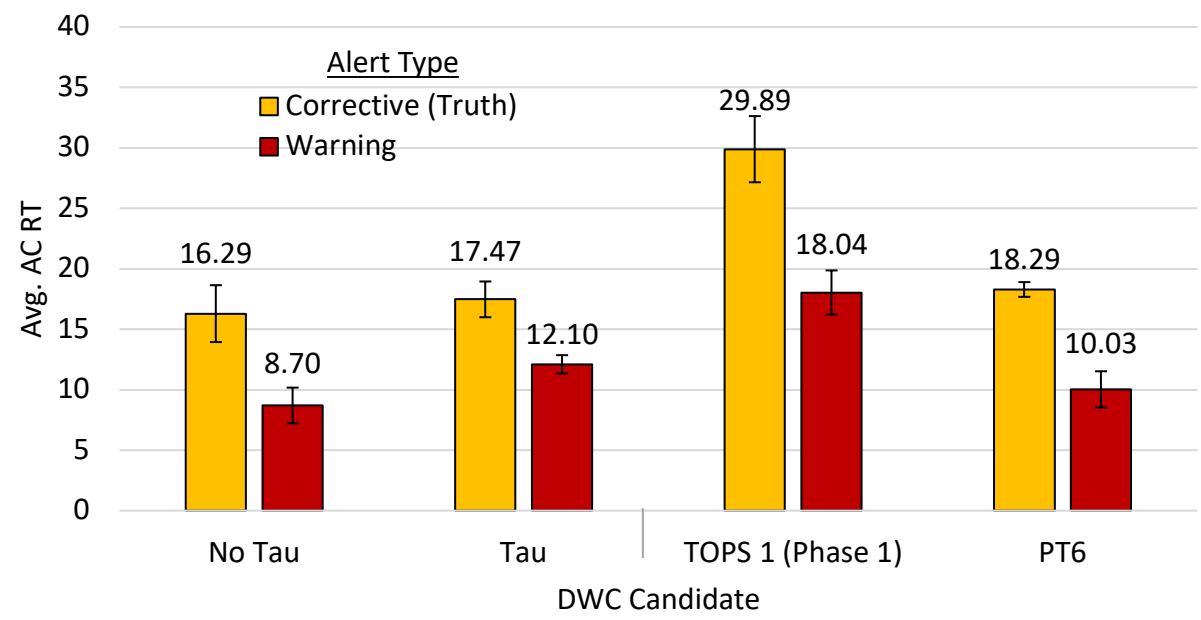




Aircraft Response Time

- Aircraft Response Time = time to upload a maneuver to the aircraft following the onset of a Corrective or Warning alert (whichever appeared first)
- Difficult to capture response times to Corrective alerts – not visible in all conditions and (as shown earlier) they were typically of short duration
- Pilots respond slightly faster to Warning alerts in the No Tau DWC condition
 - Later alerting w/ No Tau means that the threat is often more apparent by the time an alert is issued

Aircraft RT by DWC Candidate & Alert Type





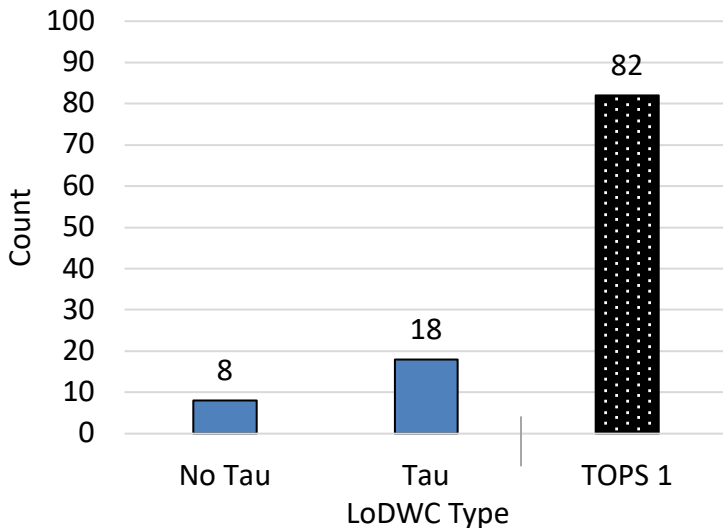
SEPARATION DATA



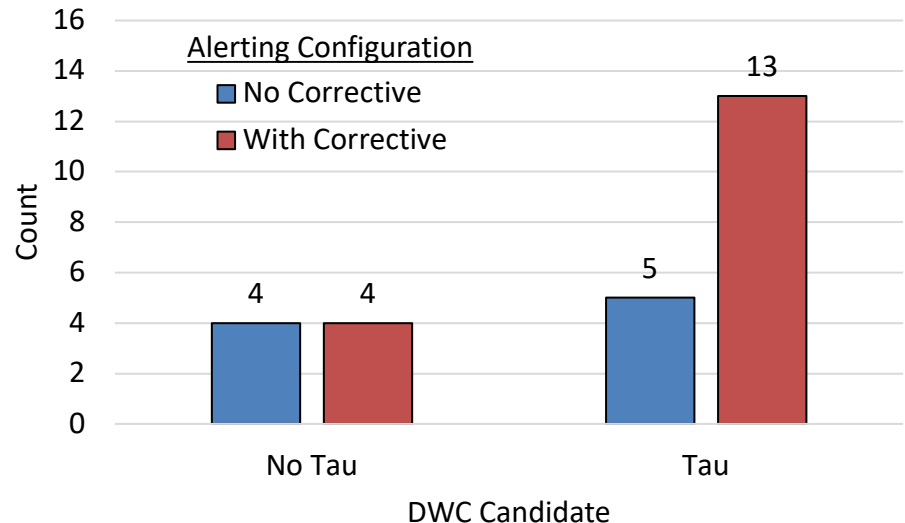
Losses of DAA Well Clear (Counts)

- Loss of DAA Well Clear (LoDWC) Criteria:
 - **No Tau:** Horz=1500ft, Vert=450ft, no tau
 - **Tau:** Horz=1500ft, Vert=450ft, 15sec modTau, 1500ft DMOD
- For reference: 82 LoDWC in TOPS 1 against similar encounters
- Tau had 10 more LoDWC than No Tau (also had larger hazard zone)
 - Tau candidate had more than twice as many LoDWC in the With Corrective alerting configuration

Total # LoDWC



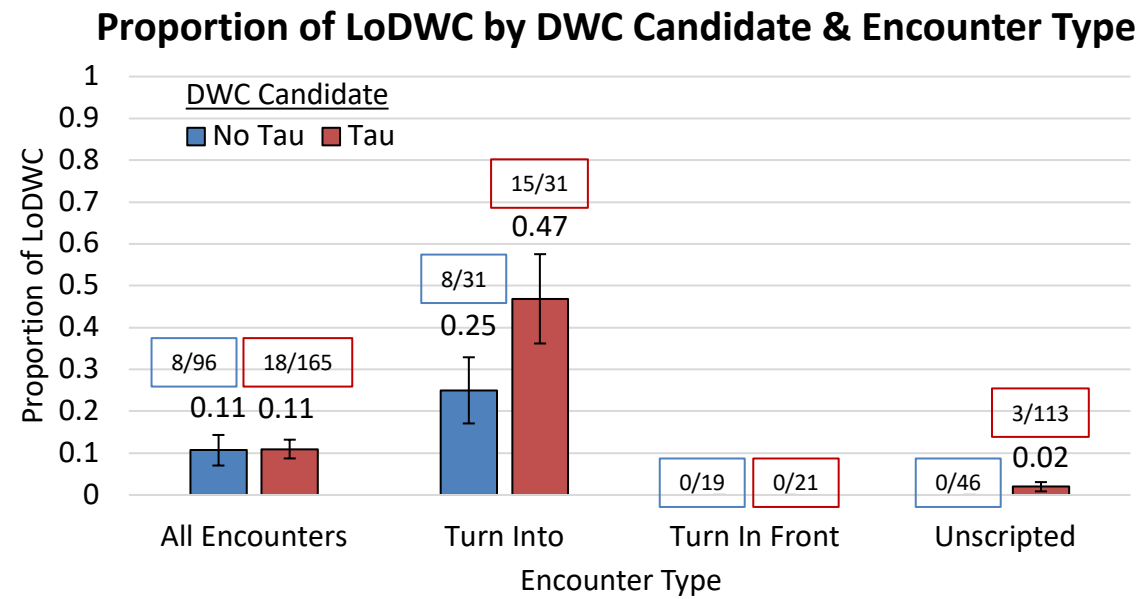
LoDWC by DWC Candidate & Alerting Configuration





Losses of DAA Well Clear (Proportions)

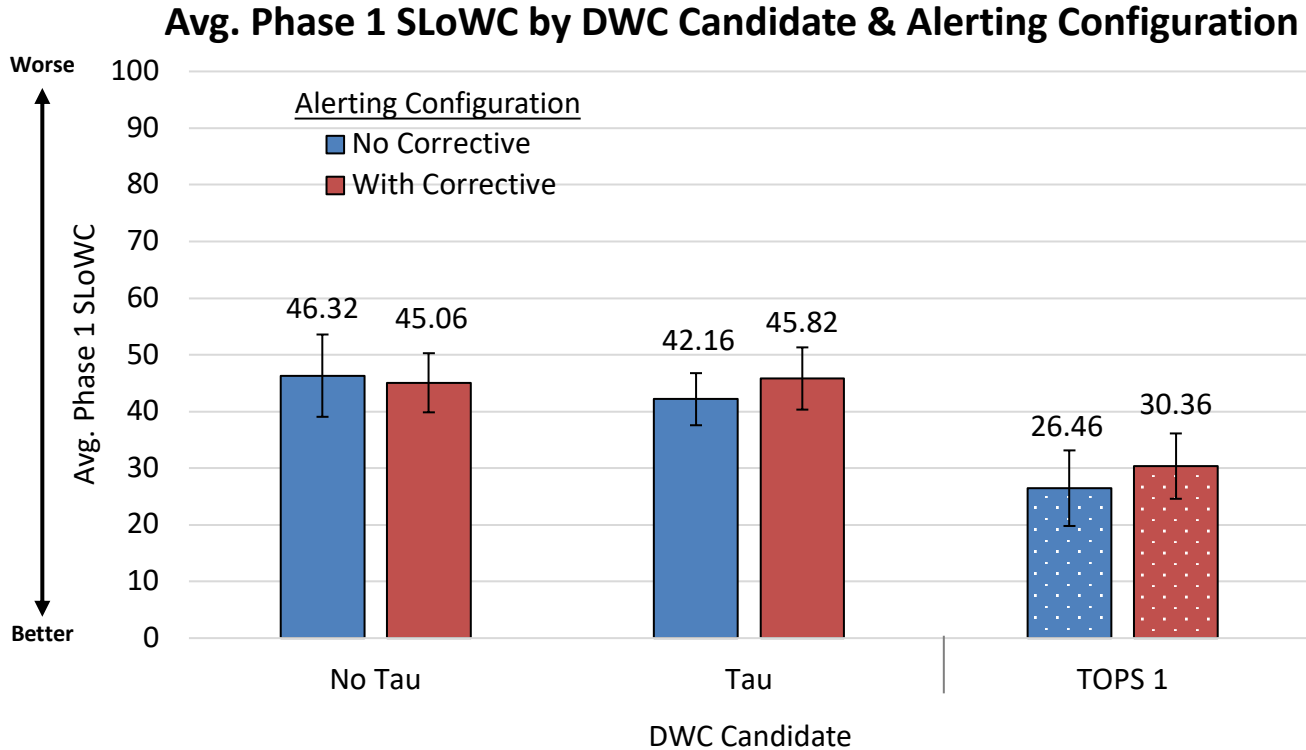
- Proportion of losses of DAA Well Clear (LoDWC)
 - # of LoDWC / # aircraft that generated a DAA Corrective or Warning
- For **All Encounters**, identical proportion of LoDWC between No Tau and Tau DWC candidates
- LoDWC was most common against **Turn Into** encounters
 - 32 total were scripted (per condition), but one encounter failed to generate in each
 - Twice as many LoDWC with Tau candidate
- **0** LoDWC in Turn In Front encounter type
- **3** total LoDWC against Unscripted encounters (all in Tau condition)





Losses of DAA Well Clear (Severity)

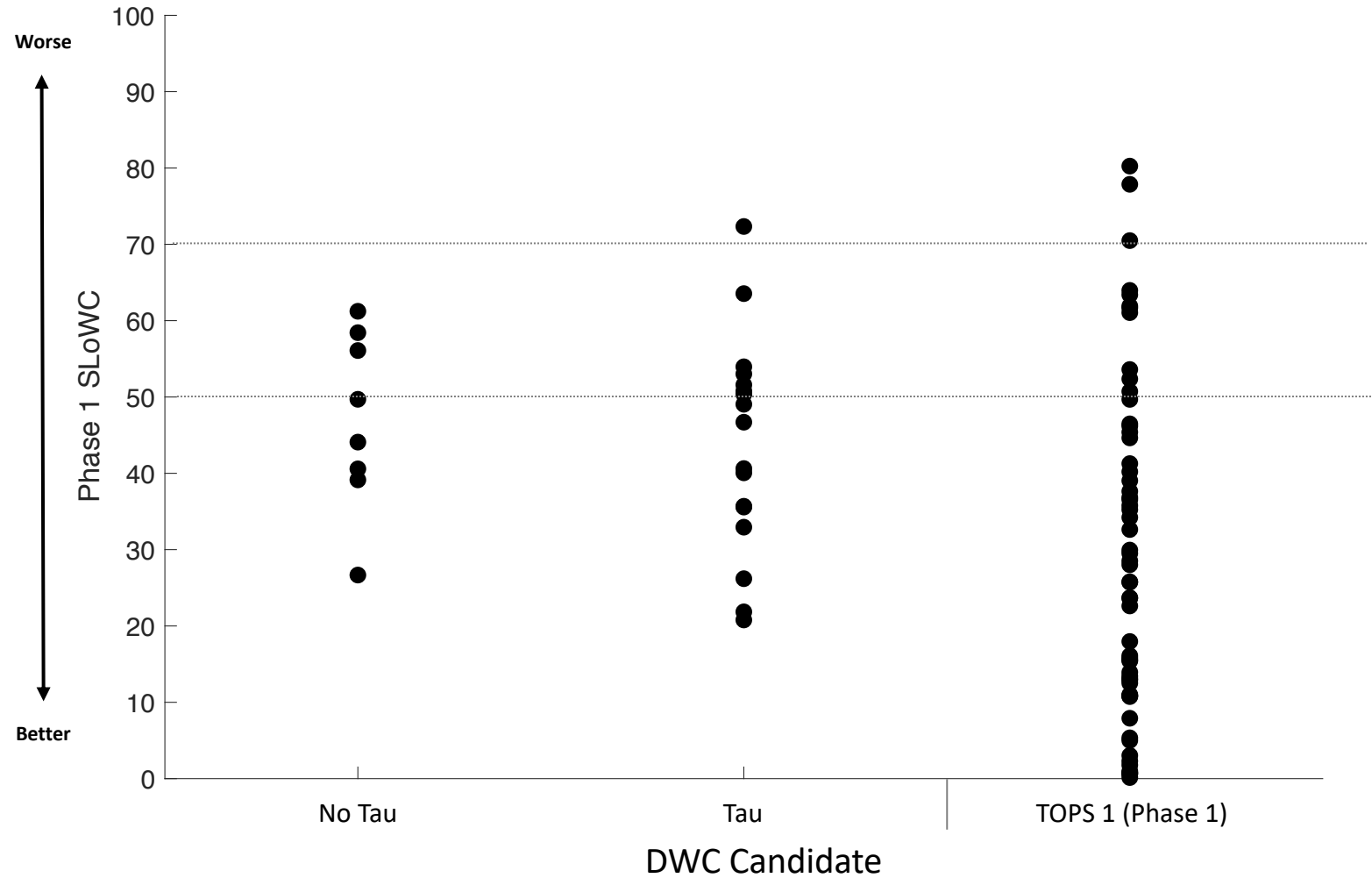
- Phase 1 SLoWC = % of the **Phase 1** DAA well clear volume (which includes tau) penetrated by intruder
 - Higher % = greater penetration
- No substantial effect of DWC candidate or alerting configuration
 - No Tau & Tau DWC candidates led to





Losses of DAA Well Clear (Severity)

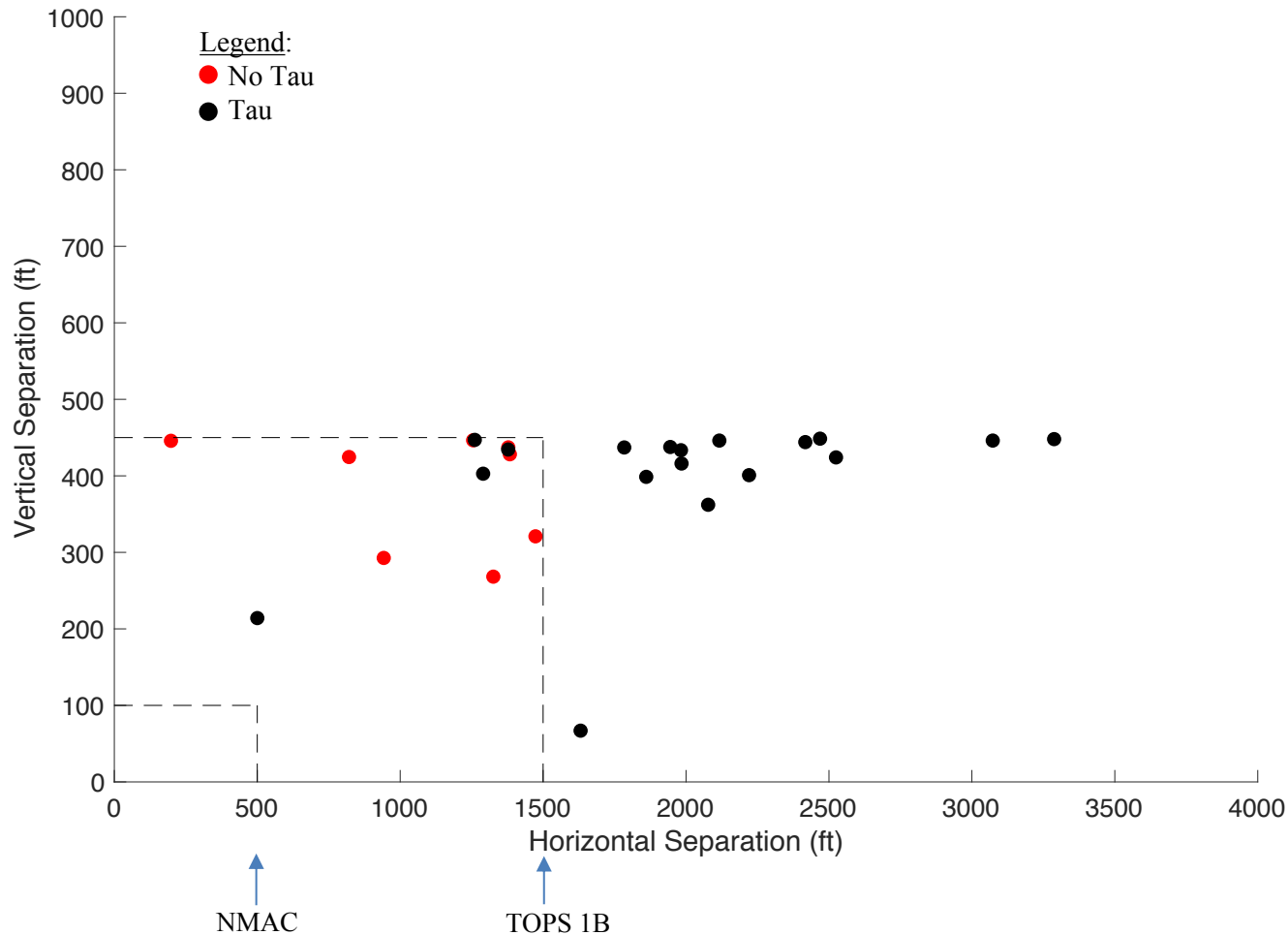
- Phase 1 SLoWC ranged overall from 20-72%
 - Highest SLoWC seen in With Corrective alerting configuration
- Fewer high-severity SLoWC with current DWC candidates than seen in TOPS 1

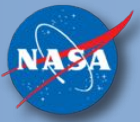




Actual Separation at Closest Point in LoDWC

- Closest point defined as minimum slant range *with vertical separation < 450ft*
- 22% (4/18) of LoDWC in the Tau DWC candidate came within 1500ft horizontal separation (i.e., violated the No Tau candidate criteria)
 - 4 intruders came within 1215ft horizontal separation (the lower-bound recommendation)

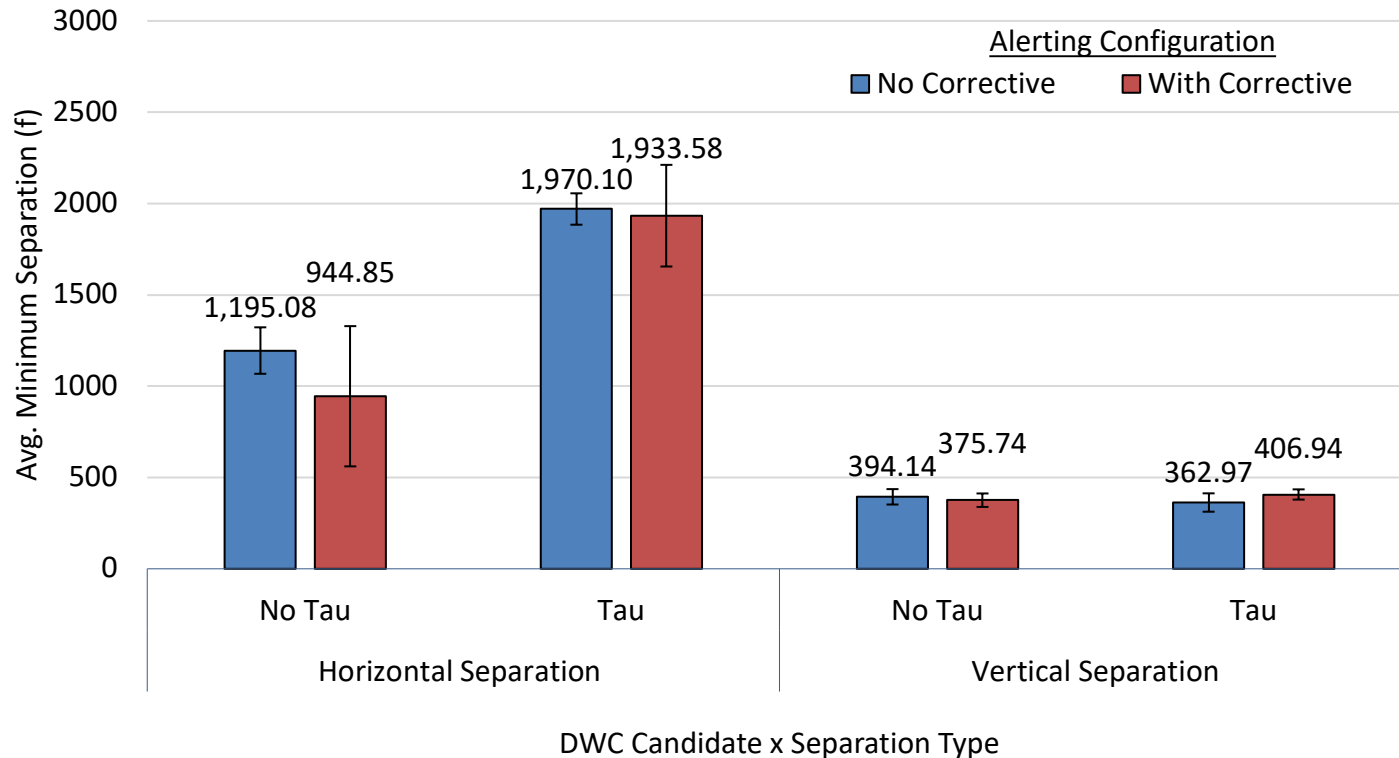




Avg. Minimum Separation at Closest Point in LoDWC

- Closest point defined as minimum slant range *with vertical separation < 450ft*
- Tau candidate adds approximately 1000ft additional minimum horizontal separation
- Minimum vertical constant across the four conditions
- No clear effect of alerting configuration

Avg. Minimum Separation by DWC Candidate, Separation Type & Alerting Configuration



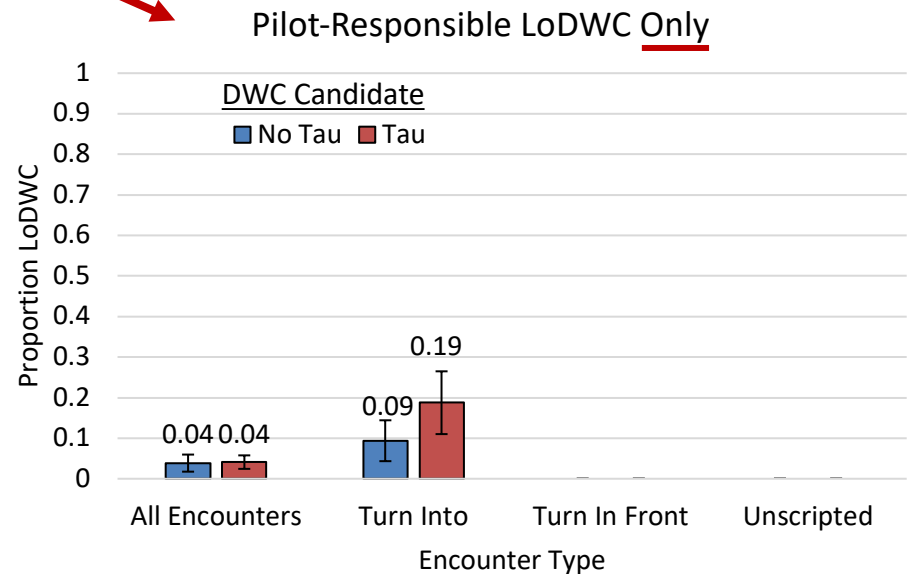
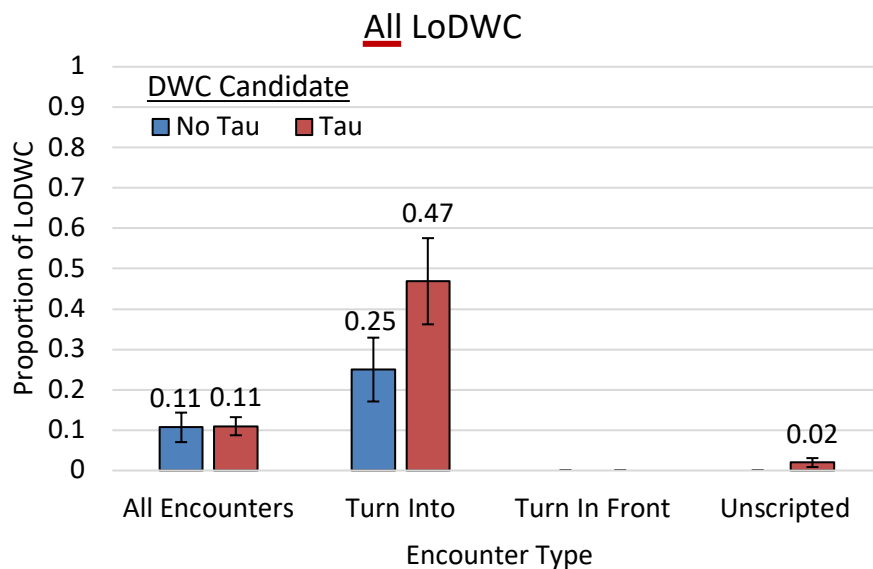


Losses of DAA Well Clear (Causes)

- Pilot responsible for LoDWC:
 - 38% (3/8) of time with No Tau candidate
 - 33% (6/18) of time with Tau candidate
 - Only one entered No Tau boundary
- Late acceleration was a disproportionate contributor to LoDWC
 - 38% (3/8) of time with No Tau
 - 56% (10/18) of time with Tau

LoDWC Causes		No Tau	Tau
Pilot Responsible	Pilot Hesitation	1	3
	Insufficient Vertical Maneuver	1	2
	Ineffective Maneuver	1	1
Pilot Not Responsible	Late Acceleration	3	10
	Intruder Mis-Flown	1	2
	No Safe Maneuver	1	0
Total		8	18

- Proportion of LoDWC drops significantly when only including pilot-responsible

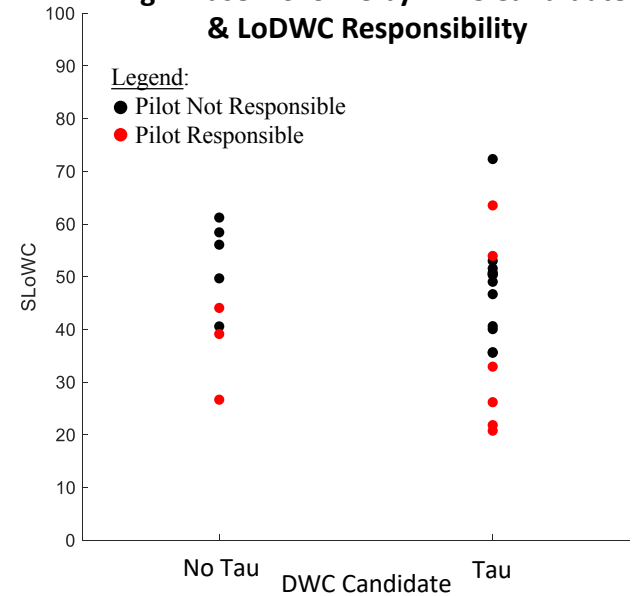




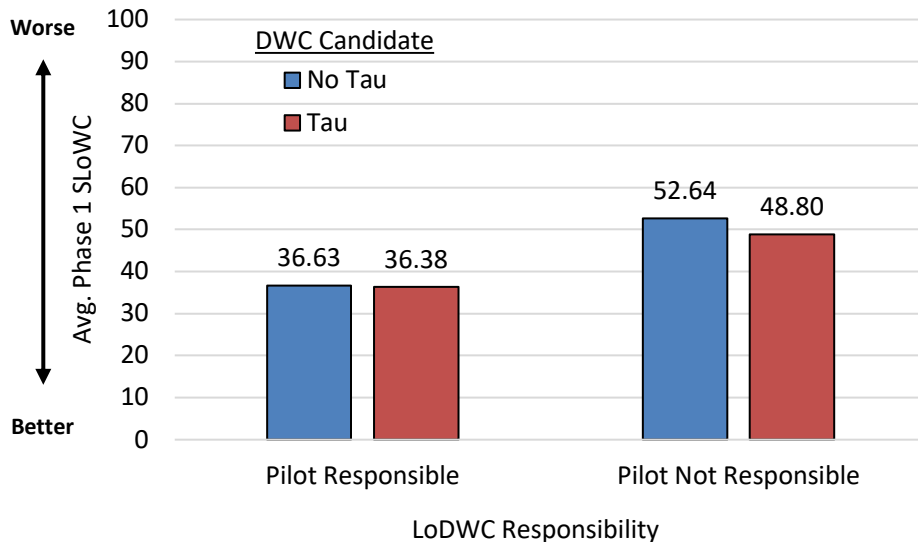
Losses of DAA Well Clear (Causes)

- SLoWC drops substantially when only including pilot-responsible LoDWC
 - Approx. reduction of 12-16% SLoWC
 - No noticeable difference between DWC candidates
- The No Tau candidate had **0** SLoWC above 50% with pilot responsible
- The Tau candidate had **2** SLoWC above 50% & **0** SLoWC above 70% (both due to 'pilot hesitation')
 - For reference: TOPS 1 had **17** SLoWC above 50% & **6** SLoWC above 70% with pilot responsible

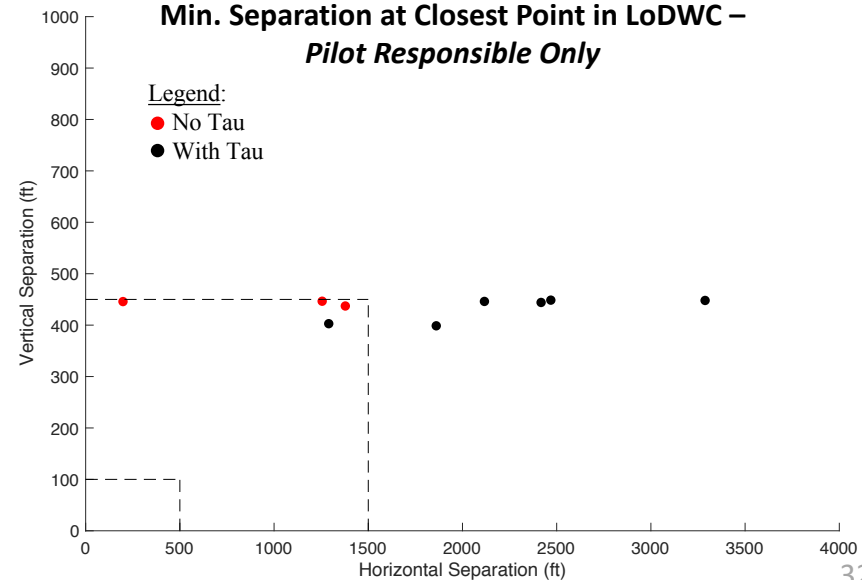
Avg. Phase 1 SLoWC by DWC Candidate & LoDWC Responsibility



Avg. Phase 1 SLoWC by DWC Candidate & LoDWC Responsibility



Min. Separation at Closest Point in LoDWC – Pilot Responsible Only





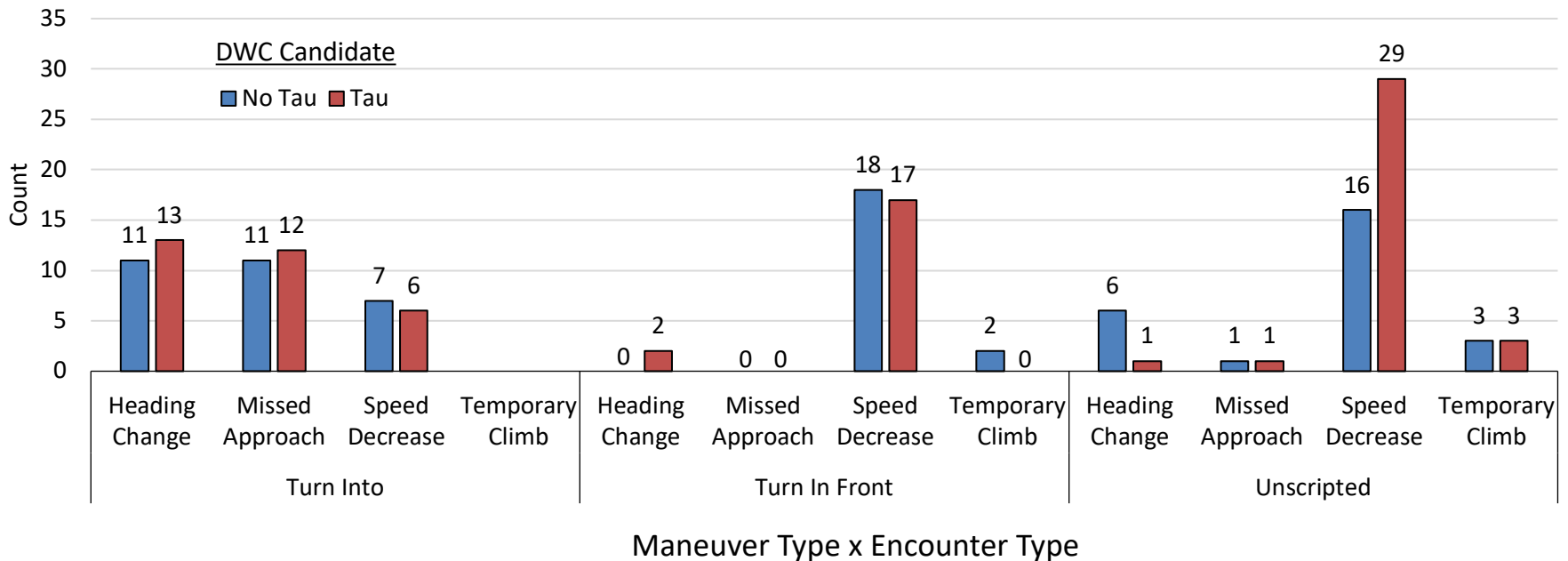
MANEUVERING & ATC INTEROPERABILITY



Initial Maneuver Types

- Heading changes and missed approaches (or go-arounds in visual scenario) were most likely in the Turn Into encounter type
 - Even split between heading changes and missed approaches
- Pilots relied on speed reductions almost exclusively to resolve perceived conflicts in the Turn In Front and Unscripted encounter types
 - Larger number of maneuvers seen for Tau DWC candidate, largely a result of more speed decreases against Unscripted encounters

Initial Maneuver Type by DWC Candidate, Maneuver Type & Encounter Type

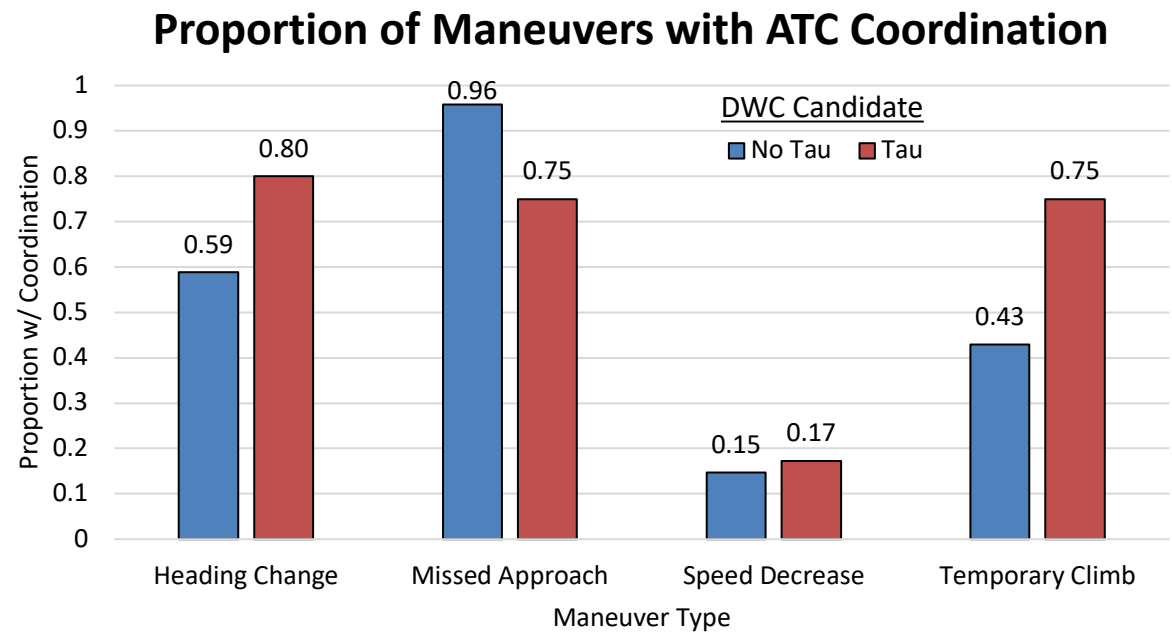




Coordination With the Tower

- Pilots were most consistent when coordinating a missed approach/go-around
 - Pilots fairly consistent in coordinating heading changes, slightly more so in Tau condition
- Speed decreases were rarely coordinated
- ATC coordination was ~20% in TOPS 1

- When pilots did coordinate, it was typically after they had made their maneuver
 - **67%** of coordination occurred after the maneuver had been made (identical rate for missed & non-missed approach maneuvers)





Conclusions

- Both DWC candidates appropriately tailored to the operational environment
 - Substantially fewer high-severity LoDWC than TOPS 1
 - The 2 candidates had identical avg. Phase 1 SLoWC when including only pilot-responsible
 - Response times returned to expected averages (consistent with PT6)
 - Pilots did not report noticing a difference between the candidates during debrief
- Tau candidate generated more alerts and more LoDWC, however:
 - Tau candidate led to more LoDWC overall but they typically stayed outside of the 1500ft x 450ft boundary
 - Additional alerts not found to correspond with more disruptive maneuvers – pilots relied heavily on speed reductions
- Corrective alerts continue to show lack of utility in the terminal area
 - Corrective duration grand mean = **7sec** (median = 5sec)
 - **81%** (61/75) of time short duration Correctives failed to progress to a Warning
 - Pilot performance in the No Corrective alerting configuration either did not differ from or was better than performance in With Corrective condition



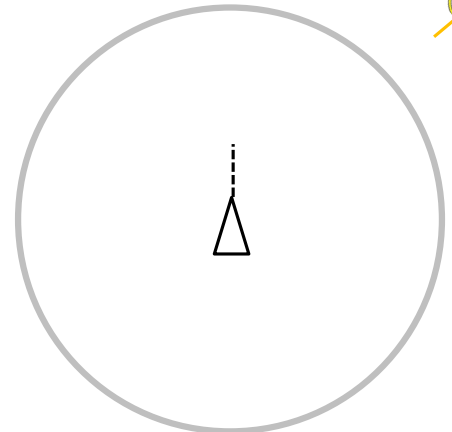
BACKUP



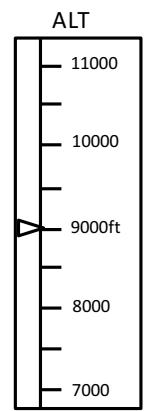
DAA Alerting & Guidance

No Corrective

Preventive (Truth) Alert

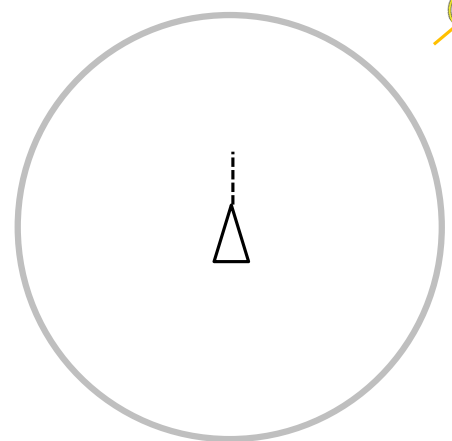


Inner Range Ring

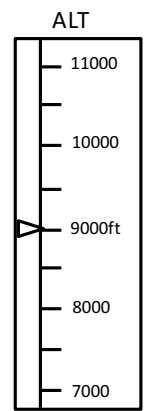


Altitude Tape

Corrective (Truth) Alert



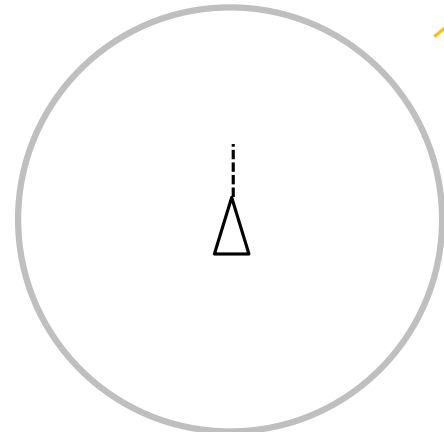
Inner Range Ring



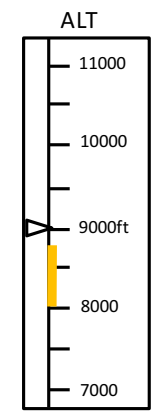
Altitude Tape

With Corrective

Preventive (Truth) Alert

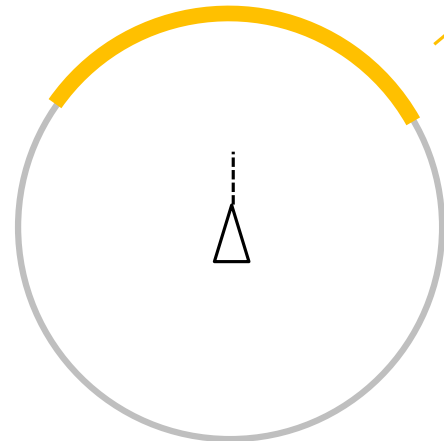


Inner Range Ring

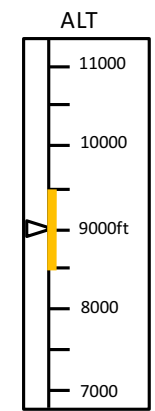


Altitude Tape

Corrective (Truth) Alert



Inner Range Ring



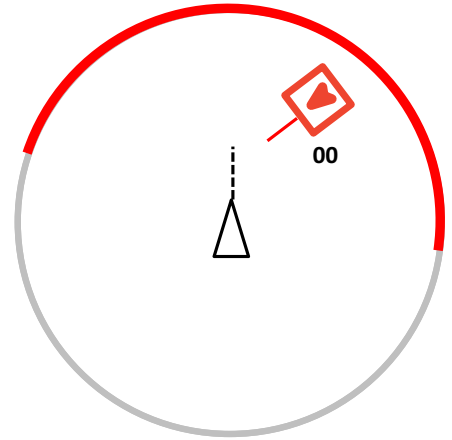
Altitude Tape



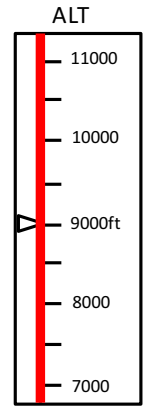
DAA Alerting & Guidance

No Corrective

Warning (Truth) Alert



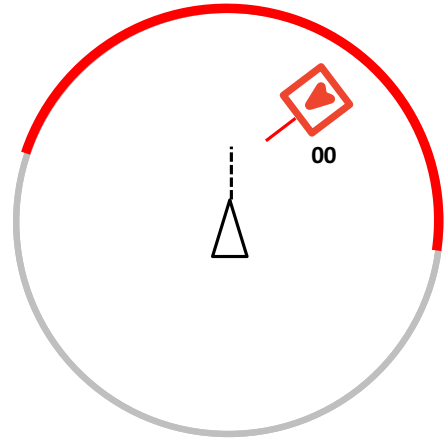
Inner Range Ring



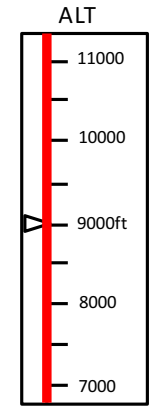
Altitude Tape

With Corrective

Warning (Truth) Alert

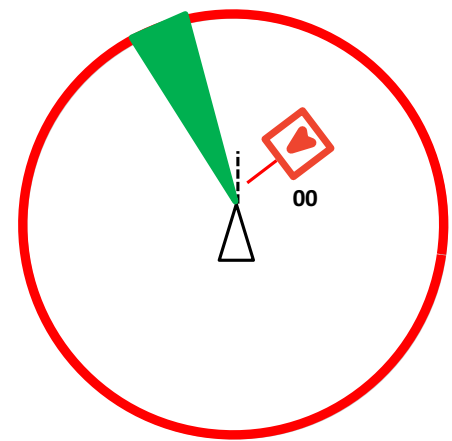


Inner Range Ring

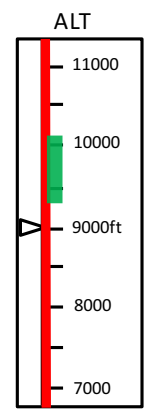


Altitude Tape

Regain DWC Guidance

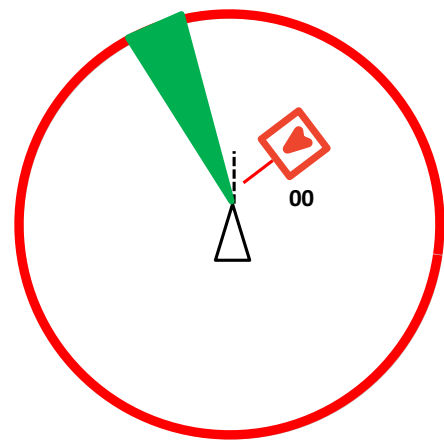


Inner Range Ring

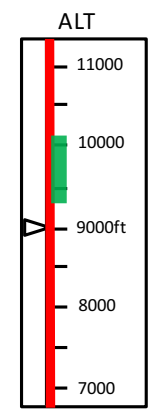


Altitude Tape

Regain DWC Guidance



Inner Range Ring

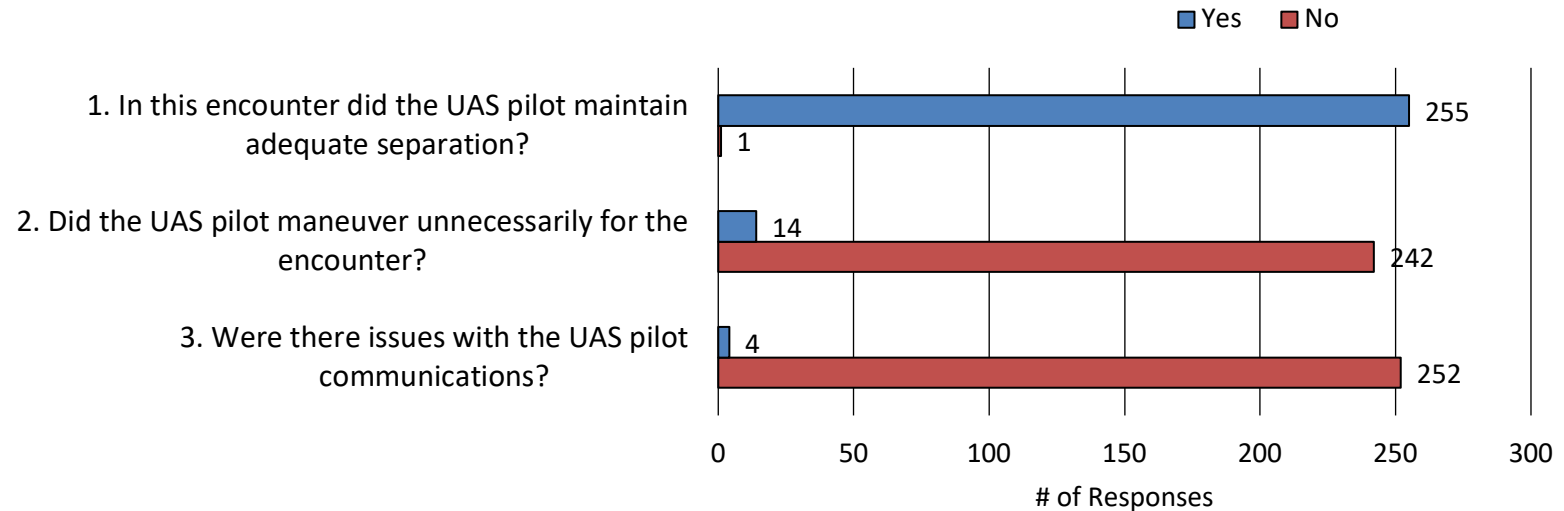


Altitude Tape



Controller & Pilot Feedback

- After each encounter, tower controller answered the following questions:

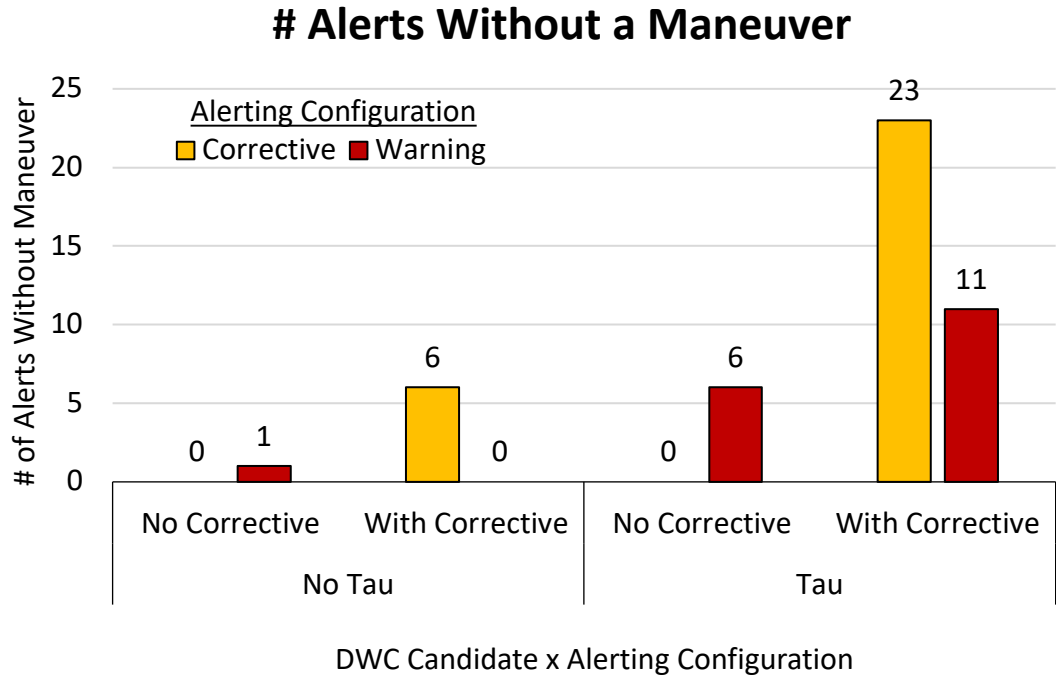


- Tower rated UAS behaviors as overwhelmingly appropriate
 - UA pilots were able to detect appropriate traffic
 - Disruptive turn-outs on instrument approach where pilots should have executed missed approach
 - 1.5 nm separation on approach worked for simulation
- Pilot responses to traffic on final was left to their discretion – although training emphasized the expectation to go missed/go-around
 - During debrief pilots explained that they (often) reflexively looked to make a heading change as a way to immediately increase separation
 - Altitude bands typically indicated that a climb would not resolve the conflict



DAA Alerts Without a Maneuver

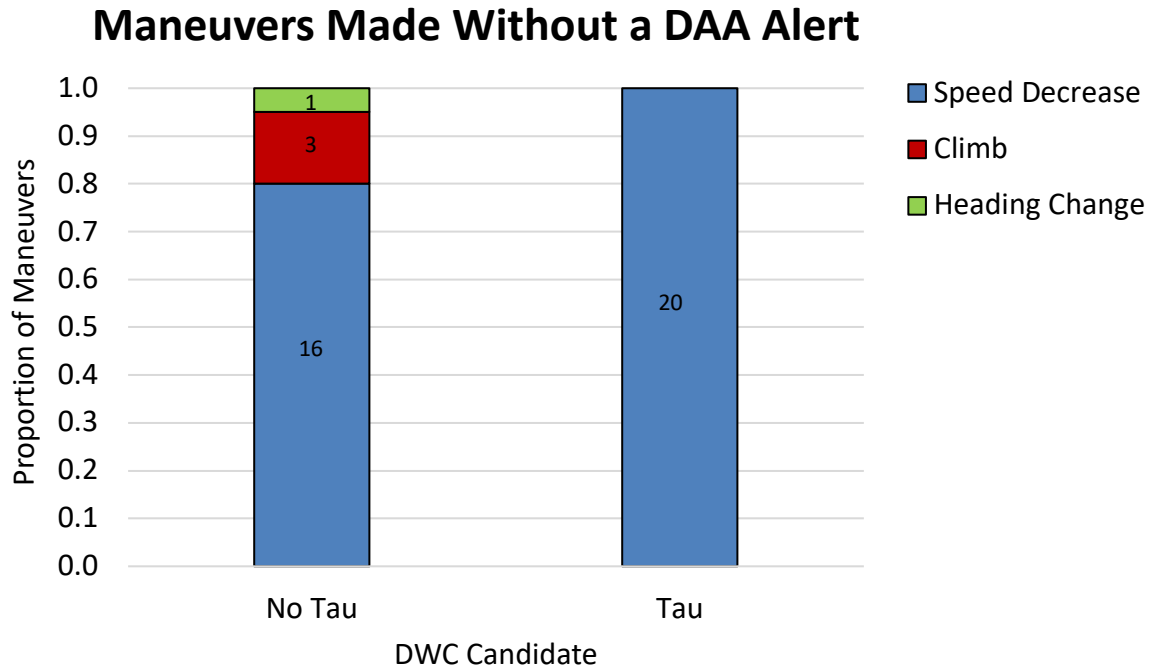
- Tau DWC candidate had far more instances of a DAA alert that did not lead to a UAS maneuver
 - No Tau = 7 alerts w/o maneuver
 - Tau = 40 alerts w/o maneuver
- 62% (29/47) of these cases were against a Corrective alert
- **None of these alerts resulted in a loss of DWC**
 - Avg. alert duration = 6sec





Maneuvers Without a DAA Alert

- 40 total maneuvers were made against traffic that did not register a DAA alert
 - Evenly distributed between the 2 DWC candidates
- Maneuvers were typically speed decreases to provide enough space for aircraft in front
 - No Tau had minority of climbs and heading changes against non-alerted traffic





Unscripted Encounter Types

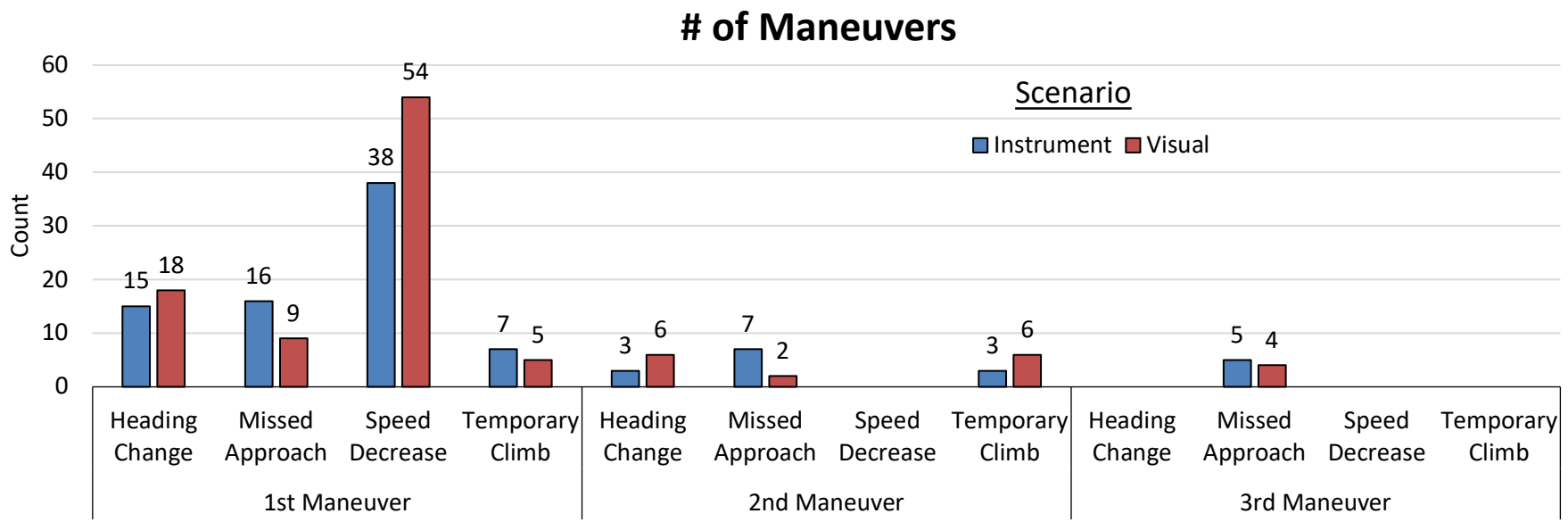
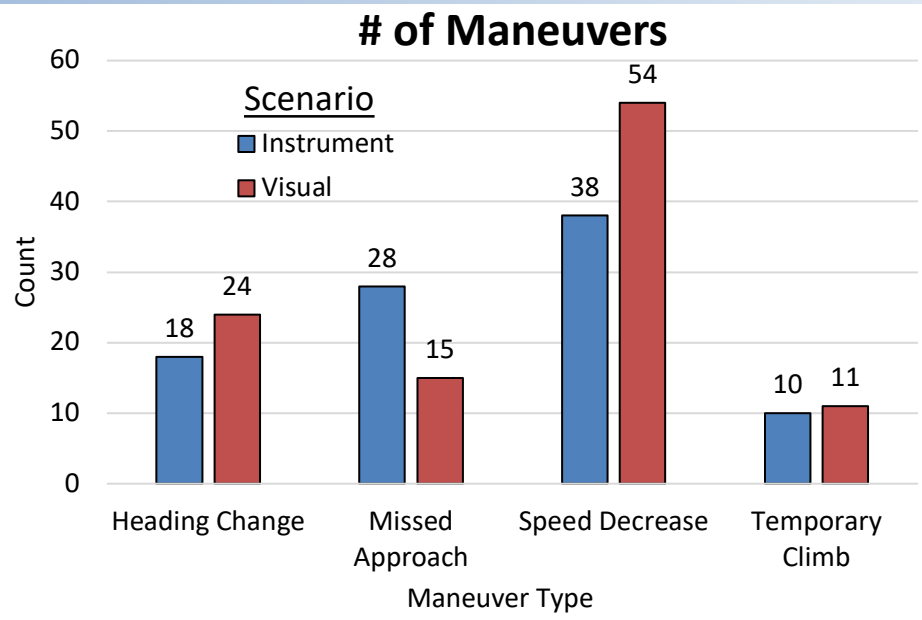
- Tau candidate was far more likely to alert to unscripted traffic, particularly jet traffic and traffic turning to base
 - Jet traffic approached KSTS from the NE before getting established on a 5nm straight-in; during the Instrument approach scenario, it briefly pointed at UA
- Discrepancy between conditions is smaller when comparing # of maneuvers
 - No Tau candidate actually led to more maneuvers than alerts; Tau candidate had ~1/2 as many maneuvers than alerts
- Count of Corrective/Warning alerts and maneuvers against unscripted traffic types by DWC candidate:

Unscripted Traffic Location	<u>No Tau</u> at First Corr/Warn	<u>Tau</u> at First Corr/Warn	<u>No Tau</u> at Maneuver	<u>Tau</u> at Maneuver
Turn to Base	12	32	8	11
Jet Traffic	0	24	2	5
Right Downwind	5	9	6	4
Left Downwind	0	3	2	2
Base	1	1	6	7
Final	0	1	2	9
Total	18	70	26	38

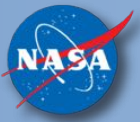


Maneuvers Made by Scenario Type

- Speed changes were the most common type of maneuver made (94 total)
- Missed Approaches & Heading Changes were equally common (43 vs. 42)
 - Missed approach more prevalent in Instrument
 - Heading changes more common in Visual
- Pilots occasionally saved their missed approach for a later upload

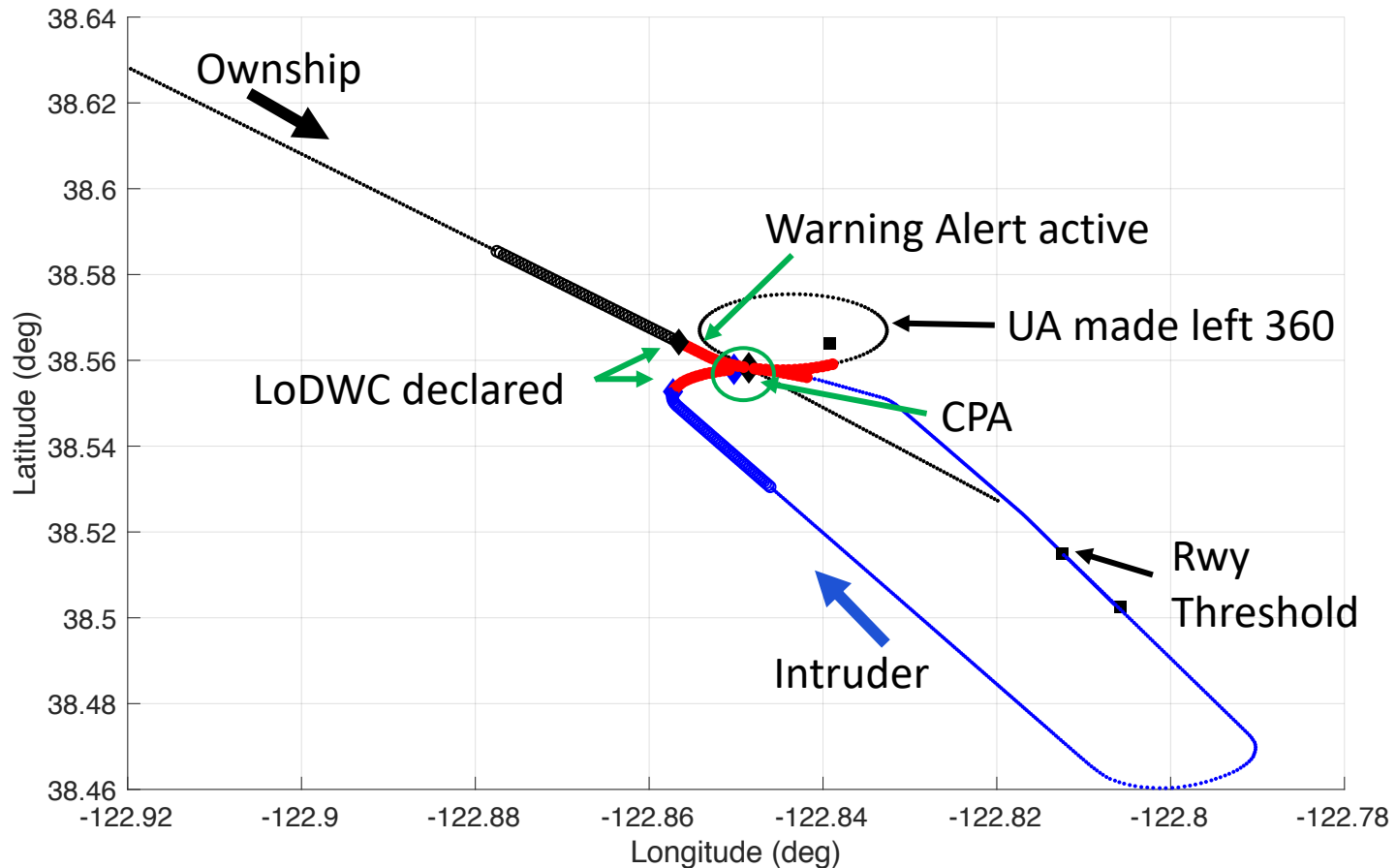


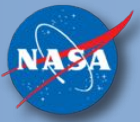
Maneuver Type x Maneuver Order



Highest SLoWC Encounter

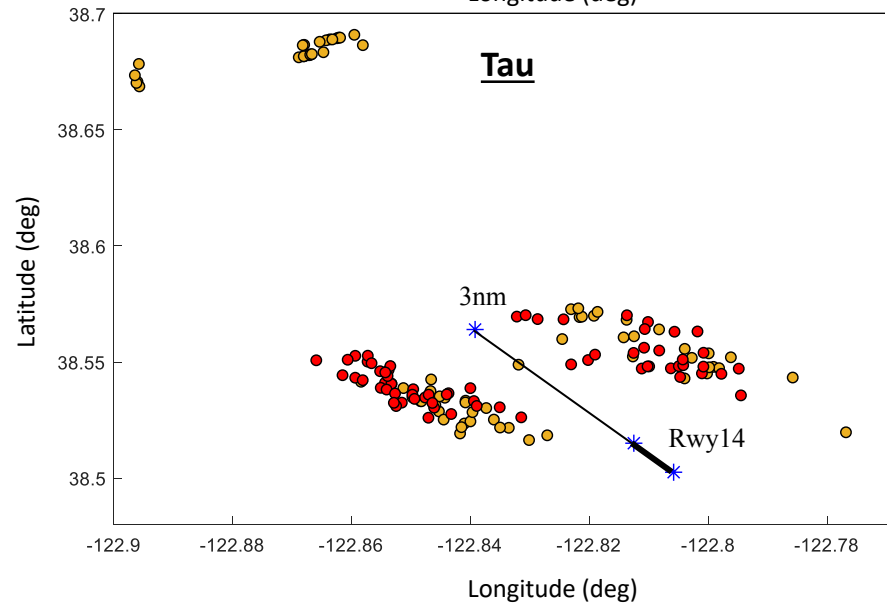
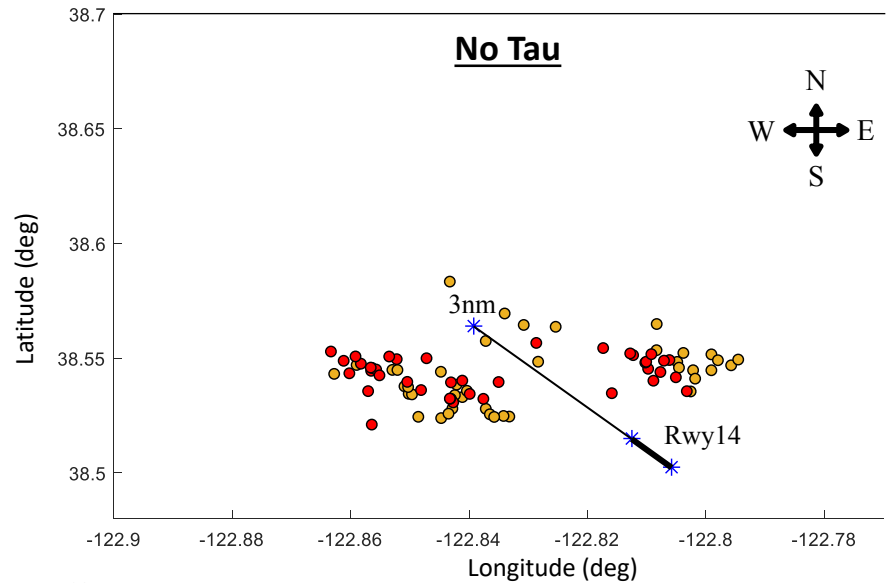
- Worst case was with the Tau DWC candidate, With Corrective alert config.
 - Instrument scenario
 - ‘Late Acceleration’ – *lost DWC at the same time it became a warning*
 - Pilot exacerbated it by turning with the traffic and delaying a climb

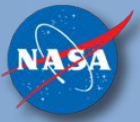




Intruder Location at First Alert

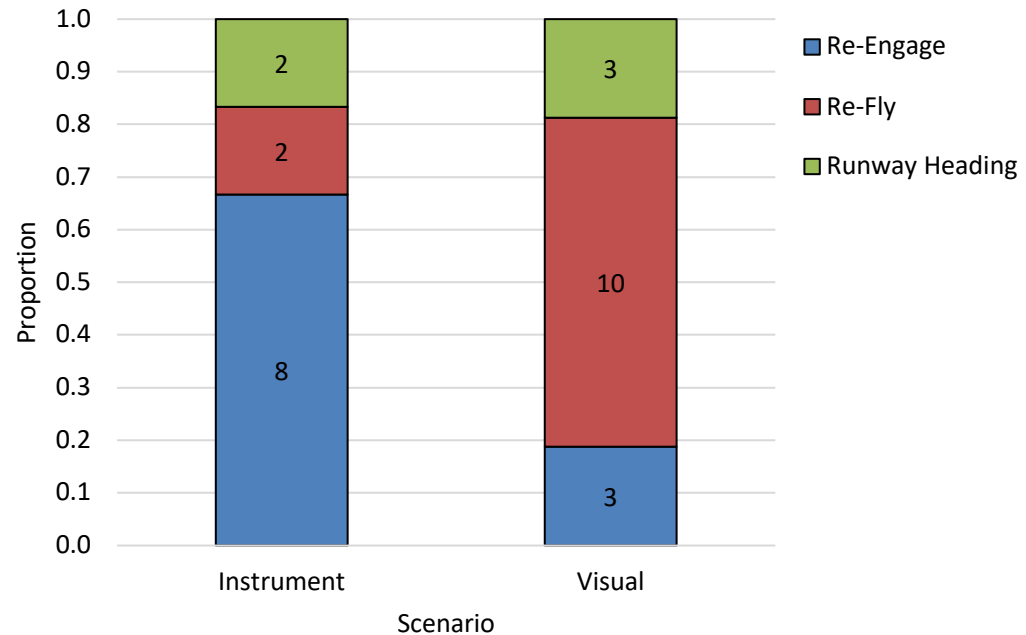
- No Tau candidate had fewer alerts
 - None occurred far away from the 2 downwind legs
- Tau candidate had more alerts overall with several occurring far away from runway
 - Tau candidate was more consistent in *where* the intruder was at first alert





Return Type

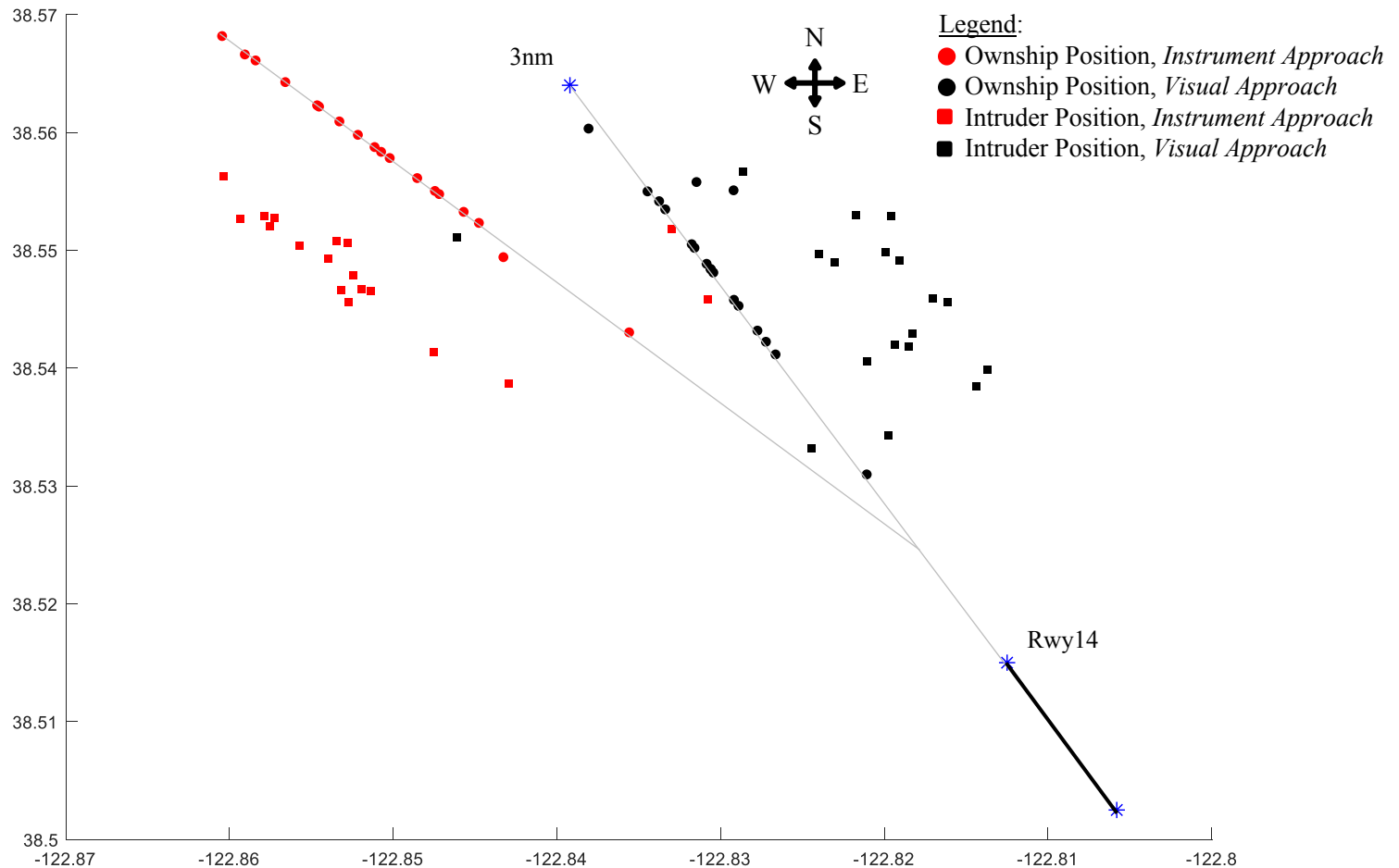
- How did pilots continue the approach when they maneuvered for traffic but did not go missed?
 - **Re-Engage:** turn back to final and/or continue descent
 - **Runway Heading:** turn back toward runway without engaging descent
 - **Re-Fly:** made a 360 or enter the right/left downwind to re-do the approach entirely
- In Instrument scenario, pilots most often tried to re-engage the approach
- In Visual scenario, pilots most often re-flew the approach





Ownship & Intruder Location at Start of all LoDWC_LaRC

- LoDWC_LaRC typically started with ownship established on final with intruder still near right/left downwind (likely at the start of the turn base)





Ownership & Intruder Location at CPA (for all LoDWC_LaRC)

- CPA typically occurred once the intruder neared or crossed our final approach path

