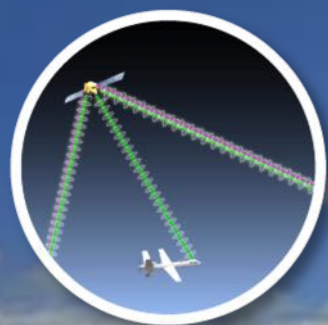




# Unmanned Aircraft Systems (UAS) Integration in the National Airspace System (NAS) Project

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





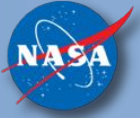
# Objective

- 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"> <li>Notify ATC as soon as practicable after taking action</li> </ul>	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"> <li>Coordinate with ATC to determine an appropriate maneuver</li> </ul>	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"> <li>On current course, corrective action should not be required</li> </ul>	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"> <li>Traffic generating guidance bands outside of current course</li> </ul>	Associated w/ bands outside current course	Associated w/ bands outside current course	X	N/A
	Remaining Traffic	<ul style="list-style-type: none"> <li>Traffic within sensor range</li> </ul>	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.

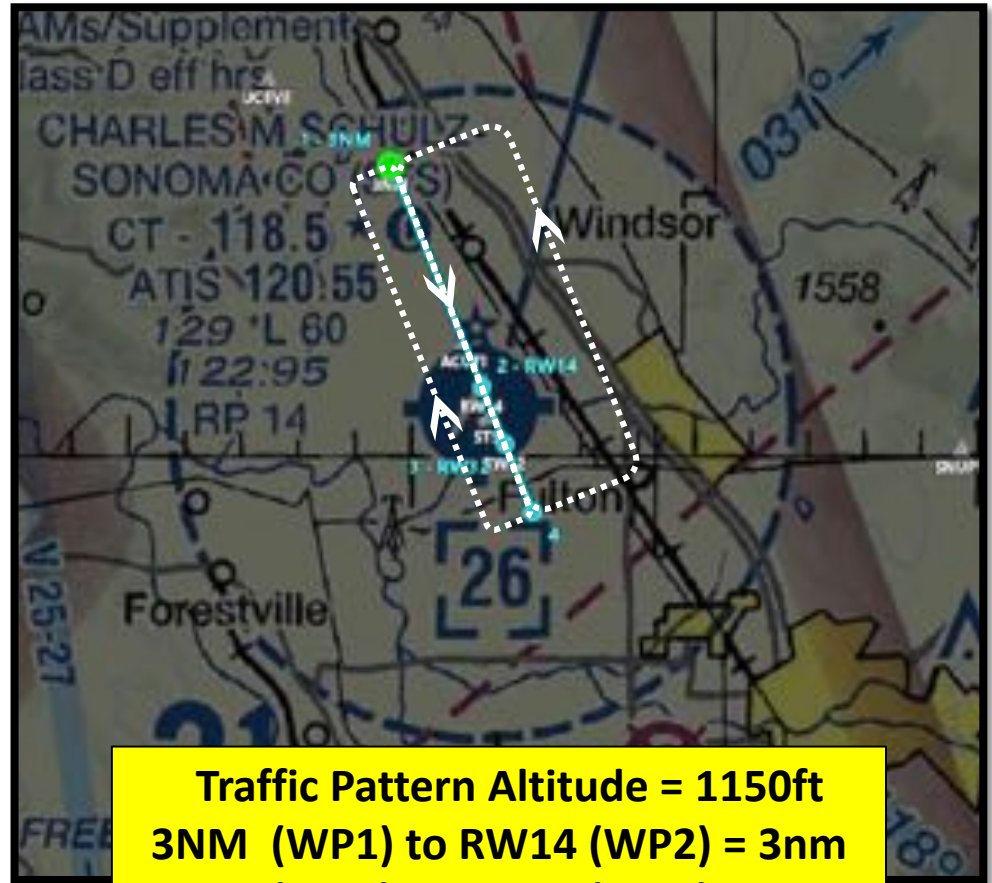






# Sonoma County Airport

- 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)

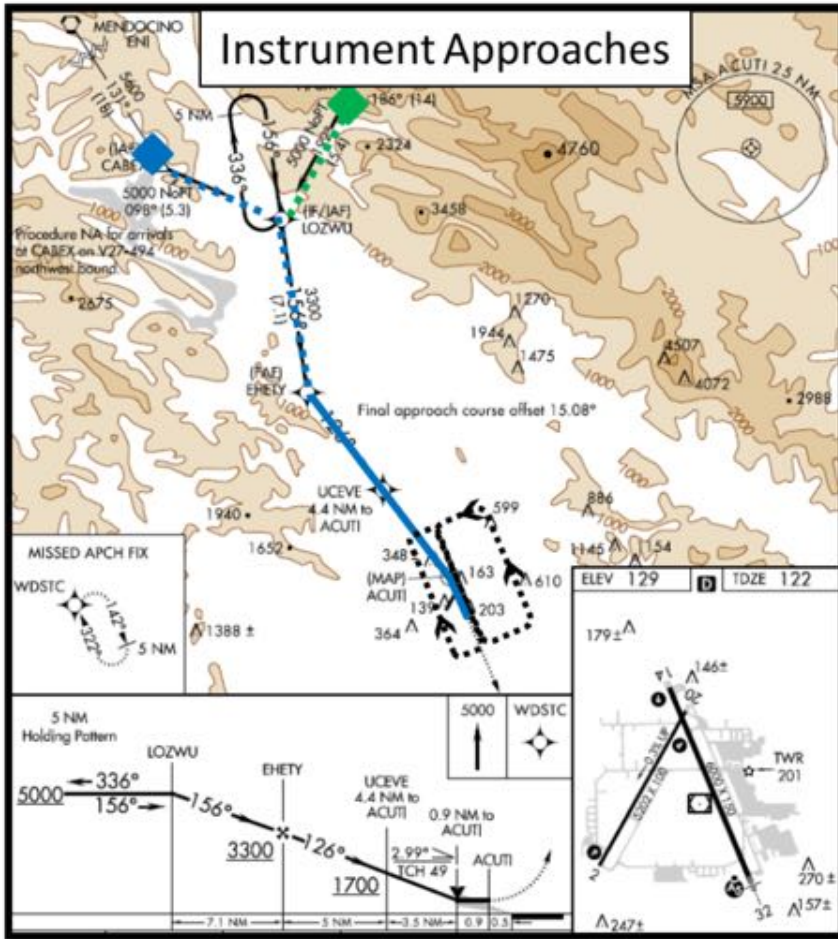


# Scenario Design

- 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)

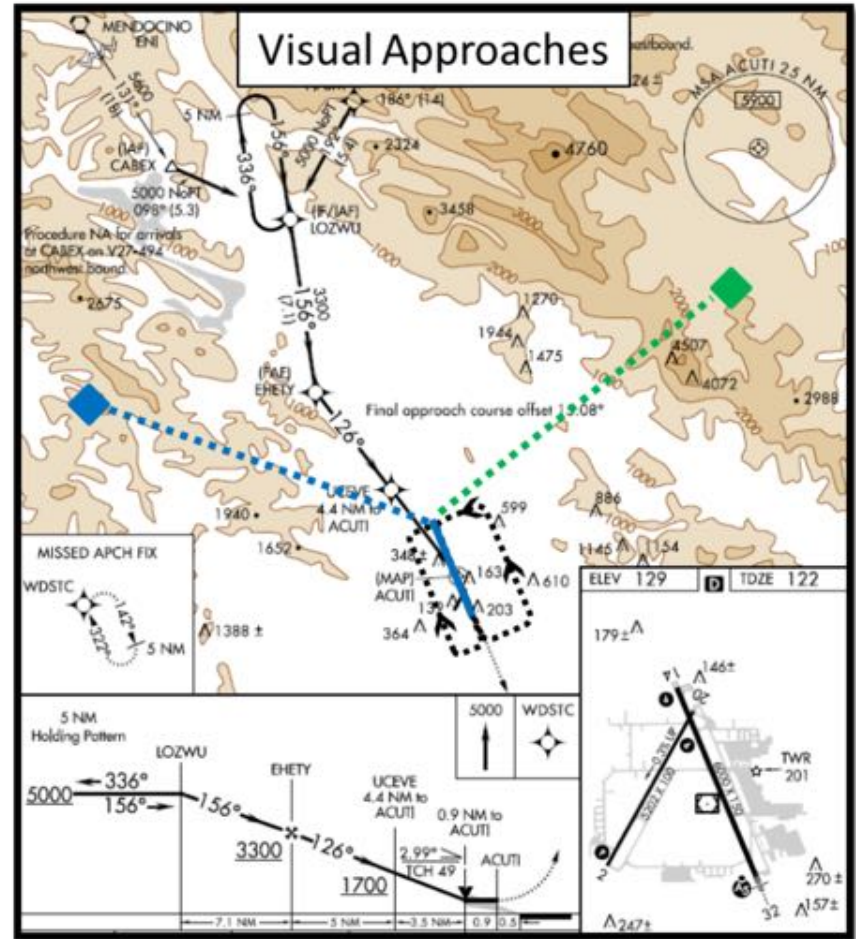


# Scenario Design



## 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:

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





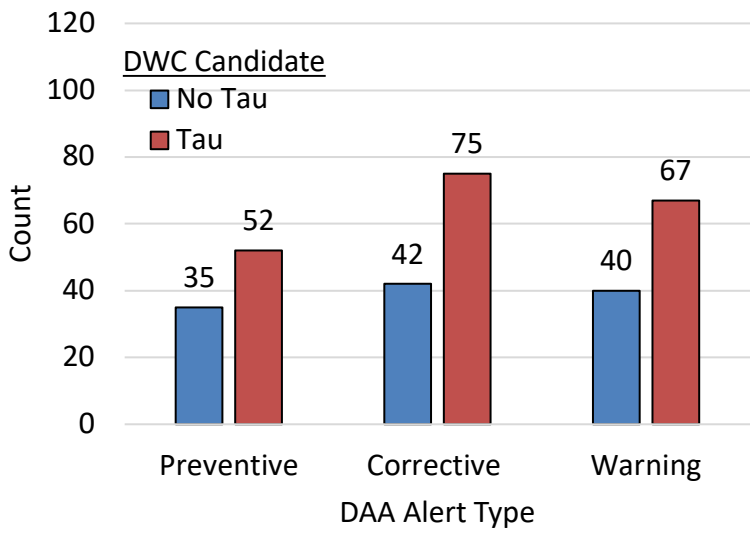
# **DAA ALERTING AND MEASURED RESPONSE**



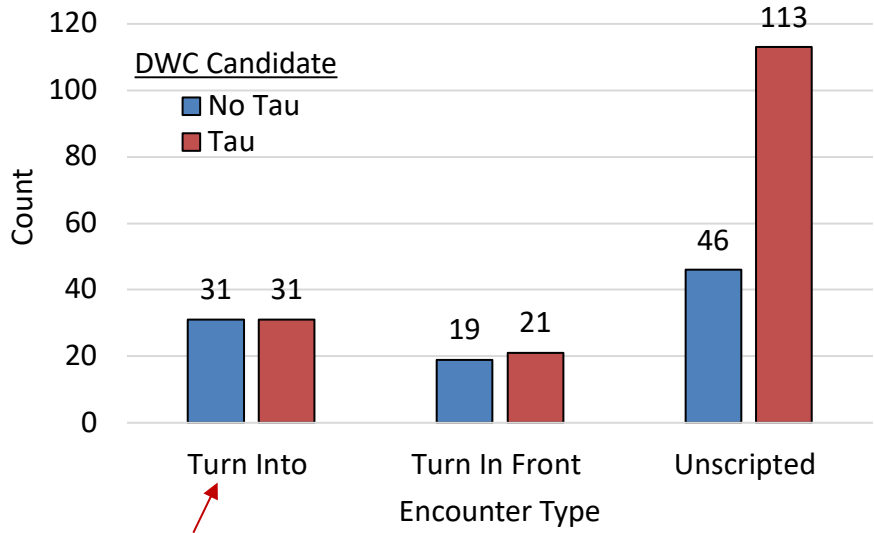
# DAA Alerting Statistics

- 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)



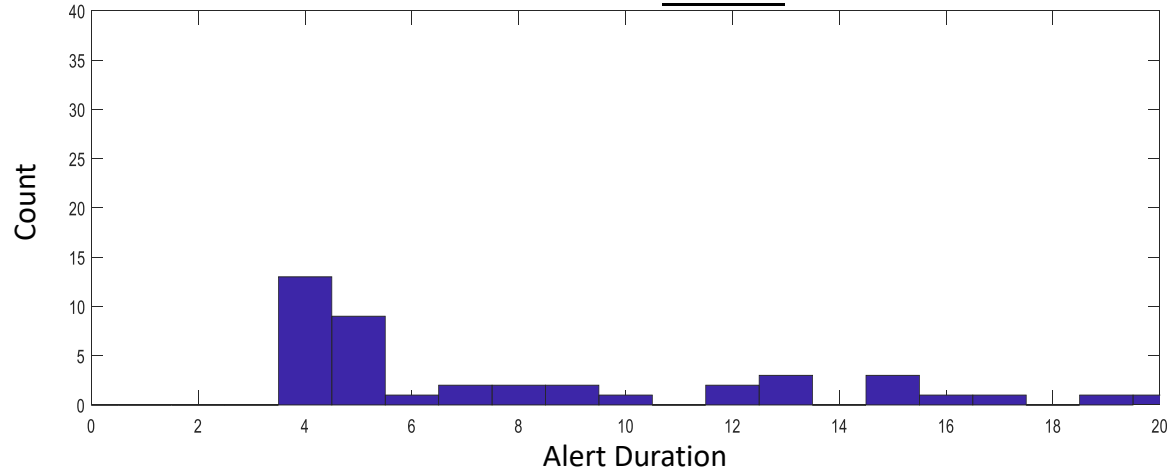
Desired alerts



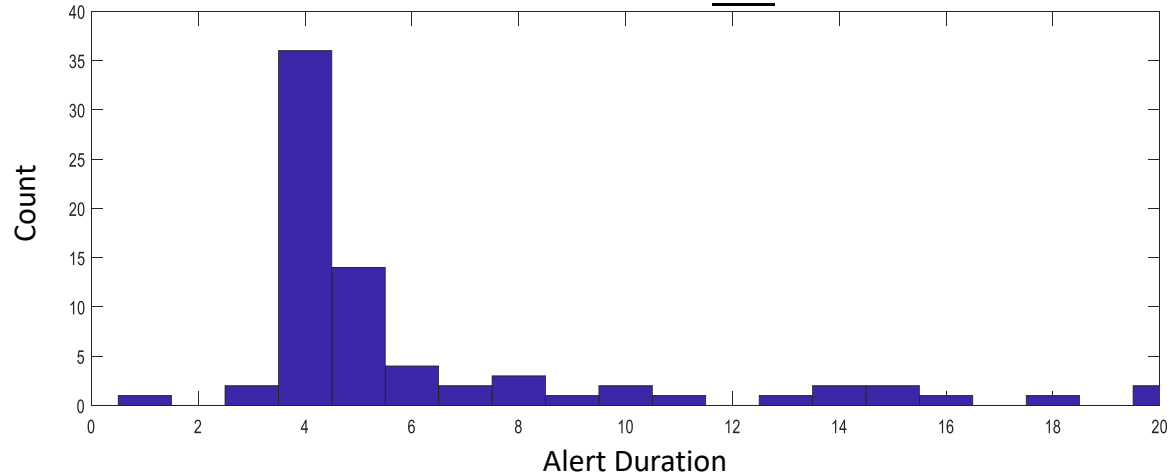
# Corrective Alert Duration

- 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

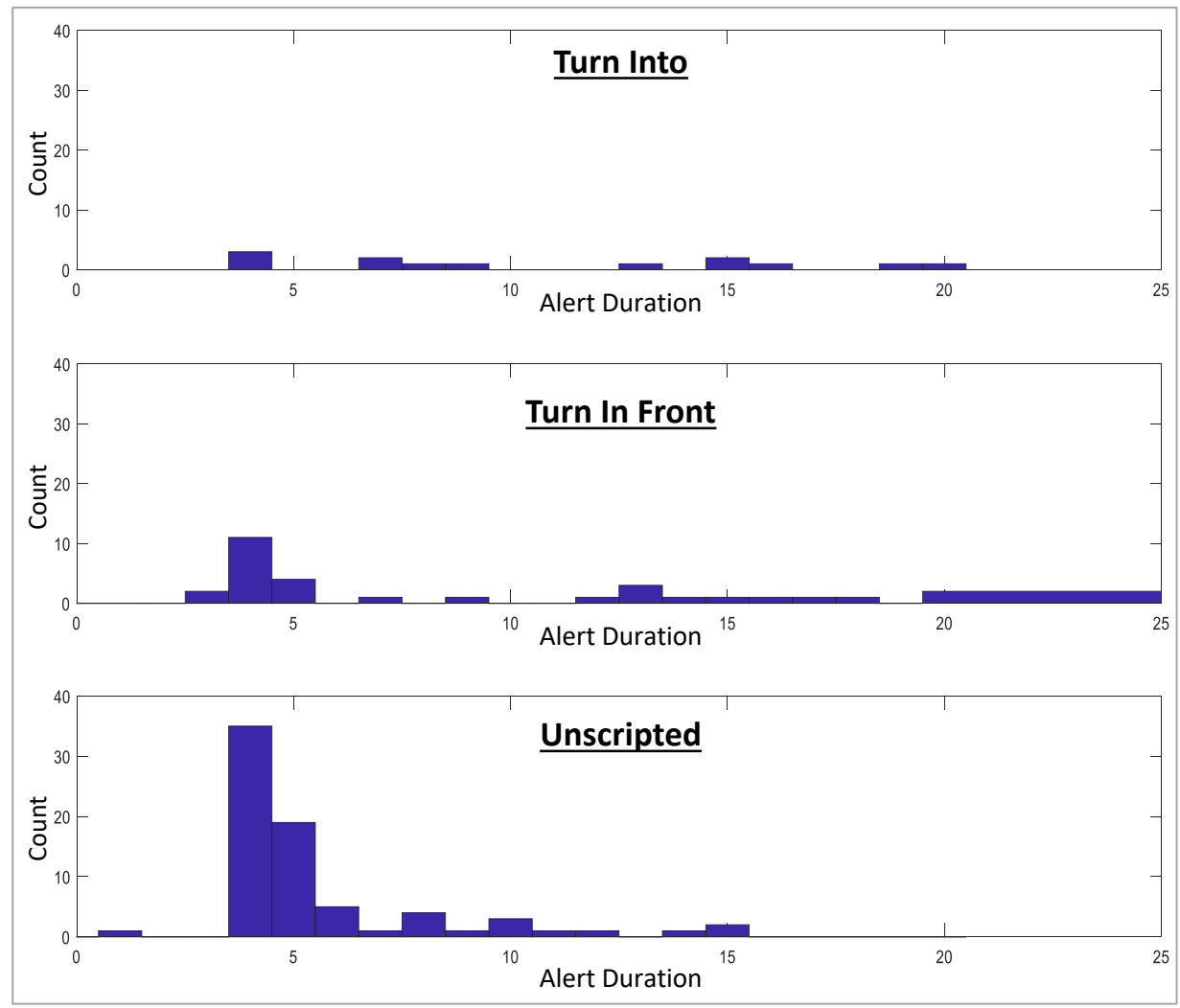




# Corrective Alert Duration

- 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

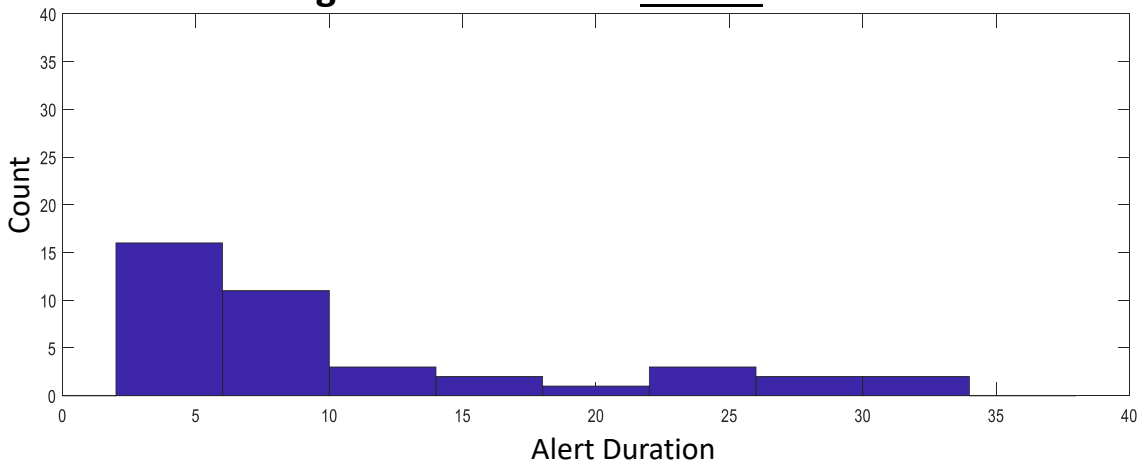




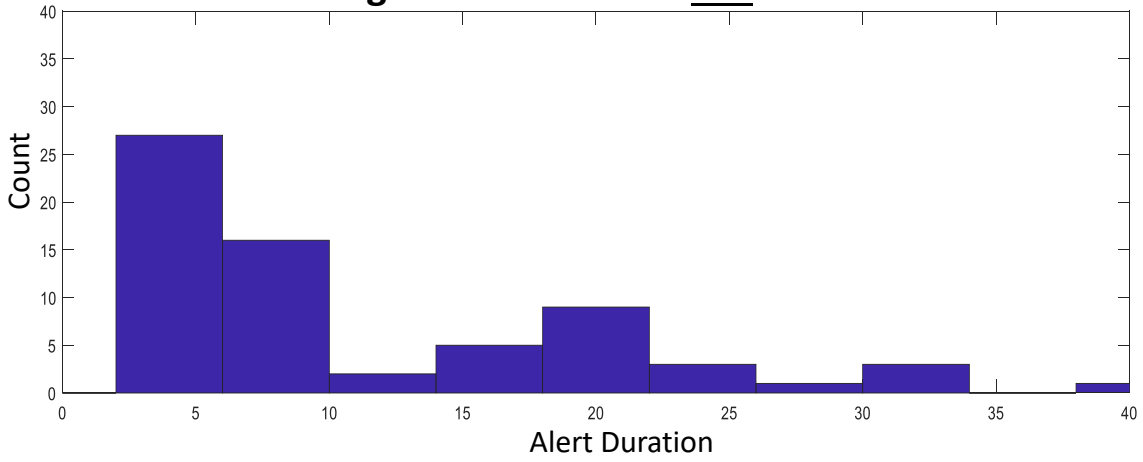
# Warning Alert Duration

- 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

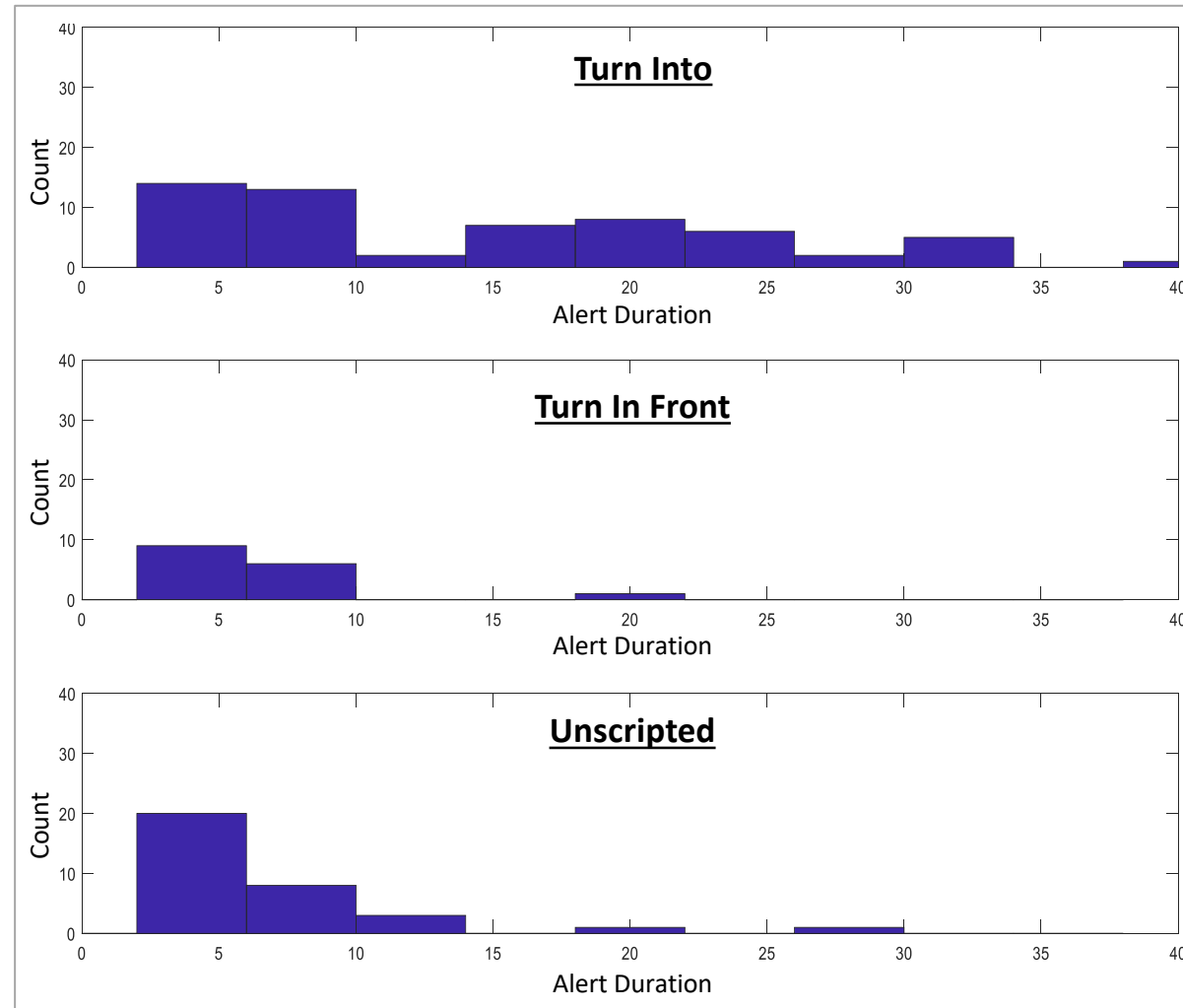




# Warning Alert Duration

- 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

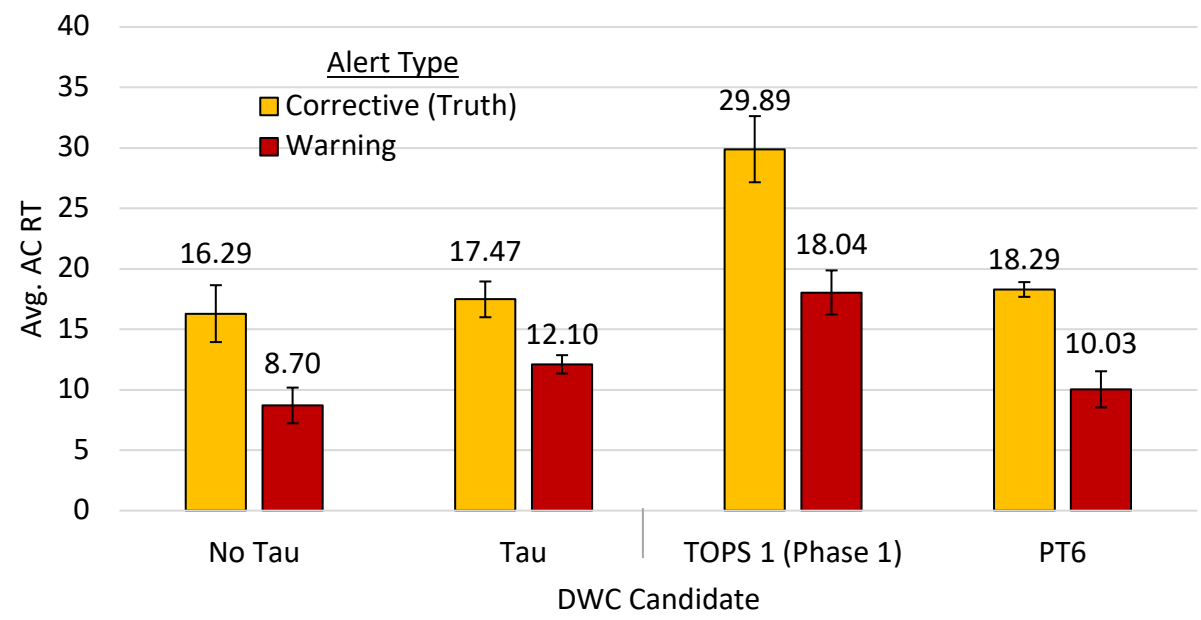




# Aircraft Response Time

- 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

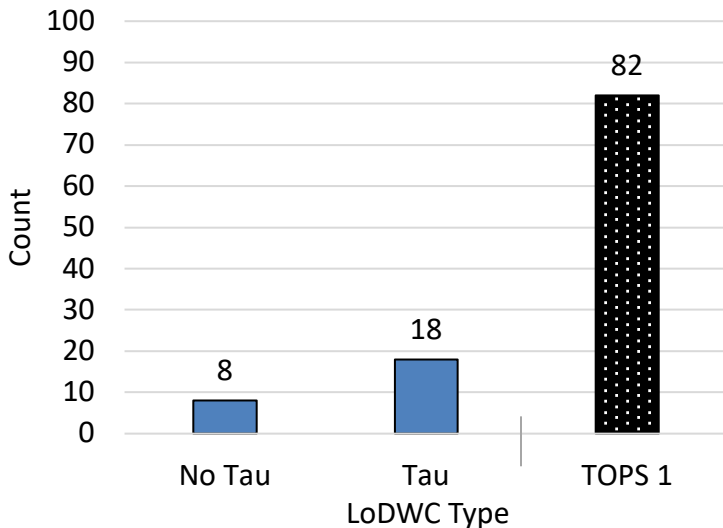




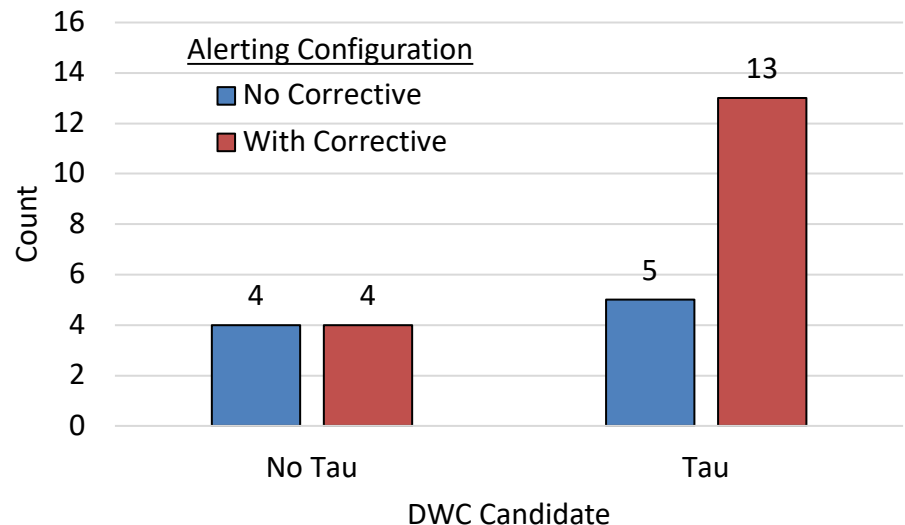
# Losses of DAA Well Clear (Counts)

- 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



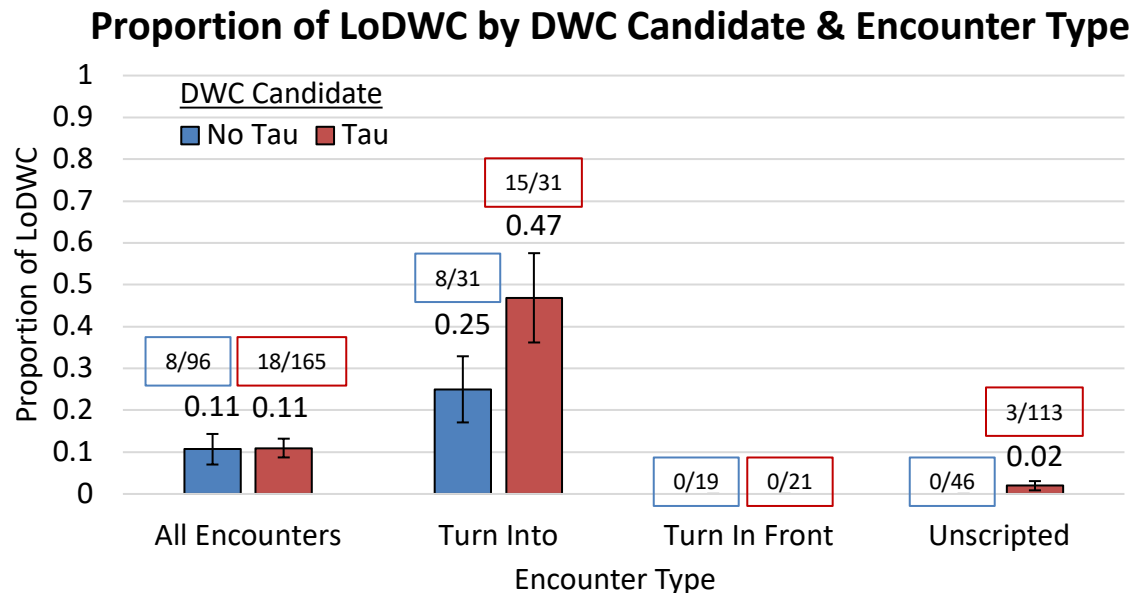
### # LoDWC by DWC Candidate & Alerting Configuration





# Losses of DAA Well Clear (Proportions)

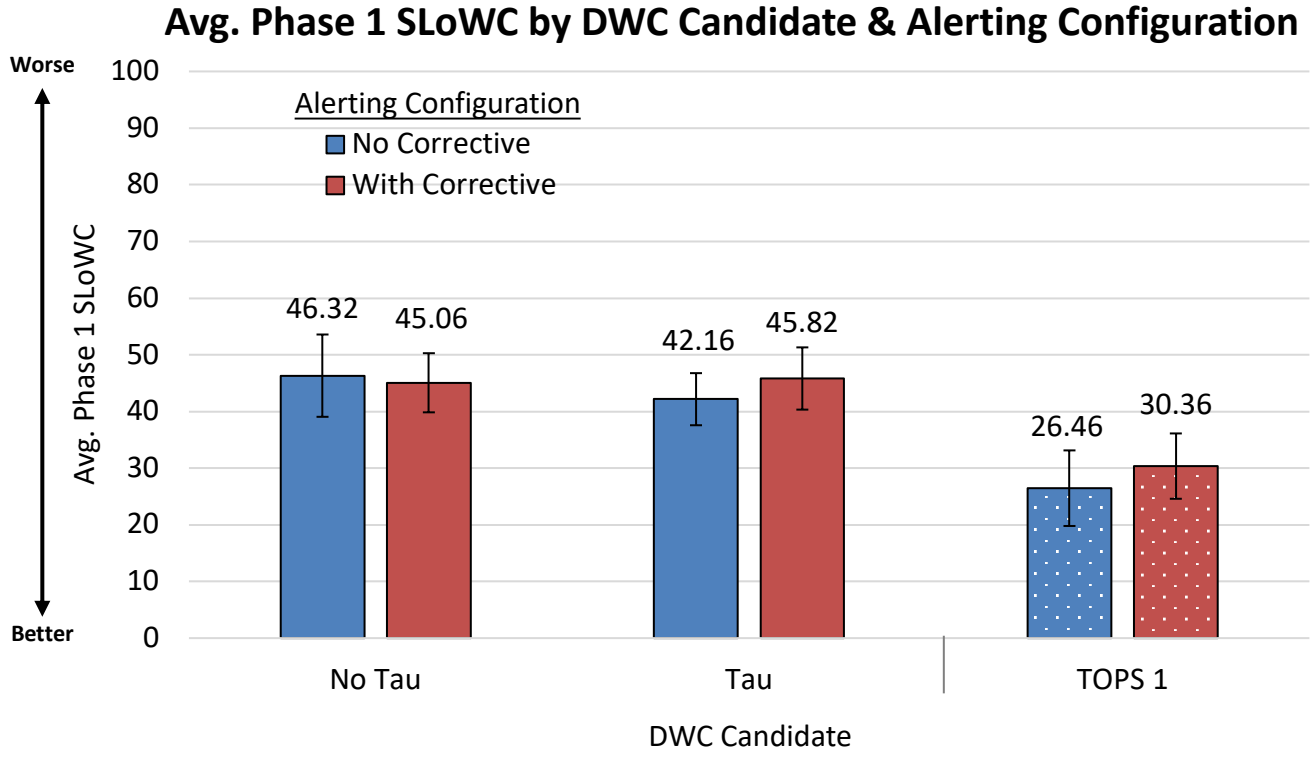
- Proportion of losses of DAA Well Clear (LoDWC)
  - # of LoDWC / # aircraft that generated a DAA Corrective or Warning
- For **All Encounters**, identical proportion of LoDWC between No Tau and Tau DWC candidates
- LoDWC was most common against **Turn Into** encounters
  - 32 total were scripted (per 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)

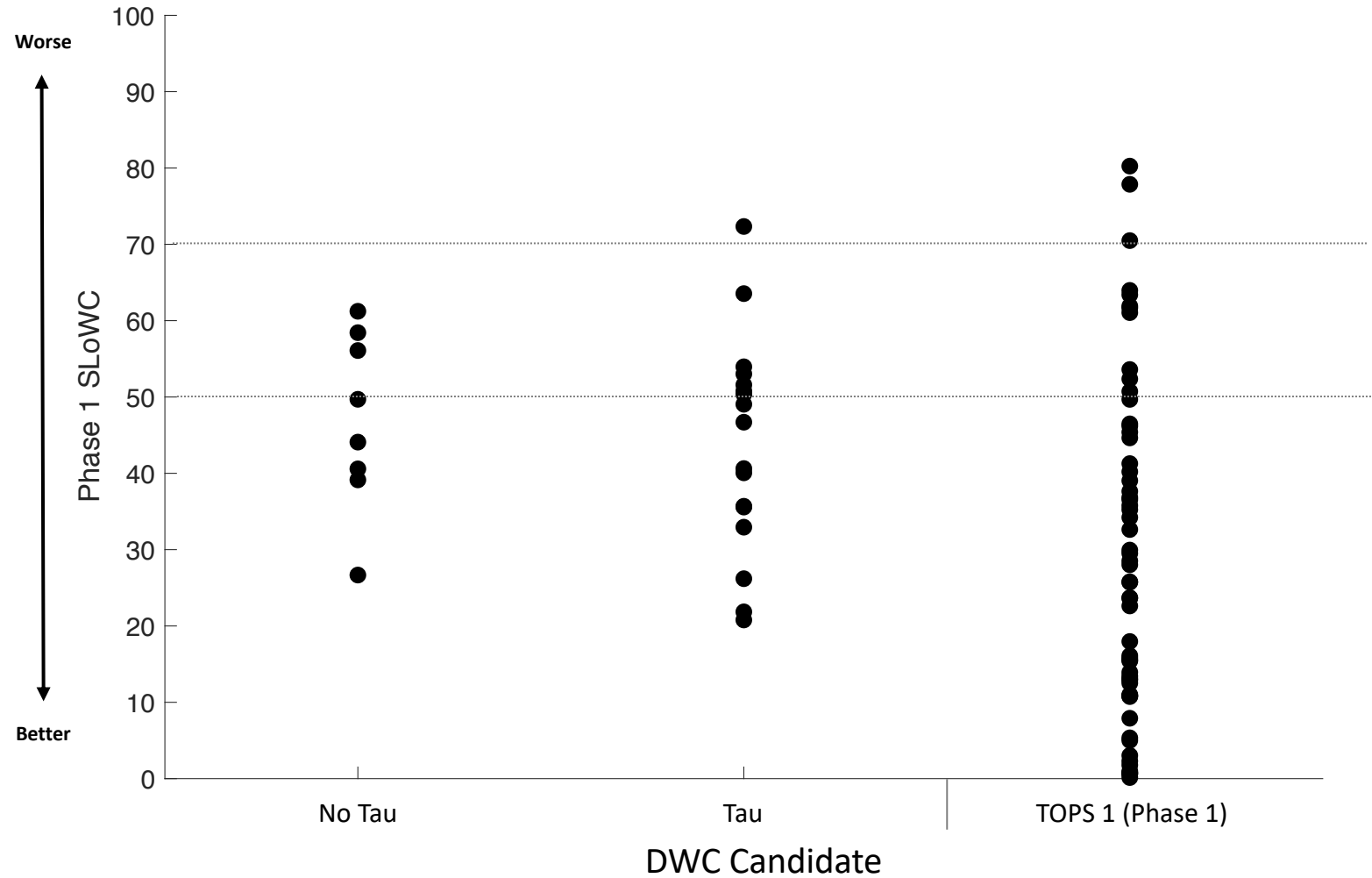
- Phase 1 SLoWC = % of the **Phase 1** DAA well clear volume (which includes tau) penetrated by intruder
  - Higher % = greater penetration
- No substantial effect of DWC candidate or alerting configuration
  - No Tau & Tau DWC candidates led to





# Losses of DAA Well Clear (Severity)

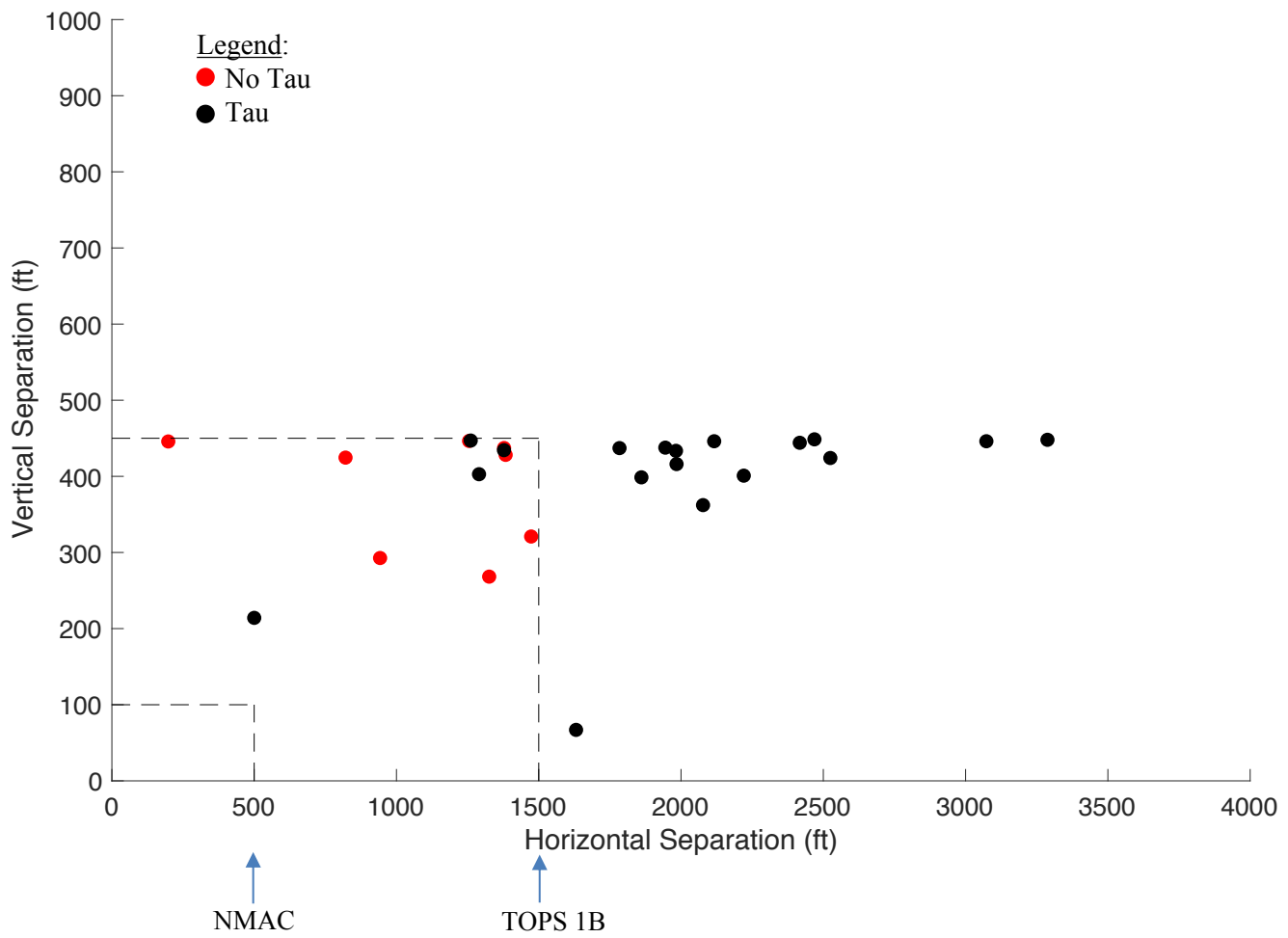
- Phase 1 SLoWC ranged overall from 20-72%
  - Highest SLoWC seen in With Corrective alerting configuration
- Fewer high-severity SLoWC with current DWC candidates than seen in TOPS 1





# 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)

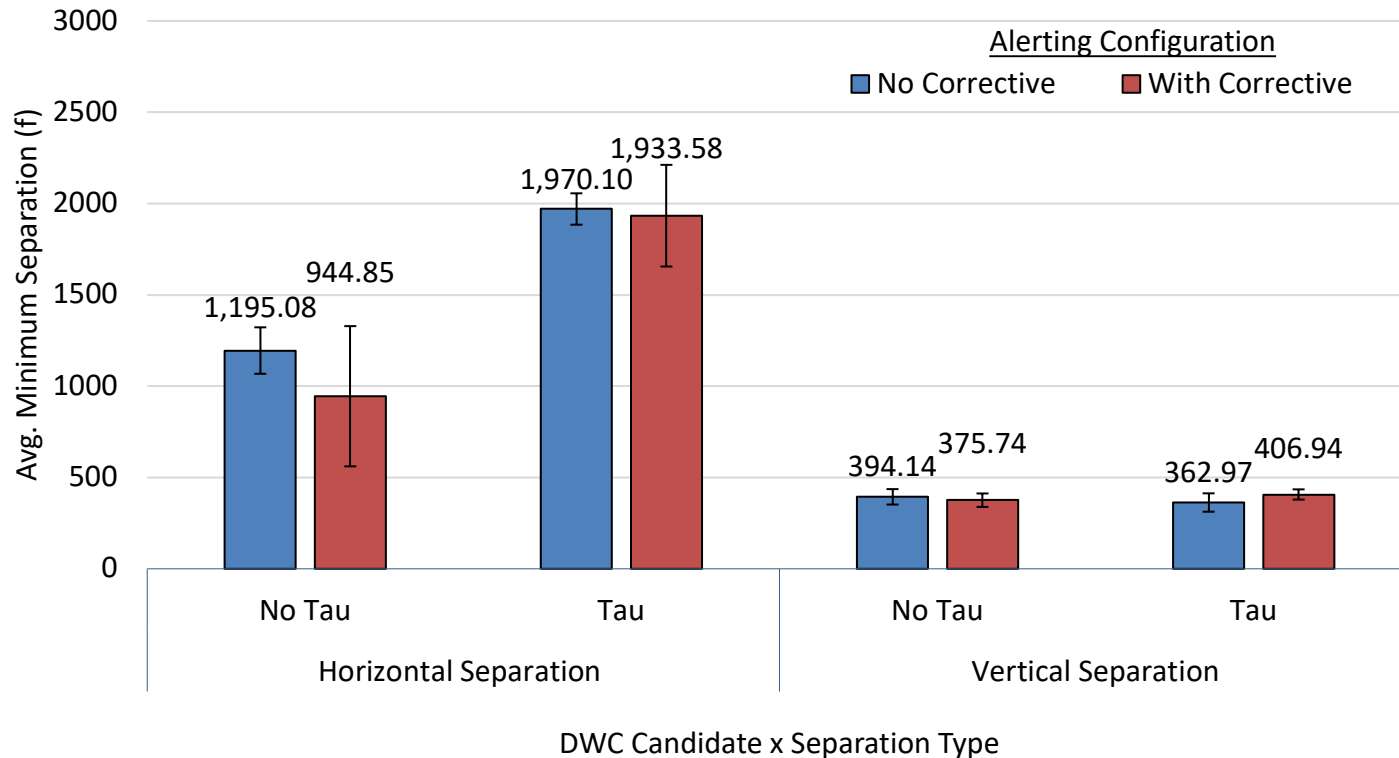




# Avg. Minimum Separation at Closest Point in LoDWC

- 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**



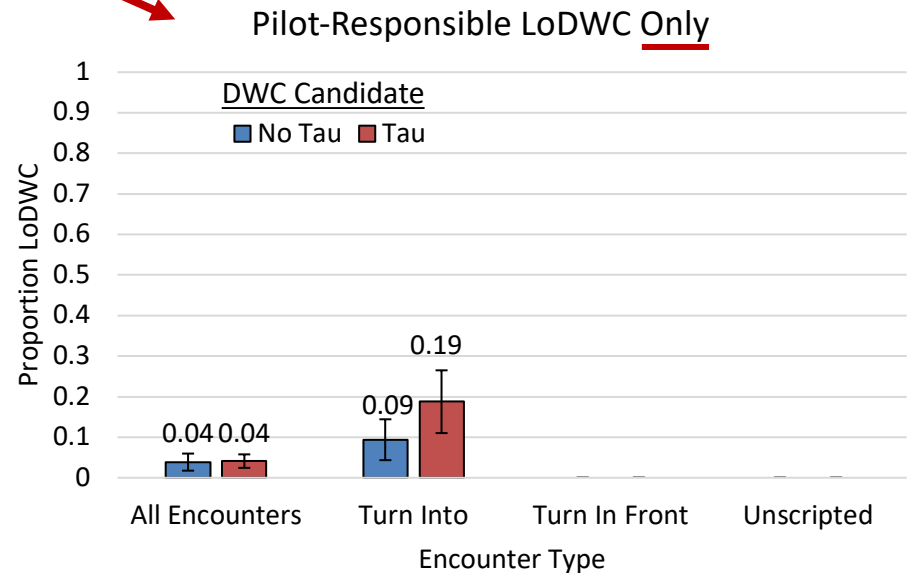
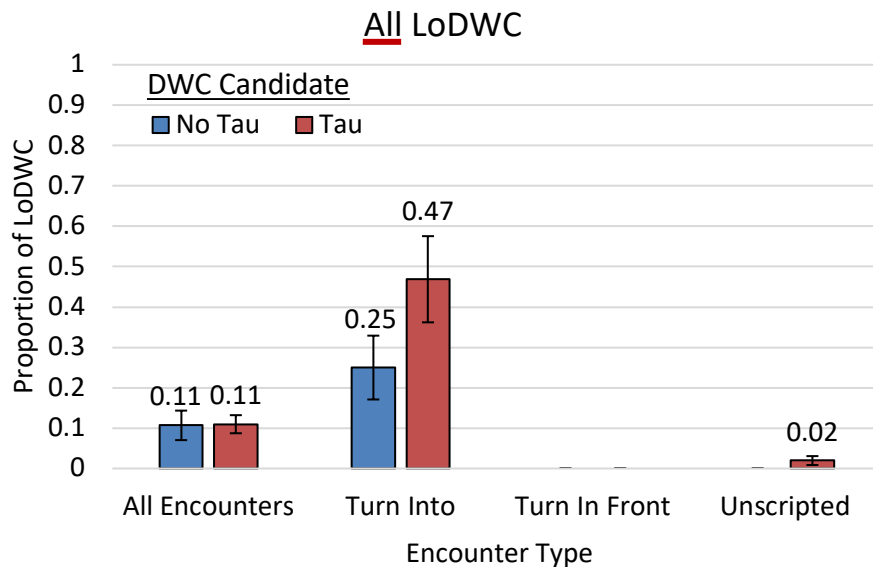


# Losses of DAA Well Clear (Causes)

- 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
<b>Total</b>		<b>8</b>	<b>18</b>

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

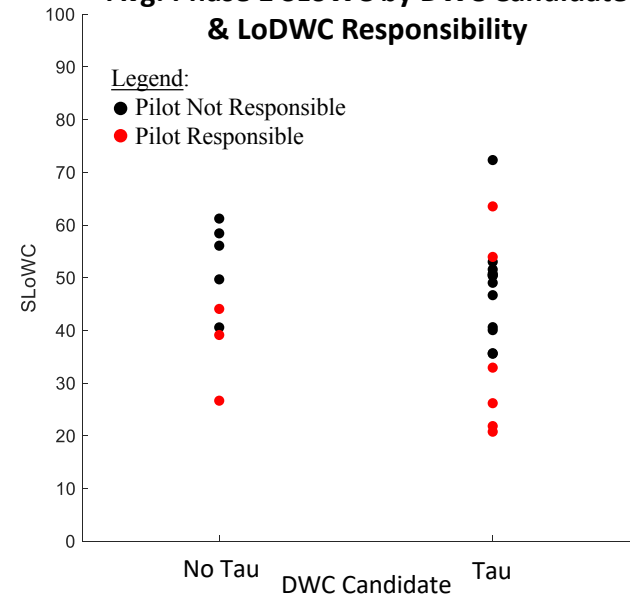




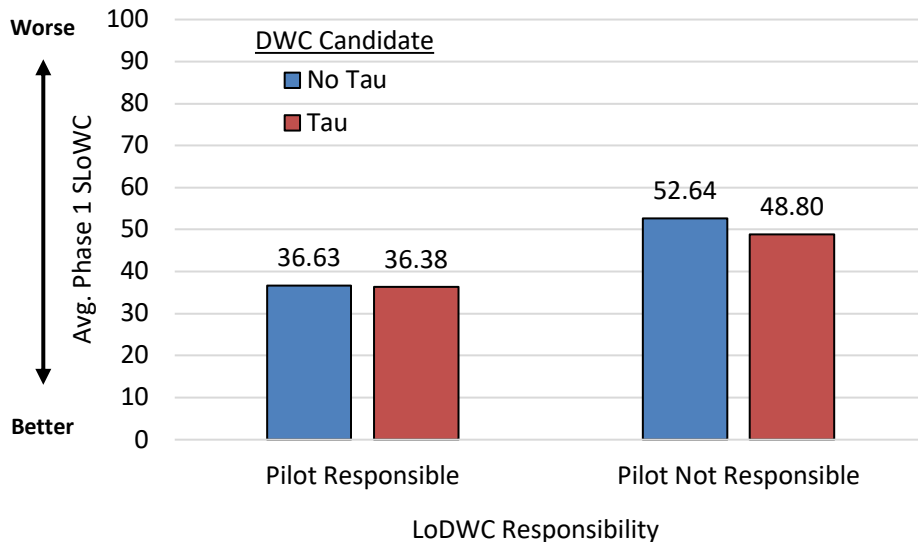
# Losses of DAA Well Clear (Causes)

- 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

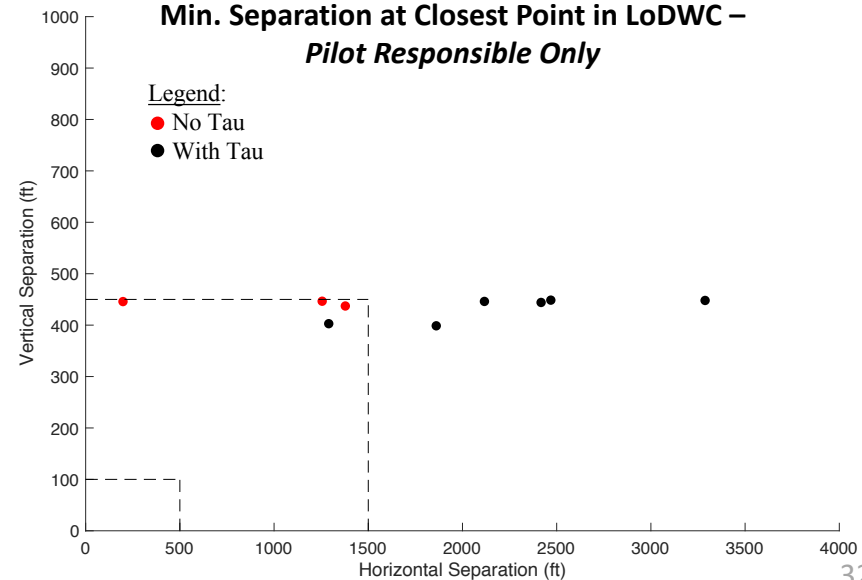
**Avg. Phase 1 SLoWC by DWC Candidate & LoDWC Responsibility**



**Avg. Phase 1 SLoWC by DWC Candidate & LoDWC Responsibility**



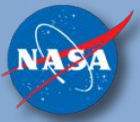
**Min. Separation at Closest Point in LoDWC – Pilot Responsible Only**







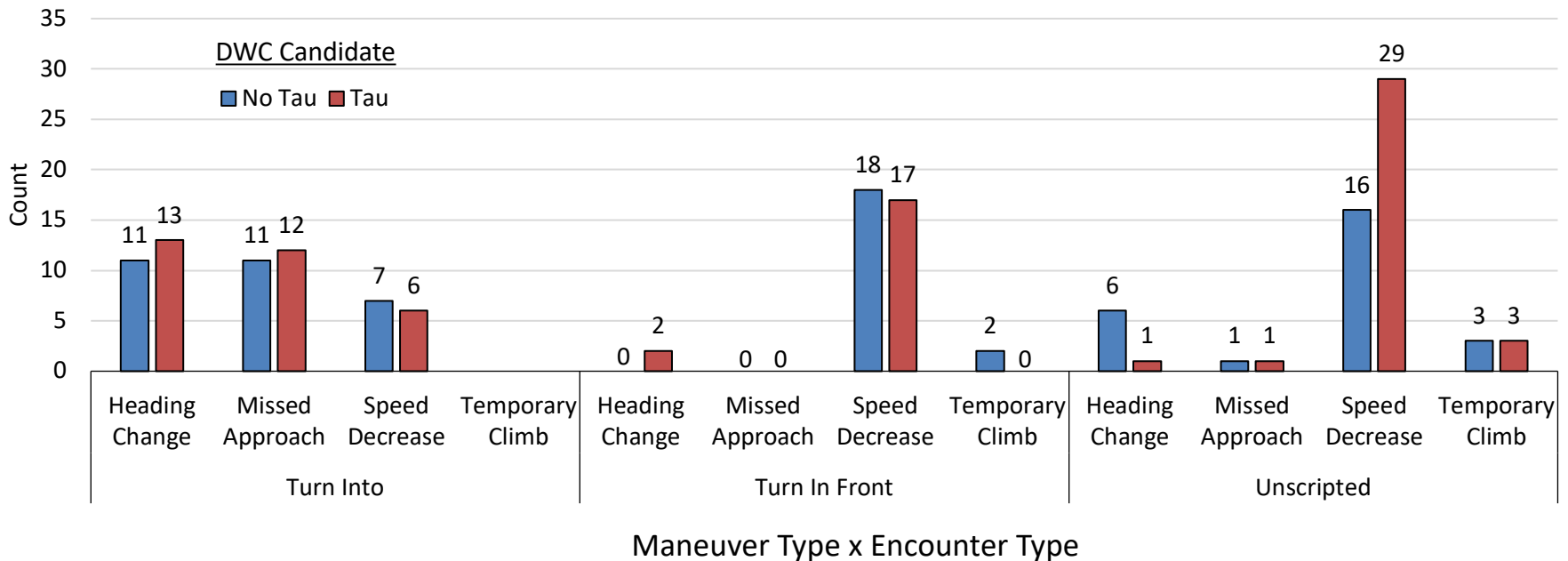
# **MANEUVERING & ATC INTEROPERABILITY**



# 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

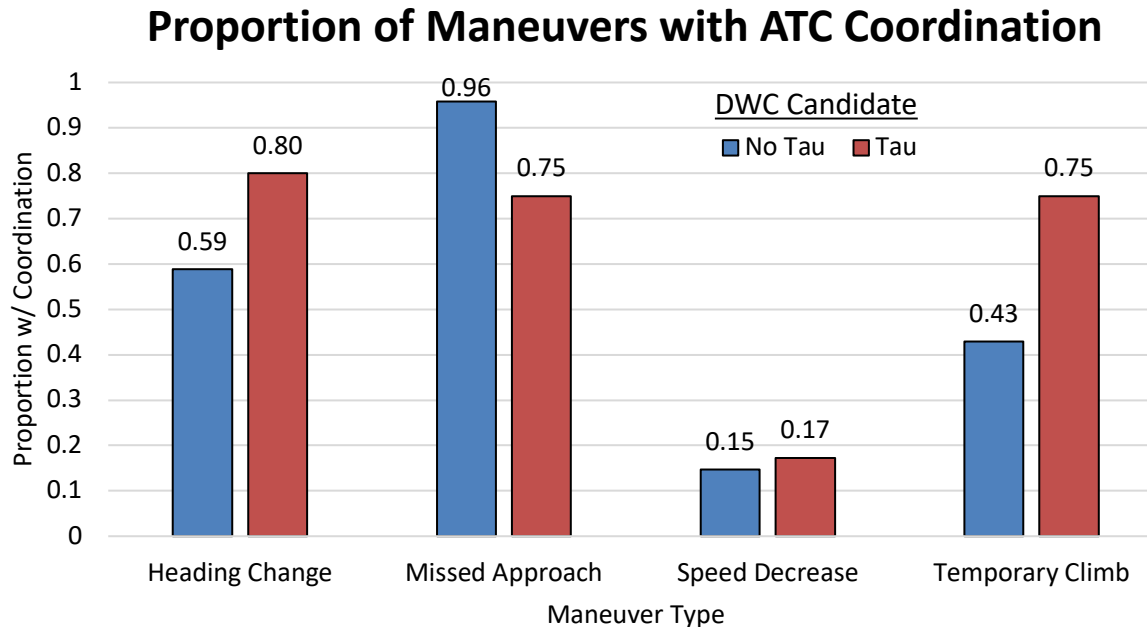
### Initial Maneuver Type by DWC Candidate, Maneuver Type & Encounter Type





# 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



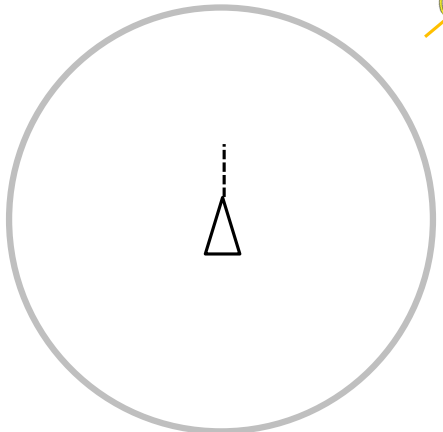
# BACKUP



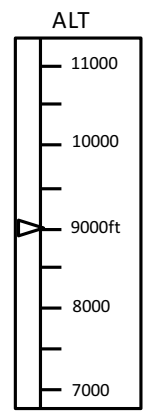
# DAA Alerting & Guidance

## No Corrective

Preventive (Truth) Alert

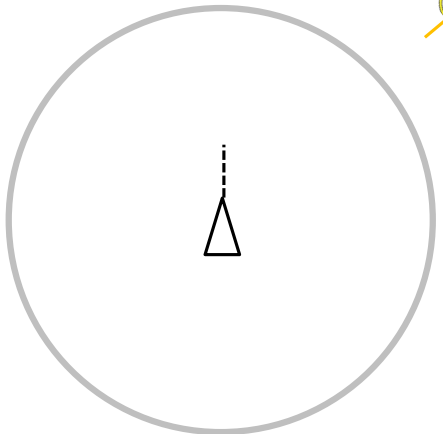


Inner Range Ring

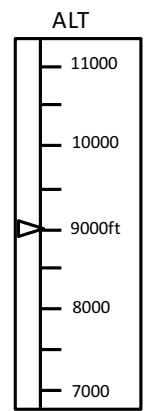


Altitude Tape

Corrective (Truth) Alert



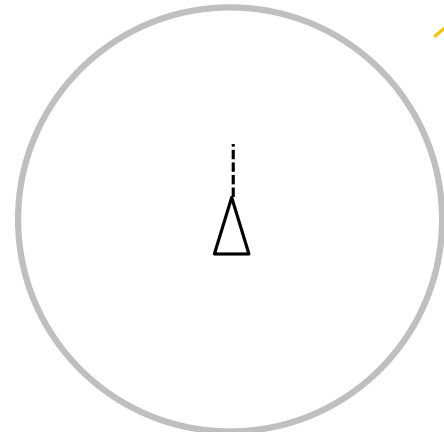
Inner Range Ring



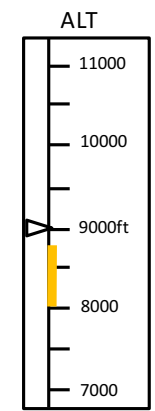
Altitude Tape

## With Corrective

Preventive (Truth) Alert

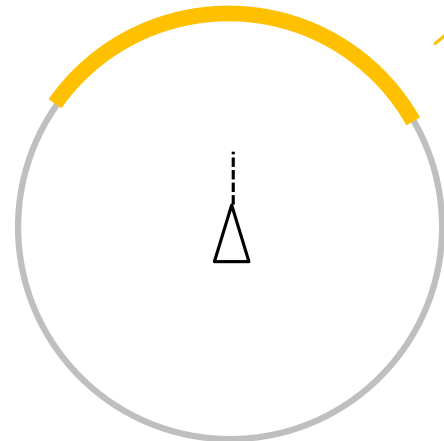


Inner Range Ring

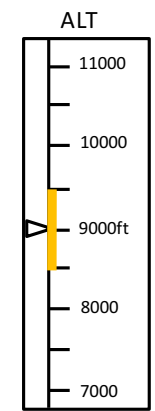


Altitude Tape

Corrective (Truth) Alert



Inner Range Ring



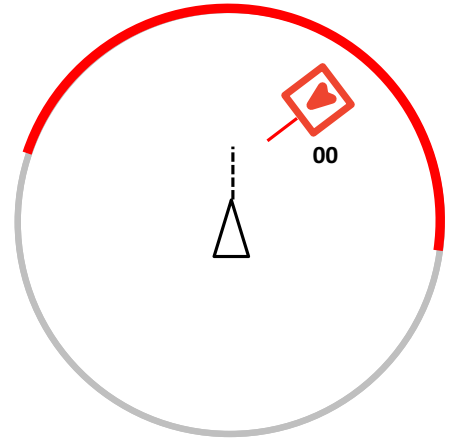
Altitude Tape



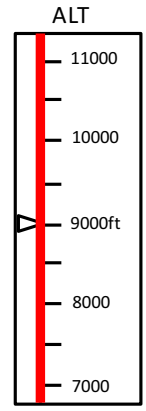
# DAA Alerting & Guidance

## No Corrective

Warning (Truth) Alert



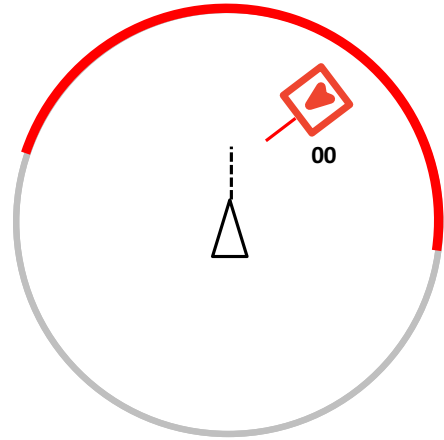
Inner Range Ring



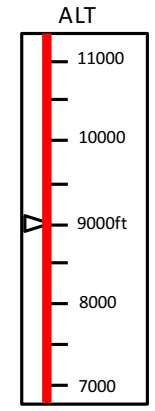
Altitude Tape

## With Corrective

Warning (Truth) Alert

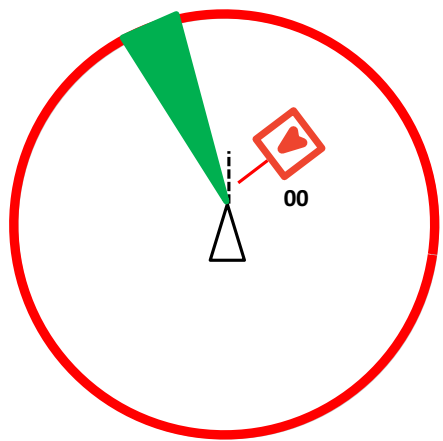


Inner Range Ring

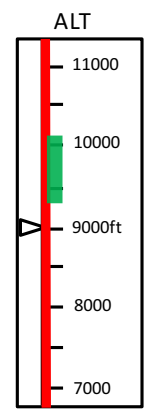


Altitude Tape

Regain DWC Guidance

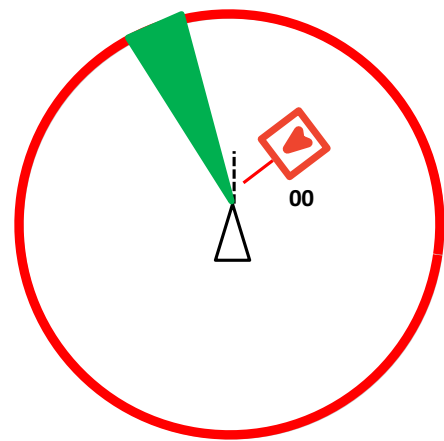


Inner Range Ring

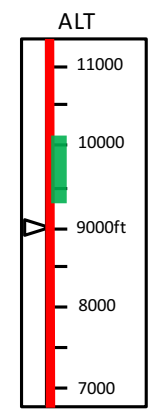


Altitude Tape

Regain DWC Guidance



Inner Range Ring

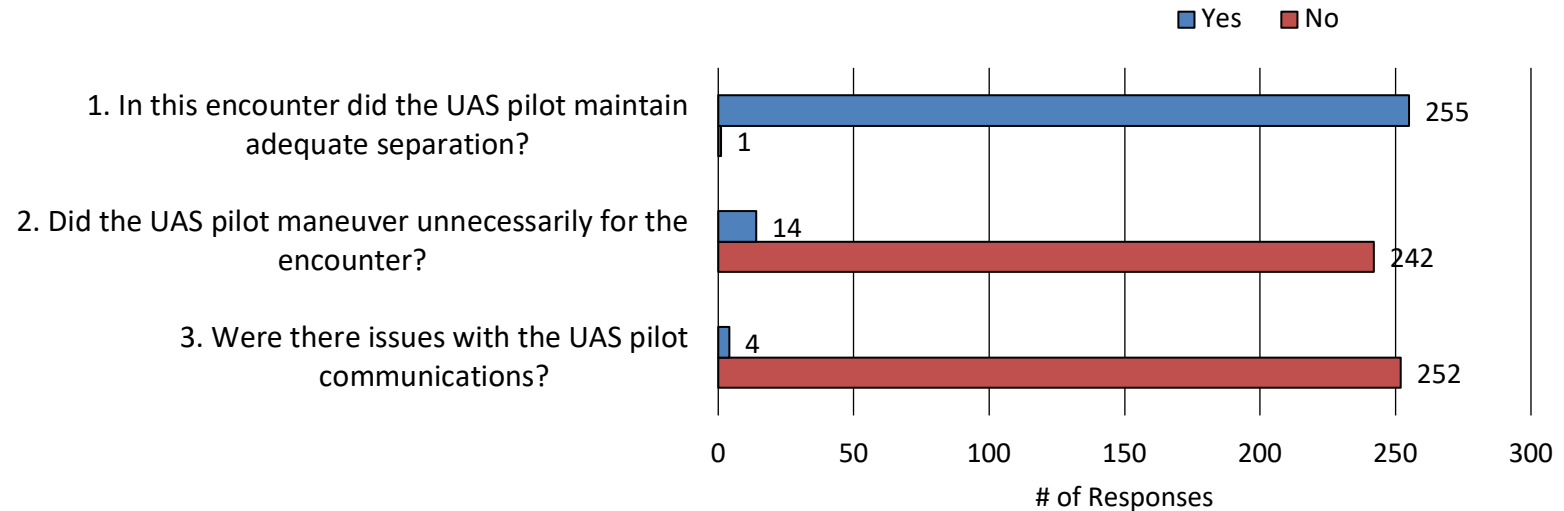


Altitude Tape



# Controller & Pilot Feedback

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



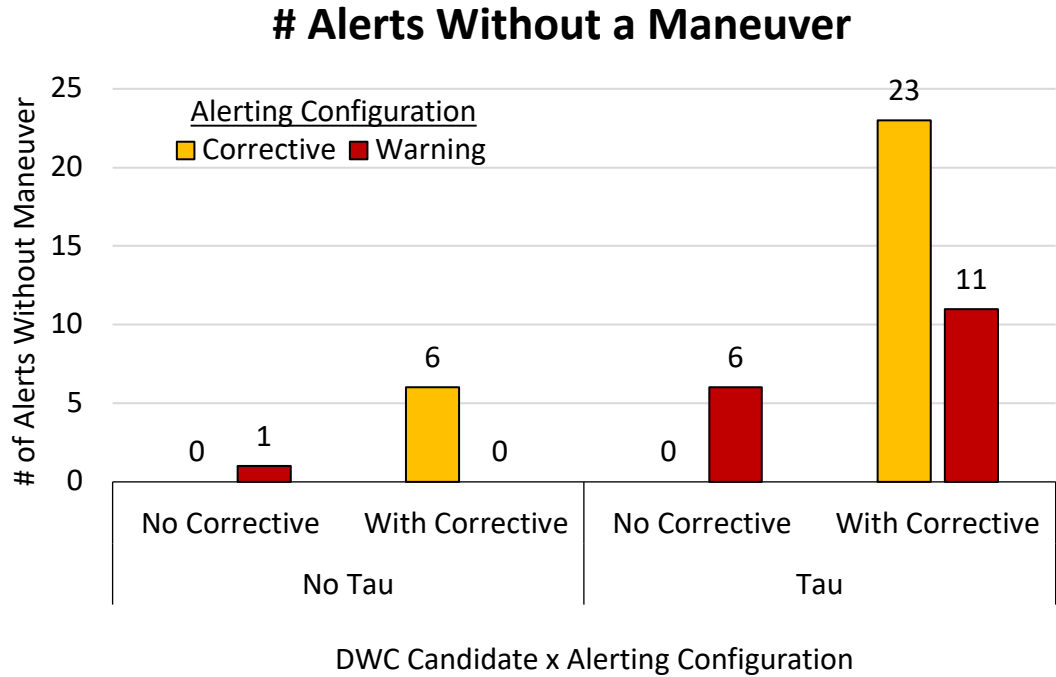
- Tower rated UAS behaviors as overwhelmingly appropriate
  - UA pilots were able to detect appropriate traffic
  - Disruptive turn-outs on instrument approach where pilots should have executed missed approach
  - 1.5 nm separation on approach worked for simulation
- Pilot responses to traffic on final 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

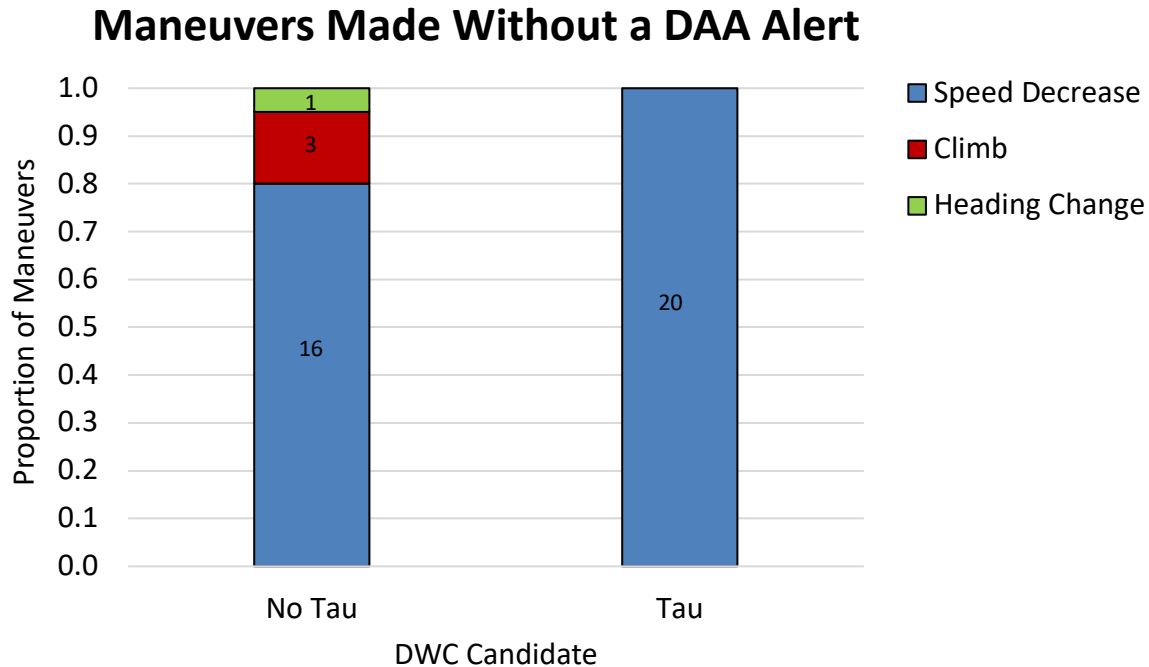
- Tau DWC candidate had far more instances of a DAA alert that did not lead to a UAS maneuver
  - No Tau = 7 alerts w/o maneuver
  - Tau = 40 alerts w/o maneuver
- 62% (29/47) of these cases were against a Corrective alert
- **None of these alerts resulted in a loss of DWC**
  - Avg. alert duration =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

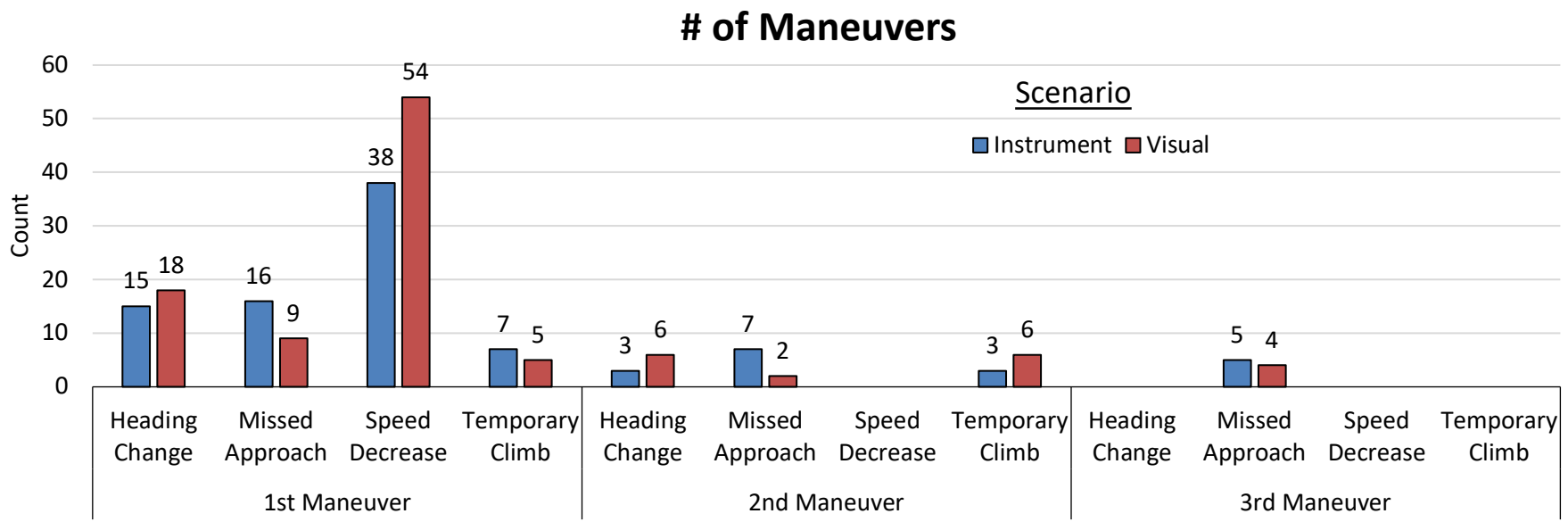
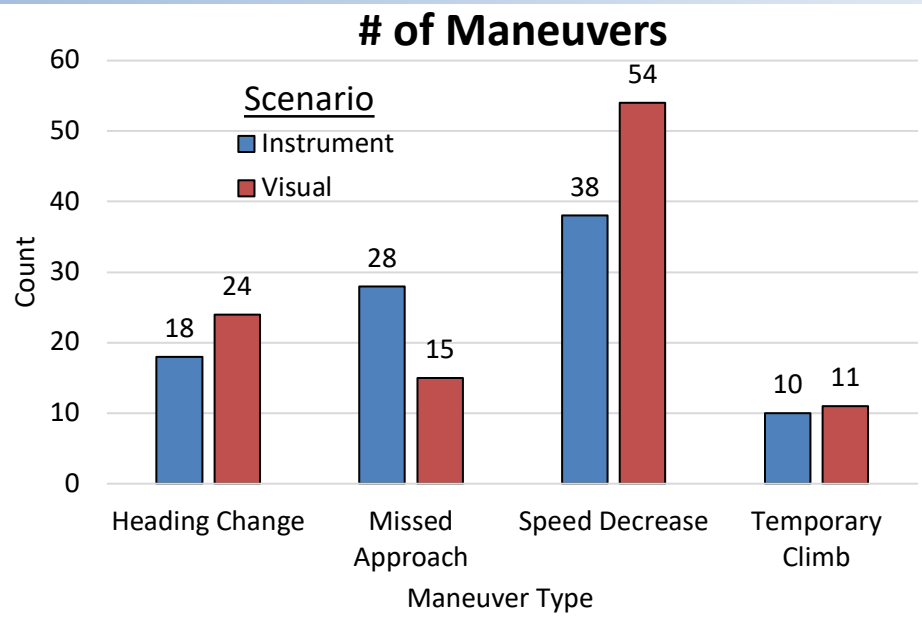
- Tau candidate was far more likely to alert to unscripted traffic, particularly jet traffic and traffic turning to base
  - Jet traffic approached KSTS from the NE before getting established on a 5nm straight-in; during the Instrument approach scenario, it briefly pointed at UA
- Discrepancy between 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
<b>Total</b>	<b>18</b>	<b>70</b>	<b>26</b>	<b>38</b>



# 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

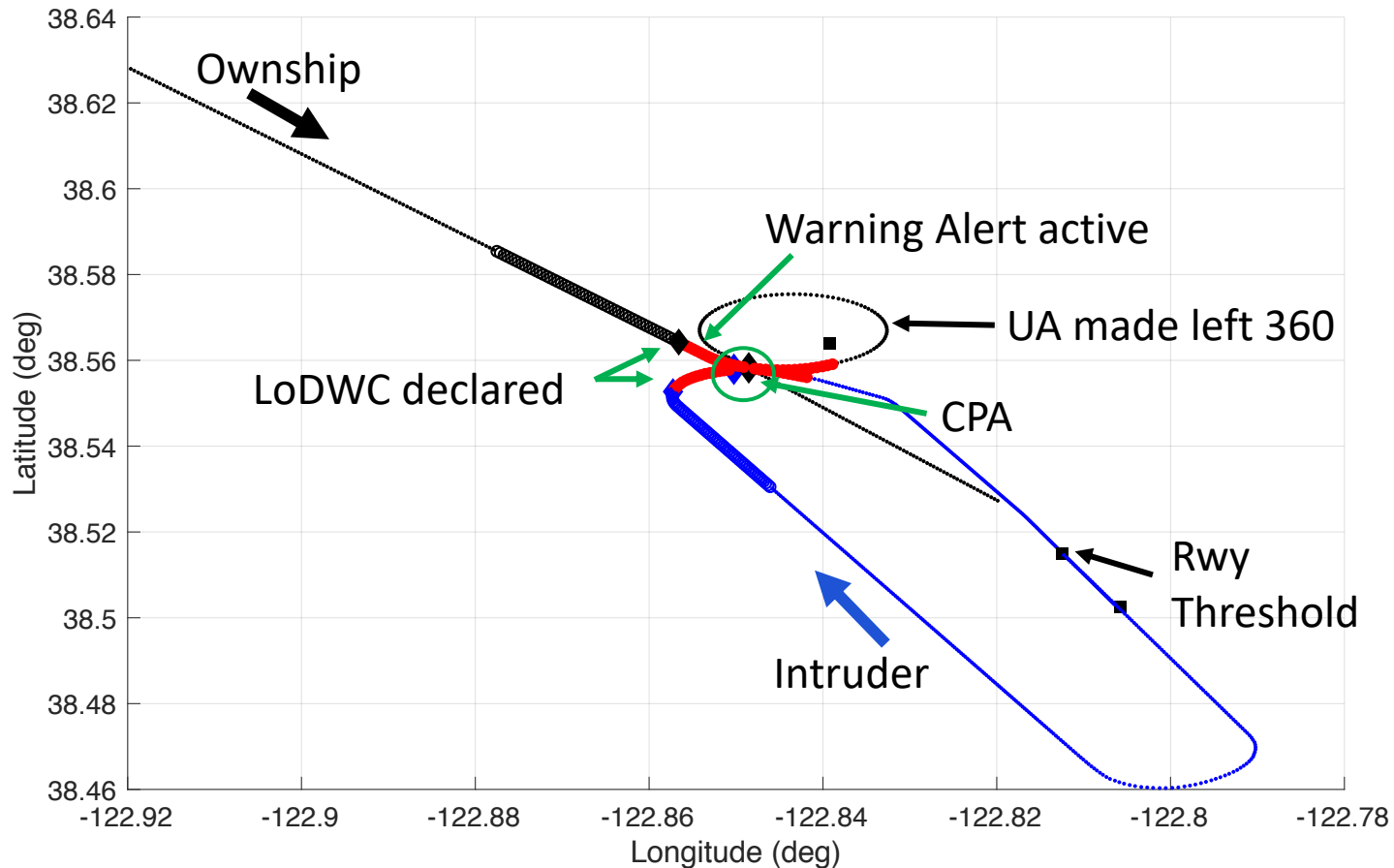


Maneuver Type x Maneuver Order



# Highest SLoWC Encounter

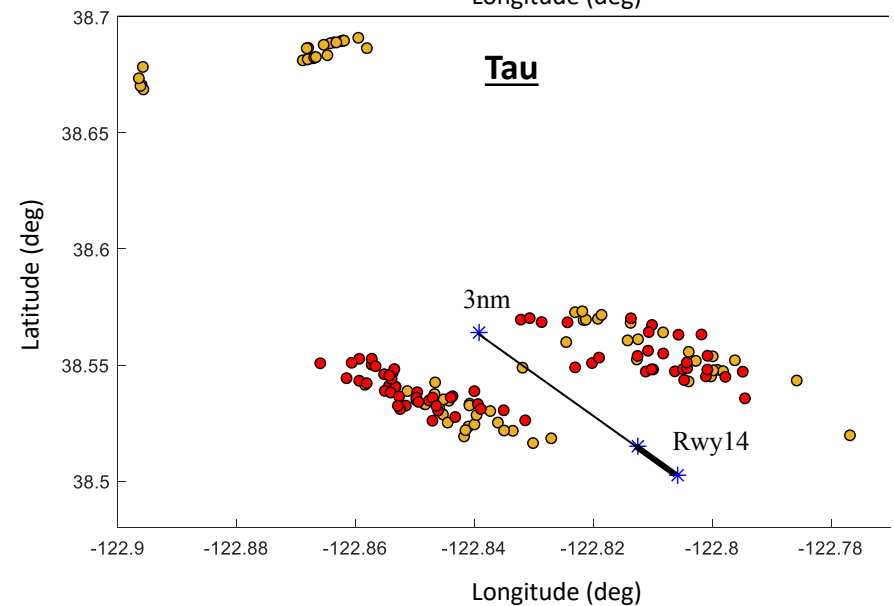
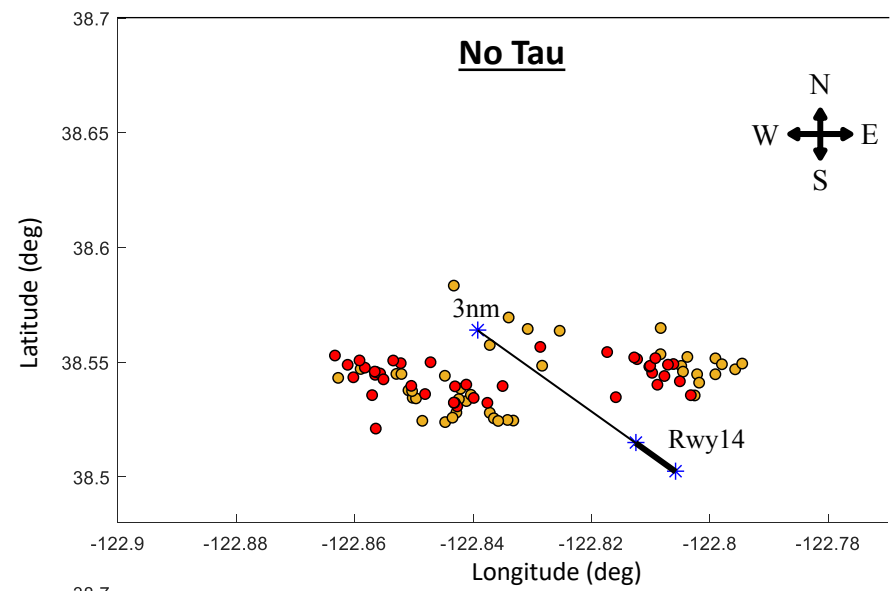
- Worst case was with the Tau DWC candidate, With Corrective alert config.
  - Instrument scenario
  - ‘Late Acceleration’ – *lost DWC at the same time it became a warning*
  - Pilot exacerbated it by turning with the traffic and delaying a climb





# Intruder Location at First Alert

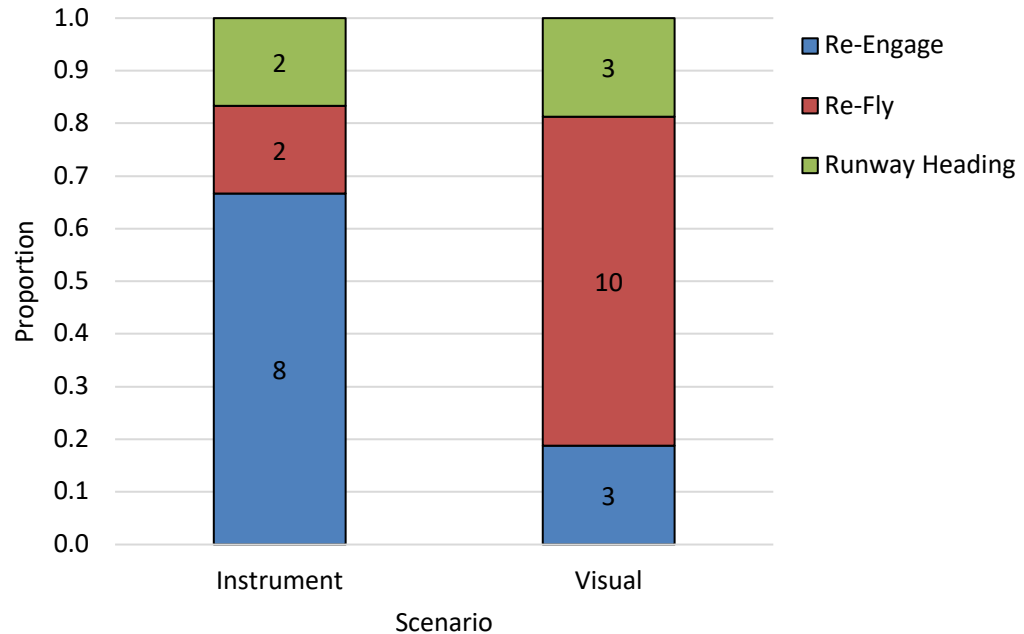
- No Tau candidate had fewer alerts
  - None occurred far away from the 2 downwind legs
- Tau candidate had more alerts overall with several occurring far away from runway
  - Tau candidate was more consistent in *where* the intruder was at first alert





# Return Type

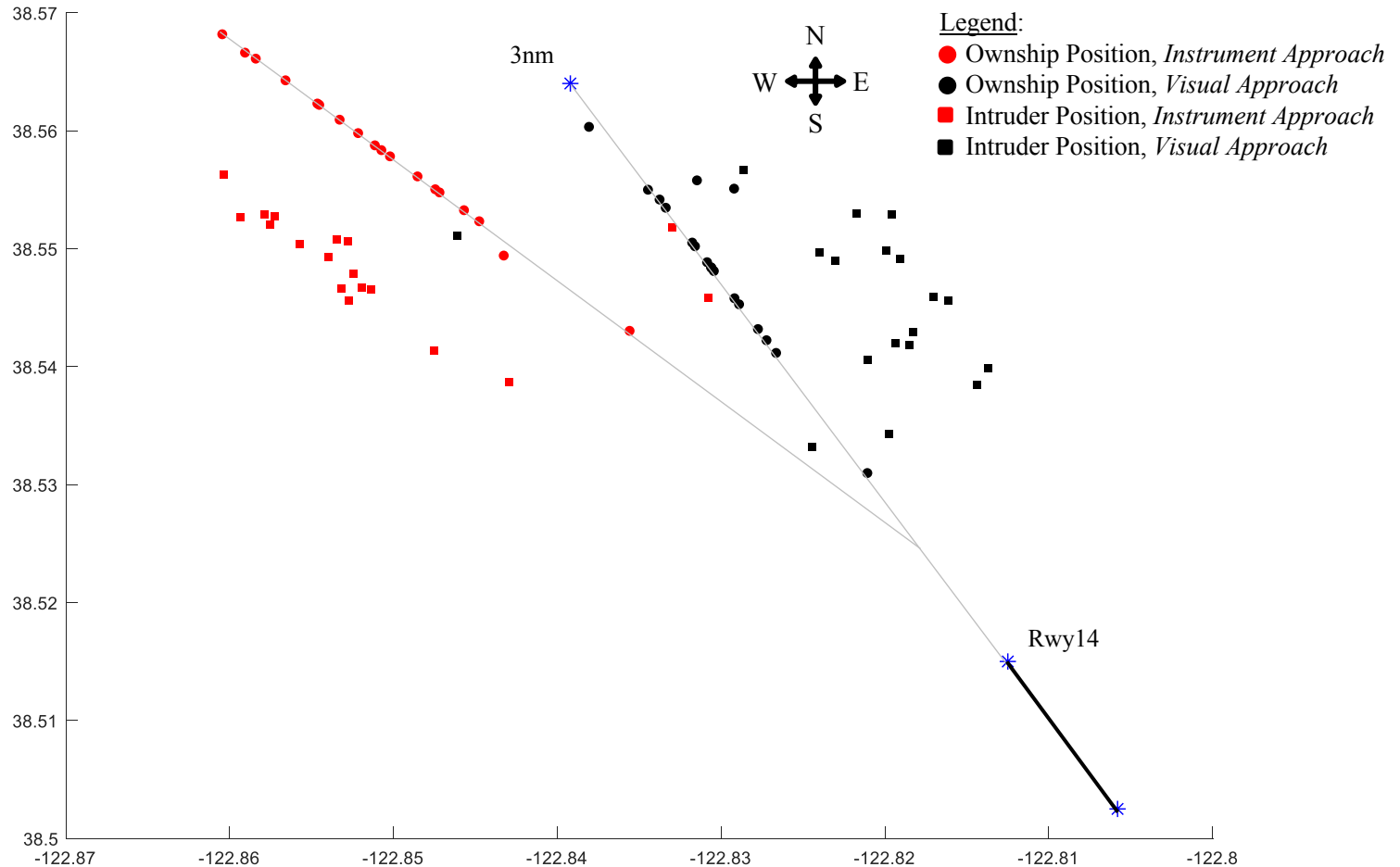
- How did pilots continue the approach when they maneuvered for traffic but did not go missed?
  - **Re-Engage:** turn back to final and/or continue descent
  - **Runway Heading:** turn back toward runway without engaging descent
  - **Re-Fly:** made a 360 or enter the right/left downwind to re-do the 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)







# Ownship & Intruder Location at CPA (for all LoDWC\_LaRC)

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

