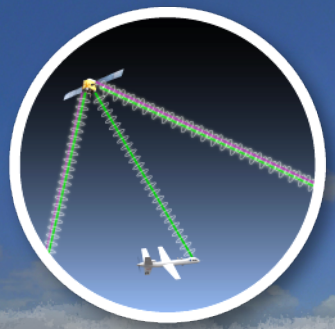


Unmanned Aircraft Systems (UAS) Integration in the National Airspace System (NAS) Project

Detect and Avoid Display Evaluations in Support of SC-228 Minimum Operational Performance Standards Development

Lisa Fern
Technical Lead,
Human Systems Integration

Presentation Overview

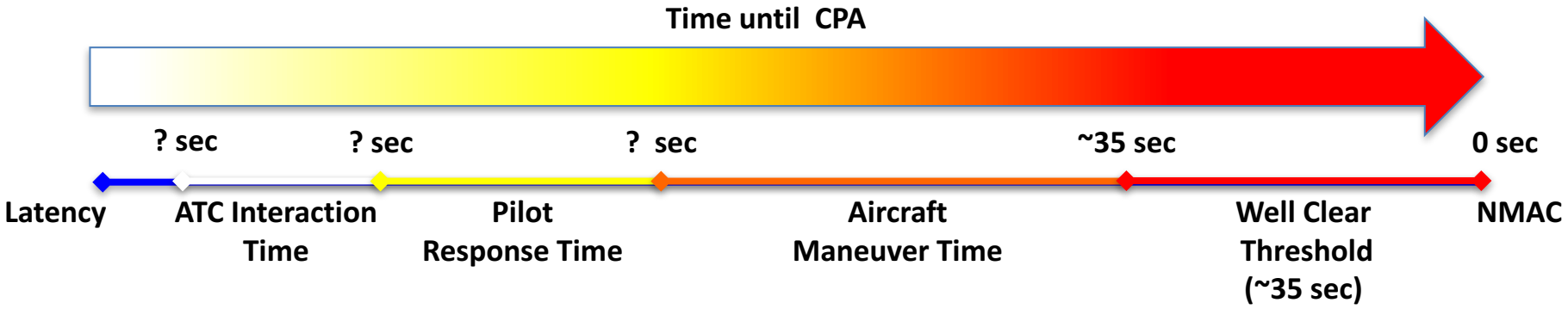
- Background
- Simulation environment components
- Key results of first three HITLs that compared different DAA maneuver guidance and display configurations
  - Key metrics used to inform SC-228 DAA MOPS:
    - Total response time: the time from when a DAA alert appears on the DAA display until the pilot uploads a final resolution maneuver
    - Proportion of losses of well clear: the proportion of encounters that were predicted to lose well clear that resulted in an actual loss of well clear
- Implications of results on SC-228 MOPS
- V&V HITL
- Summary of Contributions to Phase 1 MOPS

Background

Background

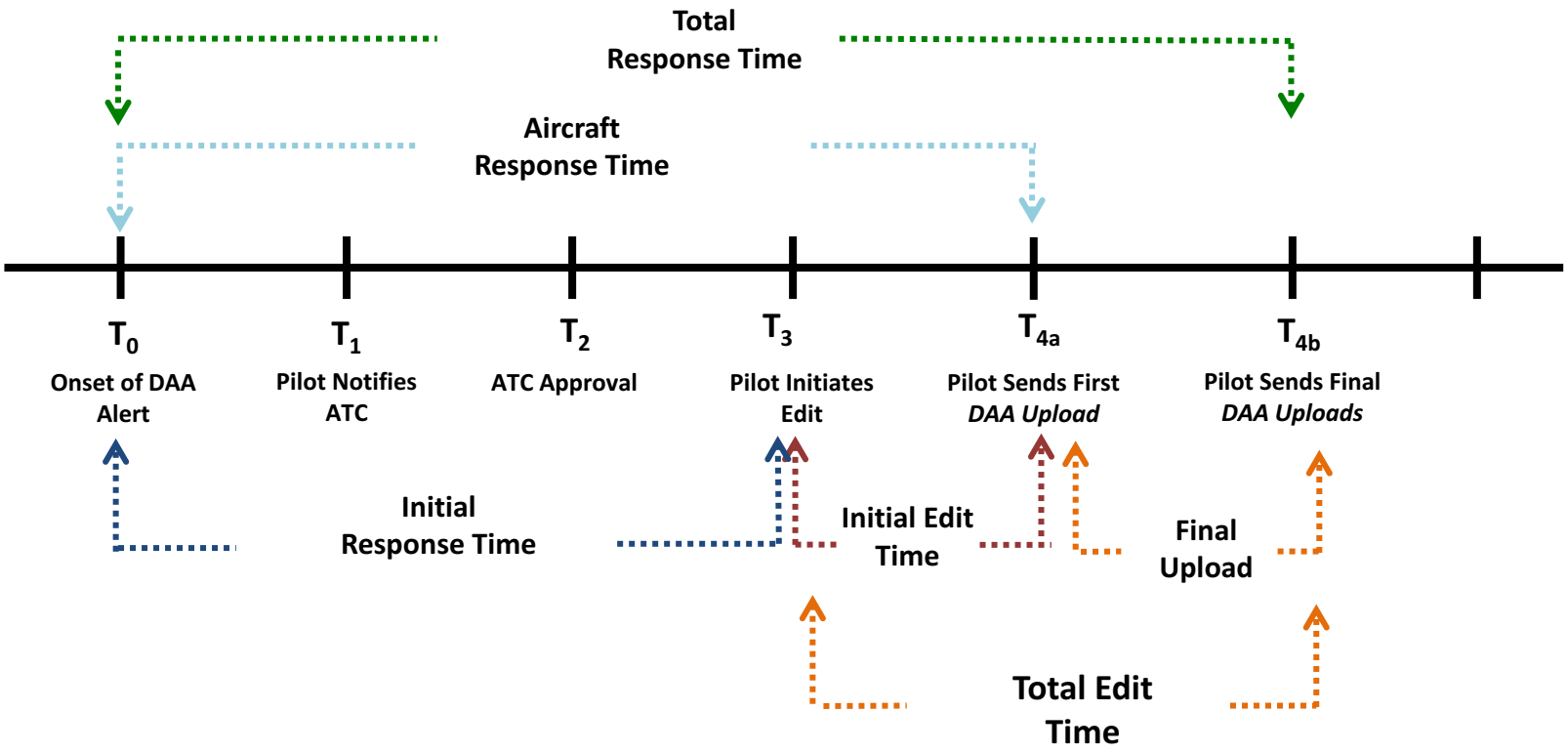
- Primary activity for the UAS-NAS Human Systems Integration (HSI) Subproject in Phase 1 was support of RTCA Special Committee 228 Minimum Operational Performance Standards (MOPS)
- Provide data on the effect of various Detect and Avoid (DAA) display features with respect to pilot performance of the remain well clear function in order to determine the minimum requirements for DAA displays
  - What is the pilot contribution to the DAA timeline in terms of expected response time to detect, determine and execute a maneuver in response to an alert of a potential loss of well clear?
  - What configuration of DAA display elements/capabilities meets a minimum acceptable level of performance?

DAA/Remain Well Clear Timeline



TOTAL RESPONSE TIME:
Detect Intruders
Pilots Determine Resolution
Negotiate Clearance with ATC and uplink maneuver to aircraft

Pilot-DAA Timeline



Background

- An early critical question for the Phase I MOPS for DAA systems was what, if any, level of DAA maneuver guidance would be required to support acceptable performance on maintaining well clear?
- Phase I MOPS assumptions specify that the pilot in command will execute maneuvers to remain well clear
  - i.e., No automatic/autonomous DAA capability
- Display types given level/type of maneuver guidance:
  - ***Informative***: Provides essential information of a hazard that the remote pilot may use to develop and execute an avoidance maneuver. No maneuver guidance automation or decision aiding is provided to the pilot
  - ***Suggestive***: Automation provides a range of potential resolution maneuvers to avoid a hazard with manual execution. An algorithm provides the pilot with maneuver decision aiding regarding advantageous or disadvantageous maneuvers
  - ***Directive***: Automation provides specific recommended resolution guidance to avoid a hazard with manual or automated execution. An algorithm provides the pilot with specific maneuver guidance on when and how to perform the maneuver

Simulation Environment

Simulation Environment

- Emulation of representative environment:
  - UAS Ground Control Station (GCS) with DAA Display
  - DAA system components:
    - Surveillance
    - Threat detection and alerting
    - Suggestive and directive guidance
  - Air Traffic Control
  - Simulated Manned Traffic
- Integrated via NASA's Live, Virtual, Constructive (LVC) architecture

Simulation Environment: Ground Control Station (GCS)

- The Vigilant Spirit Control Station (VSCS) developed by the Air Force Research Laboratory (AFRL)
- Main Features:
  - Robust, flexible interface
  - Realistic control and navigation displays
  - System status and health monitoring
  - STANAG 4586 Compliant
  - Multi-UAS control with VSCS has been tested in simulation and flight by AFRL
- Current UAS in the NAS version modifications/additions:
  - Single pilot – single UAS control
  - NAS-compatible database (low- and high- altitude charts with navigational aids/"fixes")
  - Integrated traffic display

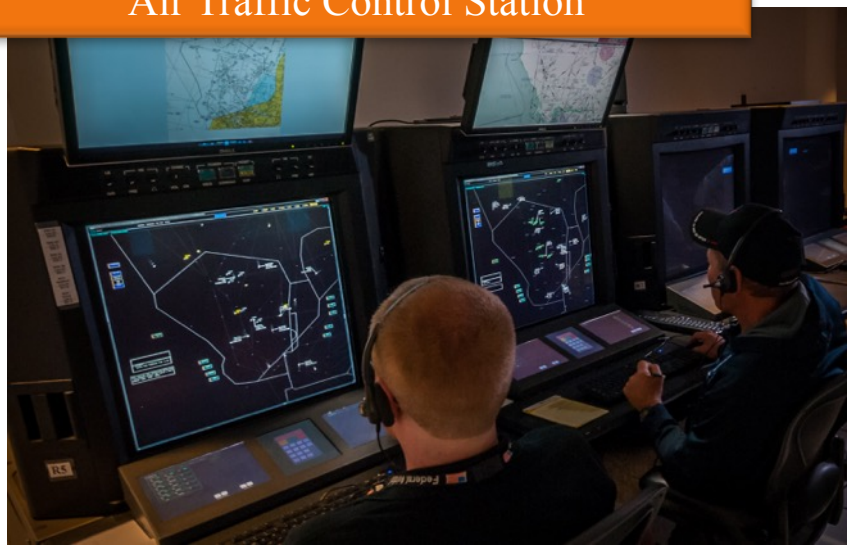
Simulation Environment: DAA System

- The Java Architecture for DAA Modeling and Extensibility (JADEM) was developed by the UAS in the NAS project at NASA Ames Research Center
- Main Functions:
  - Emulate surveillance parameters for various sensor types
    - e.g., ADS-B, active radar, TCAS, etc.
  - Receive state information from simulated traffic and ownship
  - Assign intruder alert levels based on given thresholds
  - Provide maneuver guidance

Simulation Environment: Multi Aircraft Control Station (MACS)

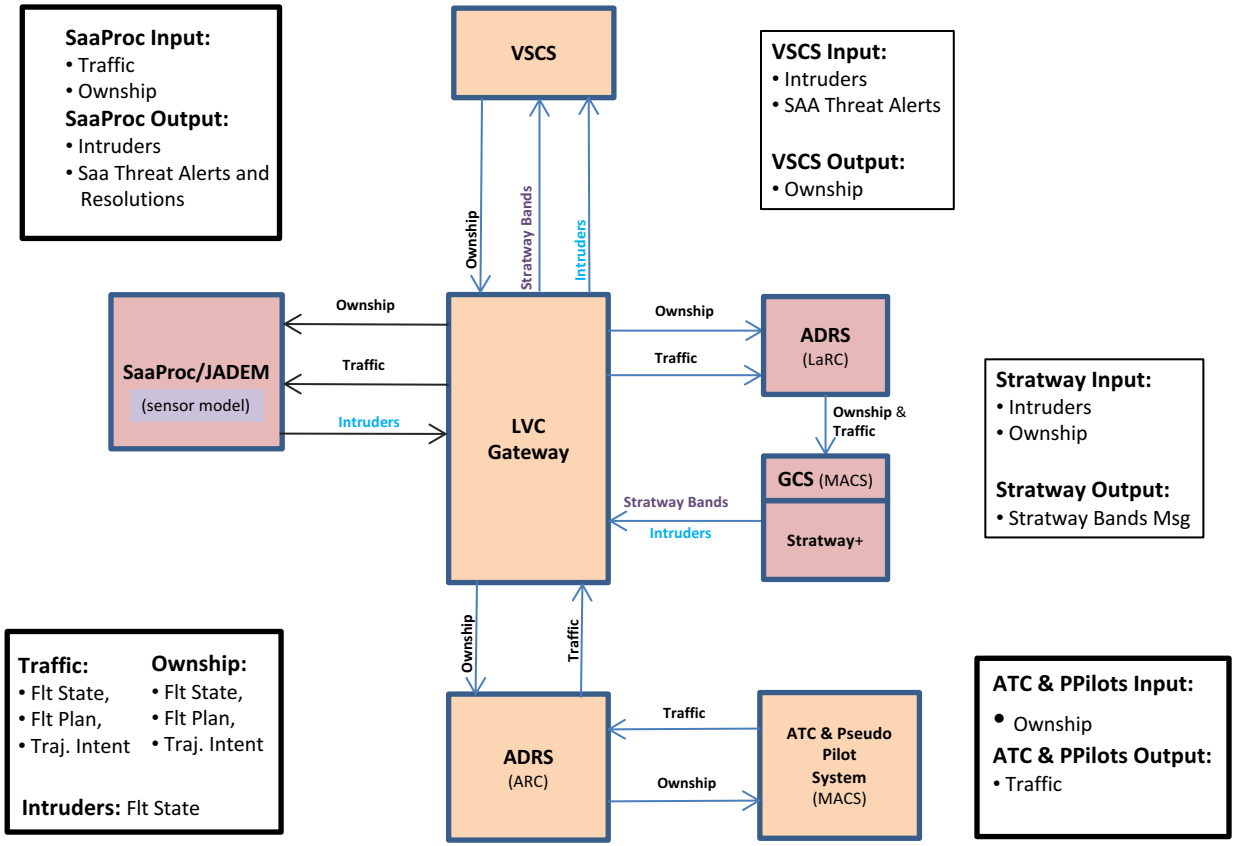
- The Multi Aircraft Control Station (MACS) developed by the Airspace Operations Laboratory (AOL) at NASA Ames Research Center
- Provides emulation of ground- and air- side Air Traffic Control (ATC) operations
  - Air Traffic Controller work stations
  - Simulated traffic generator
  - Psuedo pilot work stations
  - IFR and VFR simulated traffic
  - Traffic scenarios in Oakland Center (ZOA 40/41) airspace based on current day traffic patterns

Air Traffic Control Station



Pseudo Pilot Station

Simulation Environment: LVC Architecture



HITL Summaries

PT4 – Experimental Design

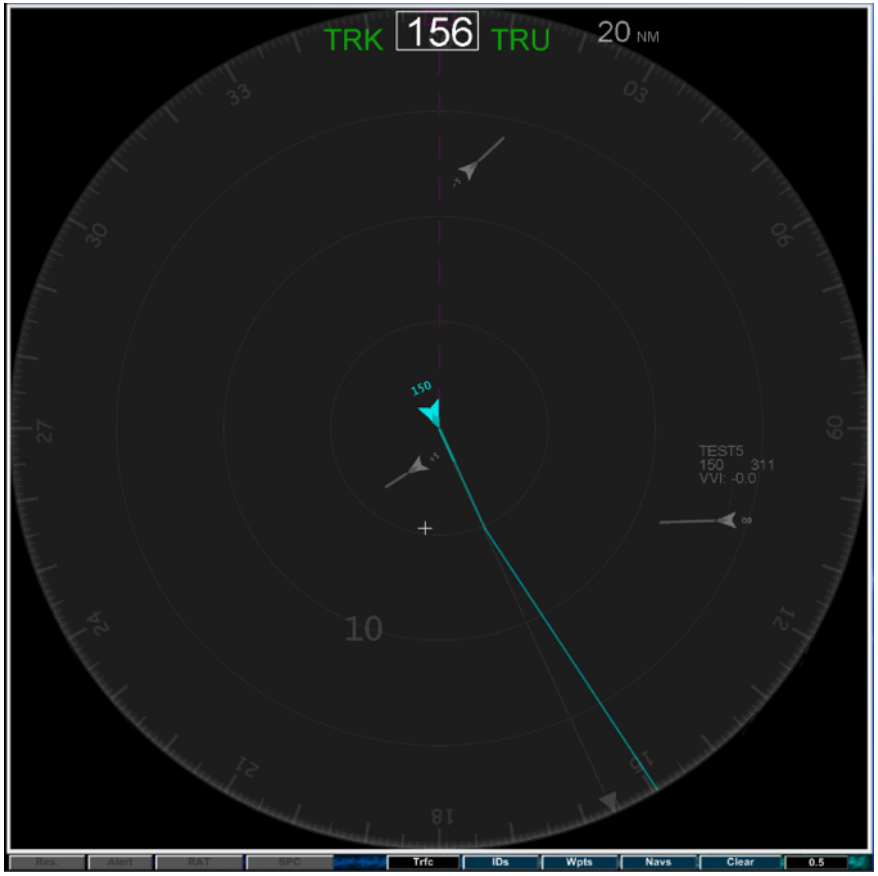
- Goal: Evaluate candidate Detect and Avoid (DAA) displays and algorithms with respect to traffic avoidance and collision avoidance.
  - What are the appropriate alerting thresholds for self separation?
  - What are the minimum information requirements for DAA displays?
  - Is there a performance difference between integrated and standalone displays?
  - What advanced display features improve pilot performance on maintaining well clear from other traffic?
- What advanced display features improve pilot performance on maintaining well clear from other traffic?
  - Experimental Design: Mixed Factorial Design
  - 2 (Display: Standalone, Integrated)
  - X 2 (Information: Basic, Advanced)
  - X 2 (Self-Separation Alerting Threshold)

PT4 – Display Configurations

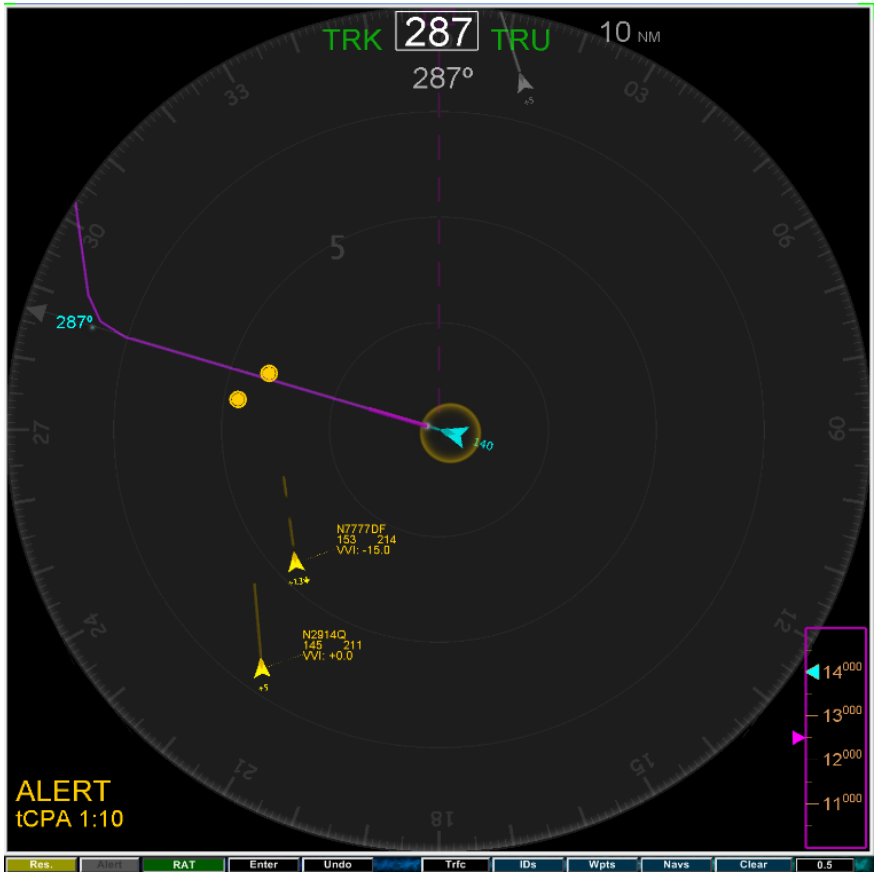
- Display Location Level: Standalone versus Integrated
  - Standalone: display located on own monitor, separate from primary moving map display
  - Integrated: display integrated with primary moving map display
- Display Information Level: Basic versus Advanced
  - Basic presents minimum information requirements only
  - Advanced information elements:
    - Implementation different between Standalone and Integrated displays
    - Additional informational elements
      - Additional alerting level (predictive CA)
      - Time to and location of predicted CPA (intruder and ownship)
      - Vertical situation display (Integrated only)
    - Maneuver guidance
      - Suggestive: Trial/vector planner
      - Directive: Maneuver recommendations

PT4 – Standalone Displays

Basic



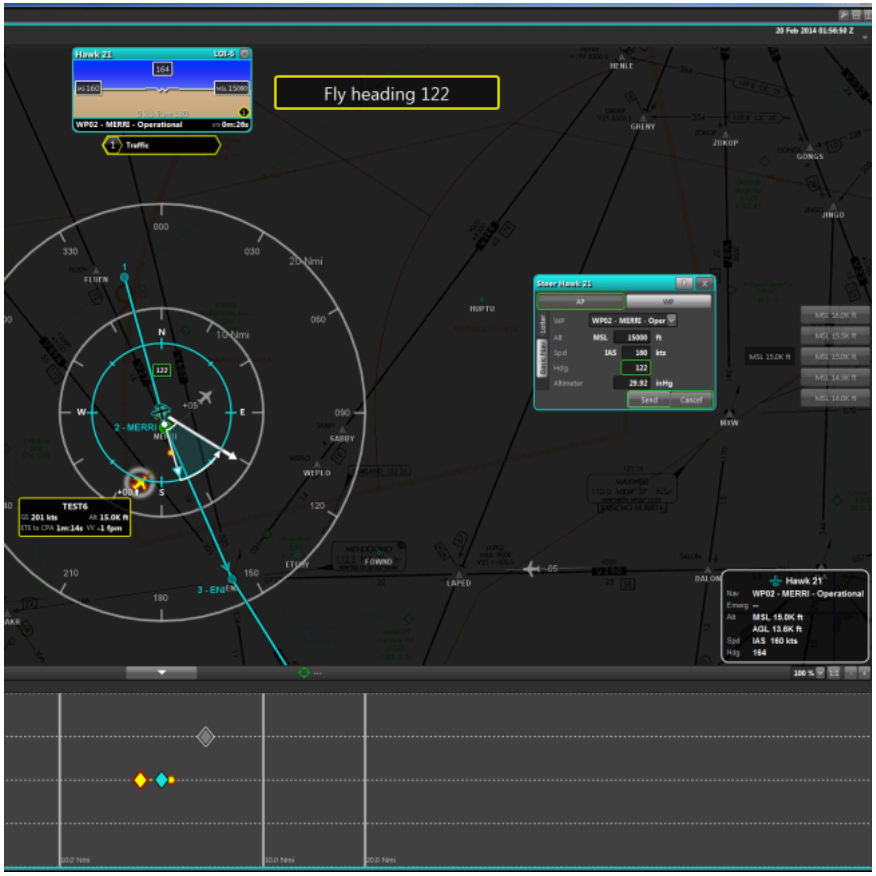
Advanced



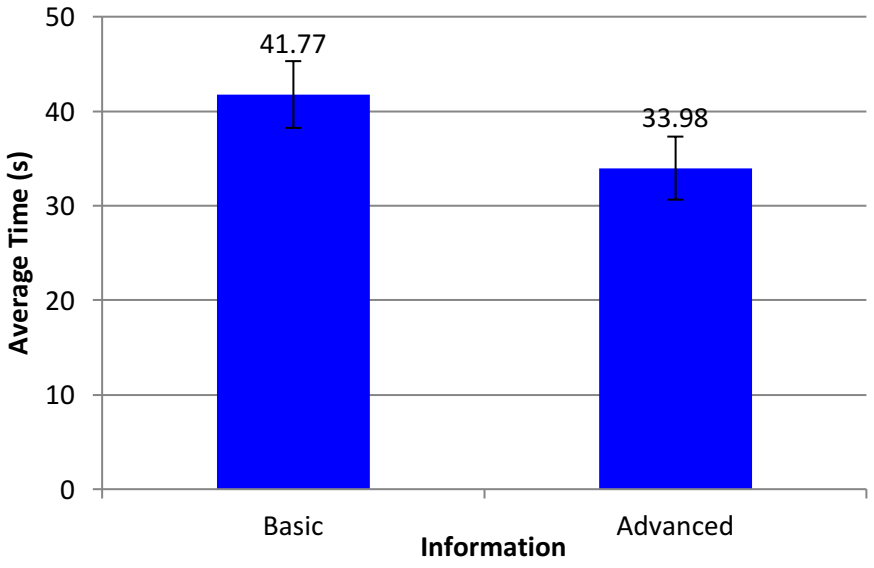
PT4 – Integrated Displays

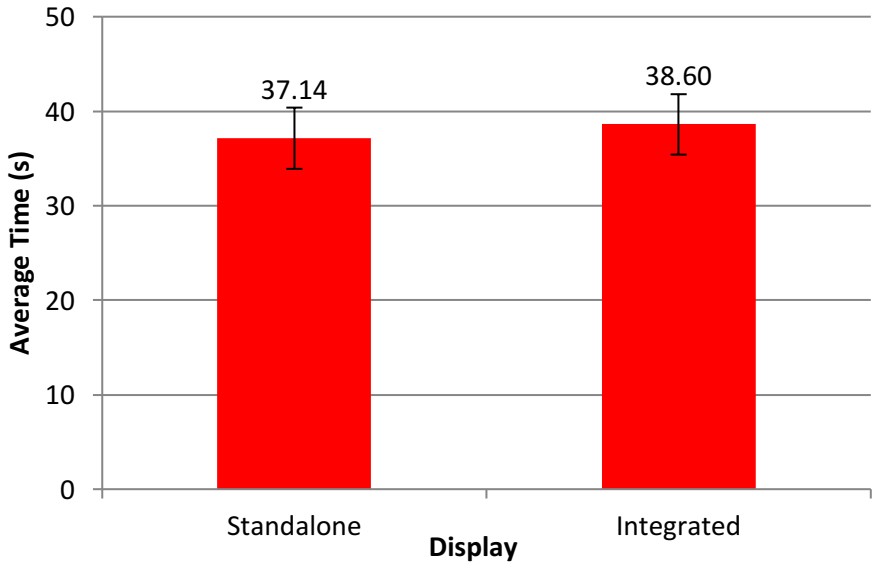
Basic

Advanced



PT4 – Total Response Time Results

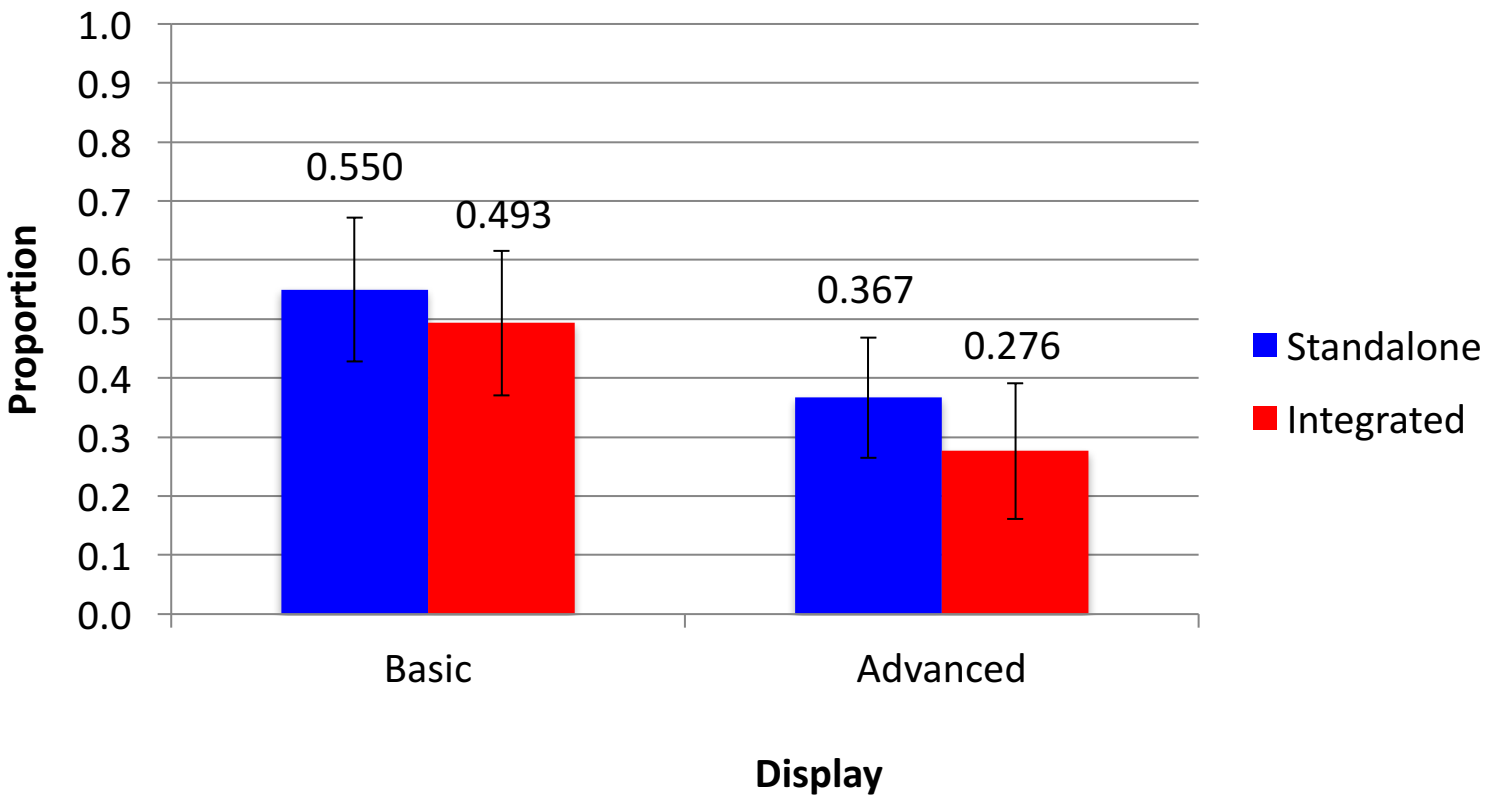




- There was a significant main effect of Information on Total Response Time, $p < .05$
  - Advanced was significantly faster (by 13.79 seconds on average) compared to Basic
- Pilots took an average of **37.87 seconds** to complete their final edit in response to DAA/CA alerts (from first alert appearance)

- There was no significant main effect of Display on Total Response Time, $p > .05$
- Pilots took an average of **37.87 seconds** to complete their final edit in response to DAA/CA alerts (from first alert appearance)

PT4 – Losses of Well Clear



- There was not a significant main effect of Information on Proportion of Losses of Well Clear, $p > .05$
- On average pilots failed avoid a loss of well clear 44% of the time

PT4 – Results Summary

- Consistent advantage seen for Advanced over Basic displays in pilot response times
- No significant differences in proportion or severity of losses of well clear, however, advanced trended toward lower rates of LoWC than basic
- There were no significant differences between the Standalone and Integrated condition

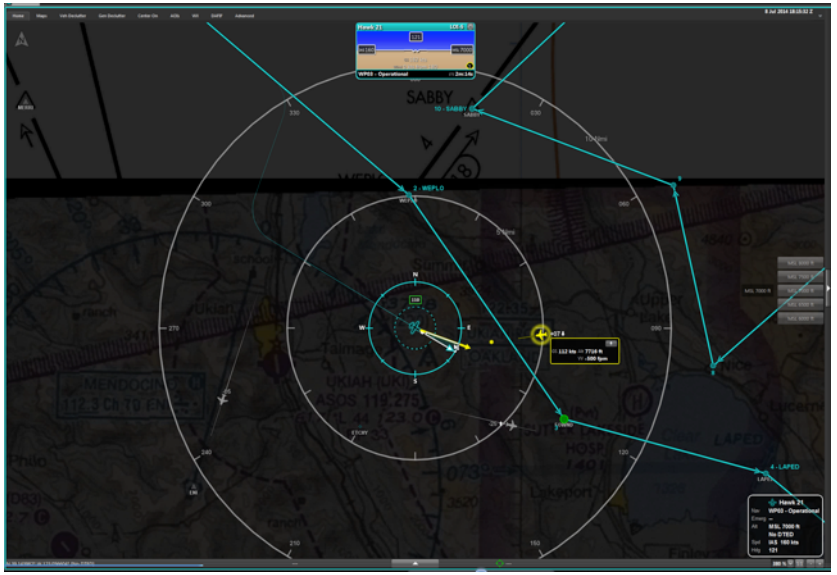
iHITL – Experimental Design

- Goal: Determine the individual contributions of the various PT4 advanced display features to pilots' response times and ability to maintain well clear
- One-Way Repeated Measures Factorial: Display Information Level (4 Level; Within Subjects)
  - D1: Advanced Display with Information Only (Informative)
  - D2: Advanced Display with Information + Vector Planner (Suggestive)
  - D3: Advanced Display with Information + Auto Resolutions (Directive)
  - D4: Advanced Display with Information + Vector Planner + Auto Resolutions (Suggestive + Directive)
    - Roughly same as 'Advanced' suite in PT4

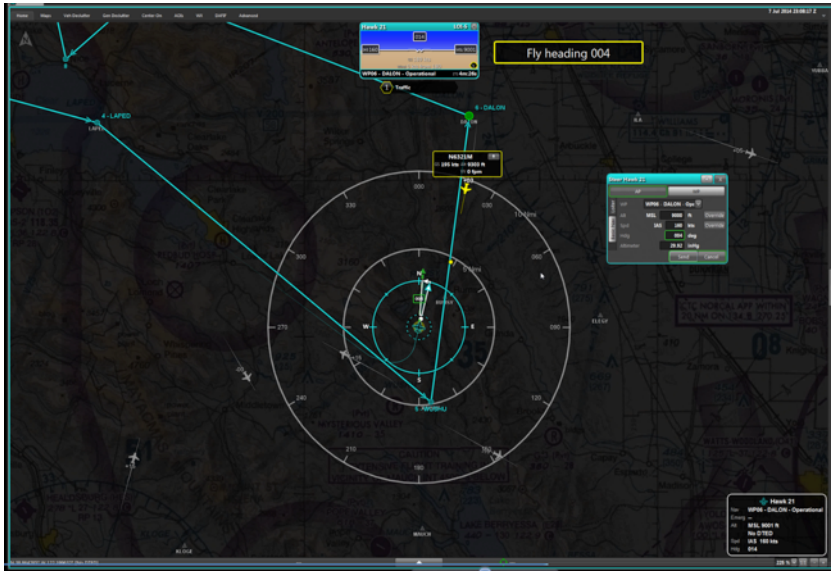
iHITL – Display Conditions

D1

D2

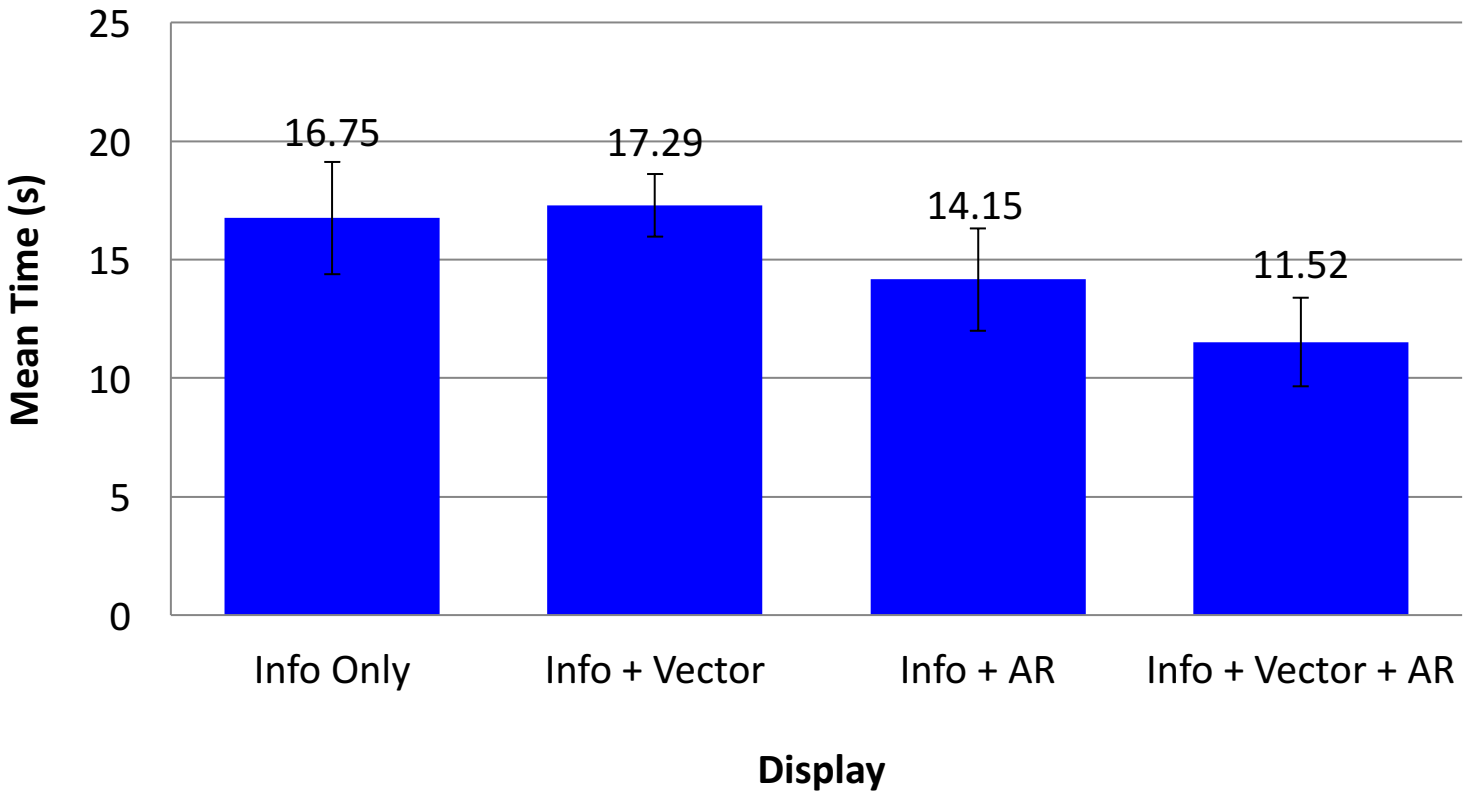


D3



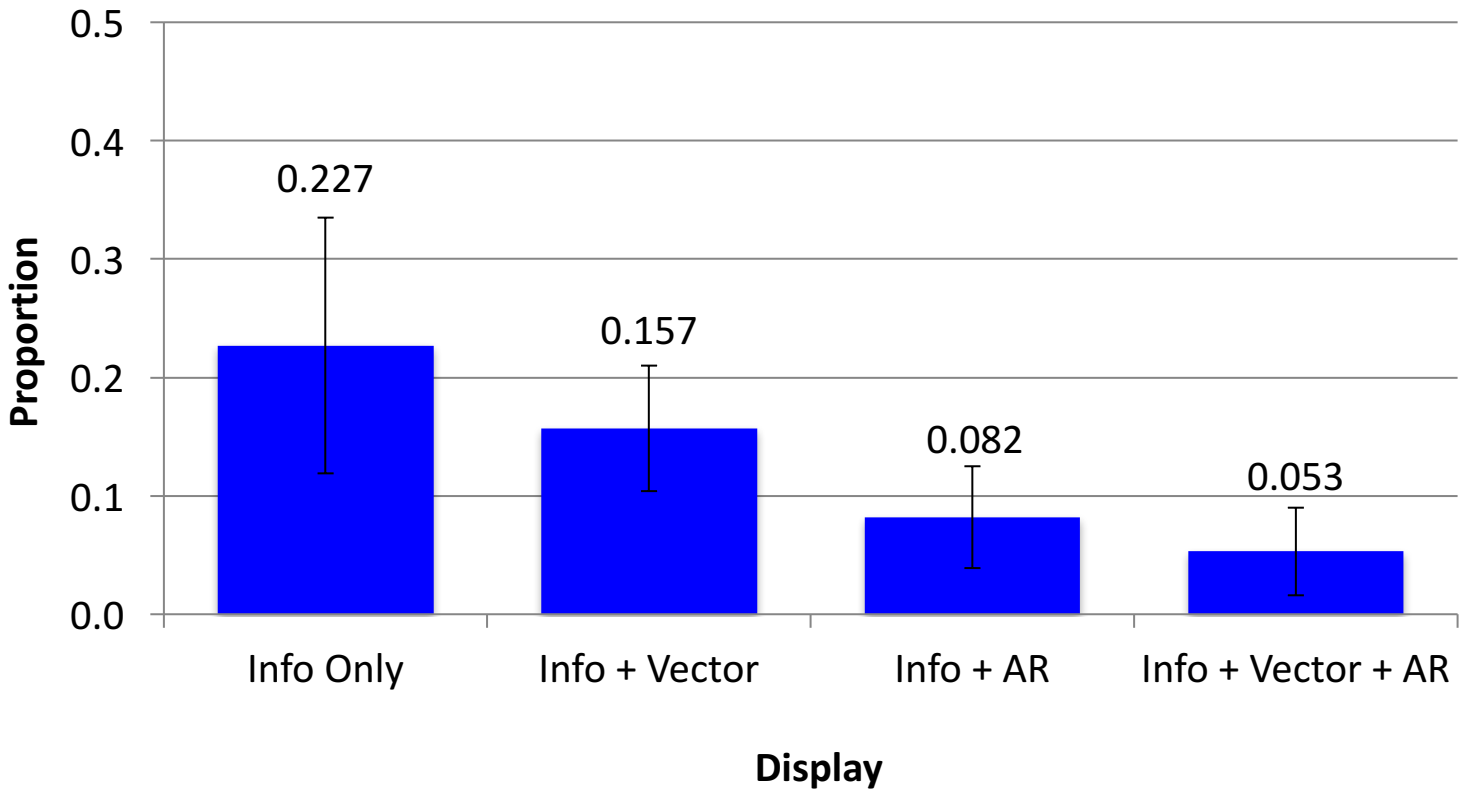
D4

iHITL – Total Response Time Results



- There was not a significant main effect of Information on Total Response Time, $p > .05$
- Pilots took an average of 14.92 seconds to complete their final edit in response to DAA/CA alerts (from first alert appearance)

iHITL – Losses of Well Clear



- There was not a significant main effect of Display Configuration on Proportion of Losses of Well Clear, $p > .05$
- On average pilots failed avoid a loss of well clear 13% of the time

iHITL – Results Summary

- Total Response Time:
  - No significant differences between displays
  - Trend shows Info + AR and Info + Vector + AR as faster than Info Only and Info + Vector
- Well Clear Metrics:
  - No significant differences between displays
  - Info Only and Info + Vector display conditions had 2.5X as many LoWCs than the Info + Vector + AR
- Overall:
  - The two displays with directive guidance (i.e., Auto-Resolutions) performed better than the informative only and suggestive only displays
  - This result is confounded by integration of Auto-Resolutions tool with auto-pilot display

PT5 – Overview

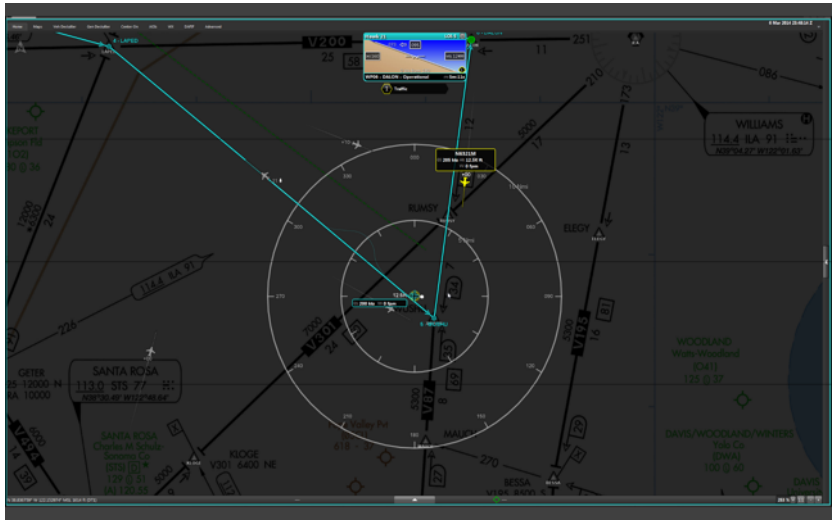
- Goal: Continue evaluation of candidate Detect and Avoid (DAA) displays and algorithms with respect to traffic avoidance and collision avoidance to inform SC-228 DAA Minimum Operational Performance Standards
- Method:
  - Build upon results of previous hitl simulations results and lessons learned to identify minimum DAA display and guidance requirements for draft SC228 MOPS
  - Take into account SC-228 decision that directive guidance would not be part of the minimum requirements by focusing on various suggestive guidance displays versus informative
  - Address issues of integrating DAA display features into the GCS control and navigation functionality

PT5 – Experimental Design

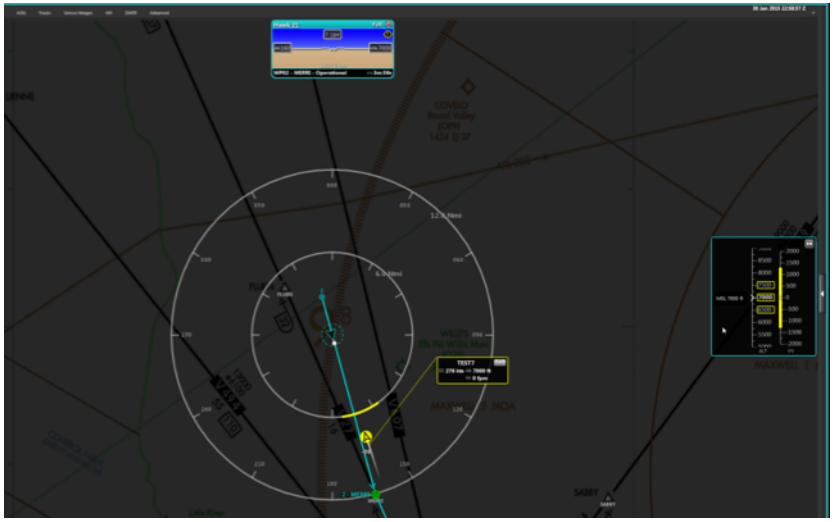
- Mixed Factorial Design
  - Display Configuration (Within-Subjects Independent Variable):
    - Configuration 1: Minimum Information Set (No Guidance)
    - Configuration 2: Stratway+ No Fly Bands
    - Configuration 3: JADEM Omni Bands
    - Configuration 4: JADEM Vector Planning Tools
  - Sensor Performance (Between-Subjects Independent Variable)
    - Level 1: Perfect Surveillance Data
    - Level 2: Imperfect Surveillance Data

PT5 – Display Conditions

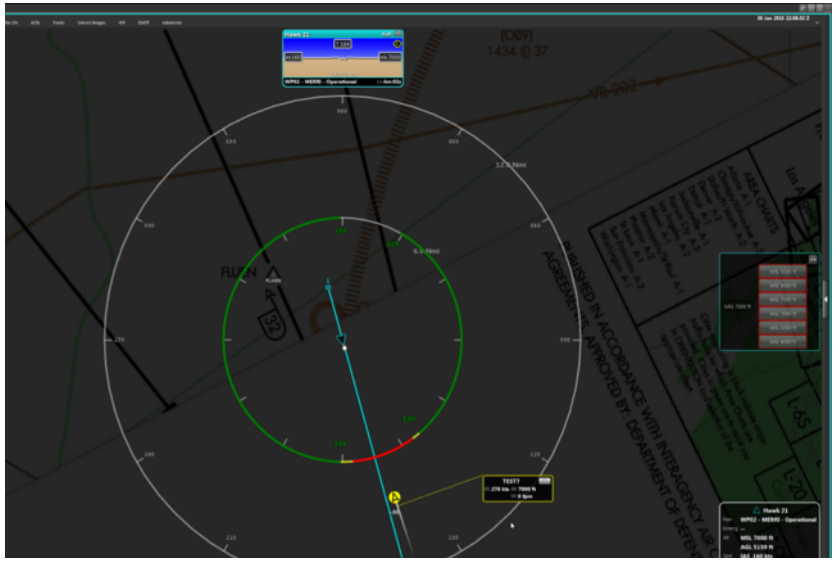
D1



D2

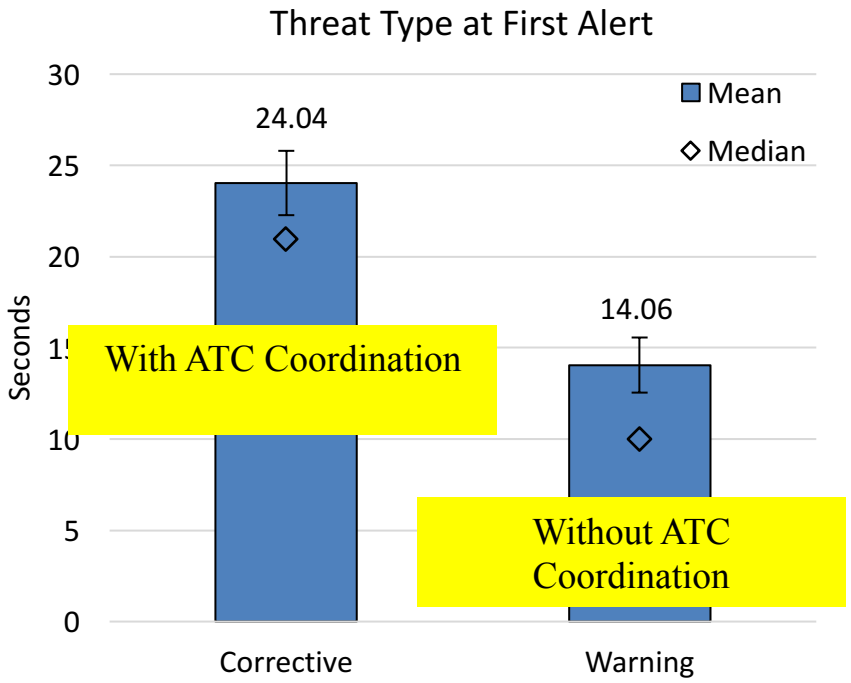


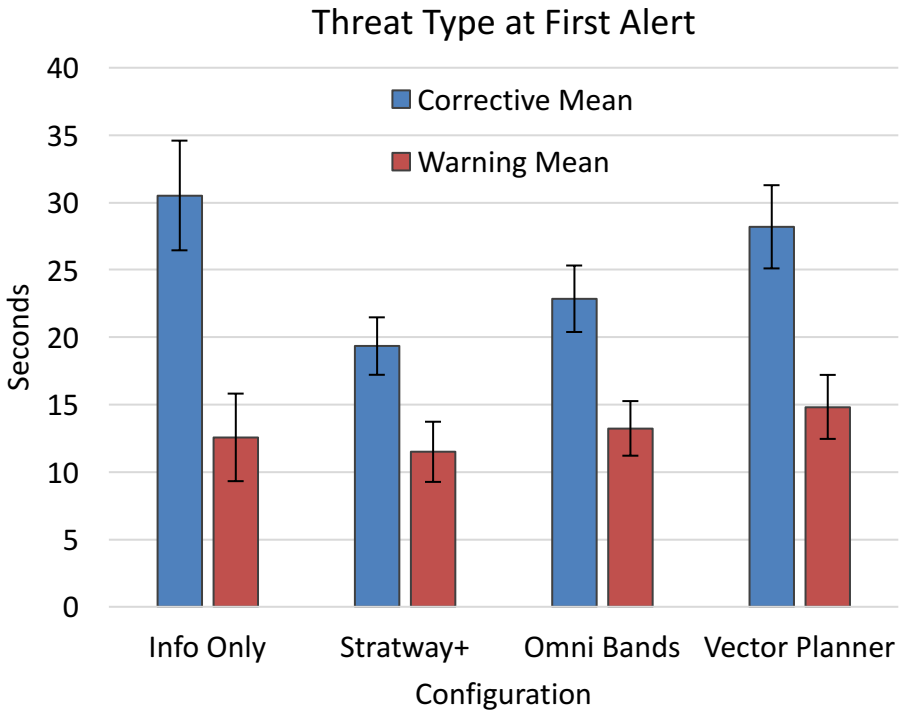
D3



D4

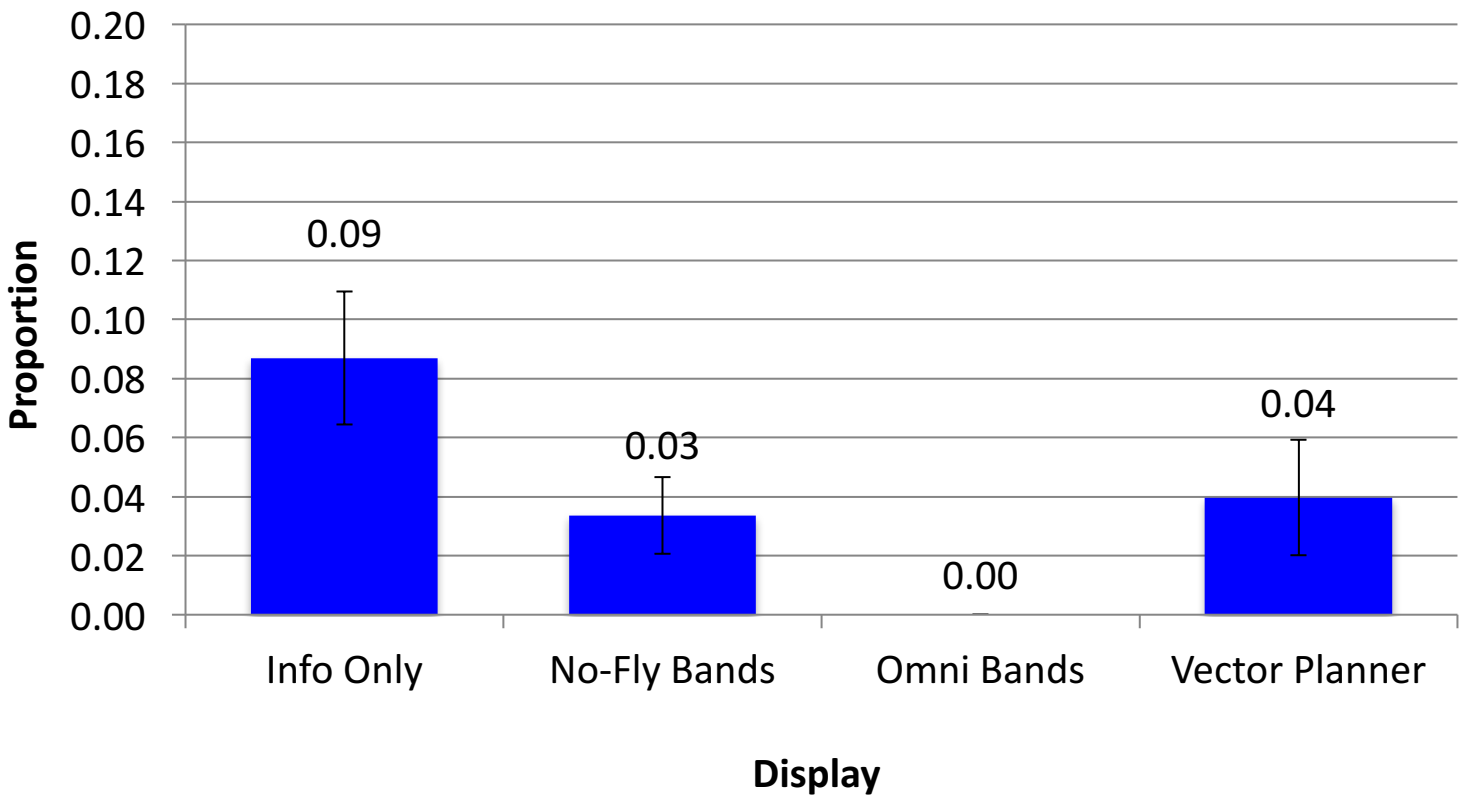
PT5 – Total Response Time Results





- Pilots responded, on average, 10s faster to SS Warning Alerts than they did to Corrective SS Alerts
  - Pilots exhibited less variability between displays when responding to DAA Warning Alerts than to Corrective DAA Alerts
    - Range for DAA Warning Alerts: 11s - 15s
    - Range for Corrective DAA Alerts: 19s – 30s
  - Variability due to coordination with ATC – adds ~ 10 secs to total response time

PT5 –Losses of Well Clear



- There was a significant main effect of Display Configuration on Proportion of Losses of Well Clear, $p < .05$
  - Pilots in the Omni Bands condition had significantly fewer losses of well clear than those in the Info Only condition
- On average pilots failed avoid a loss of well clear 4% of the time

PT5 – Results Summary

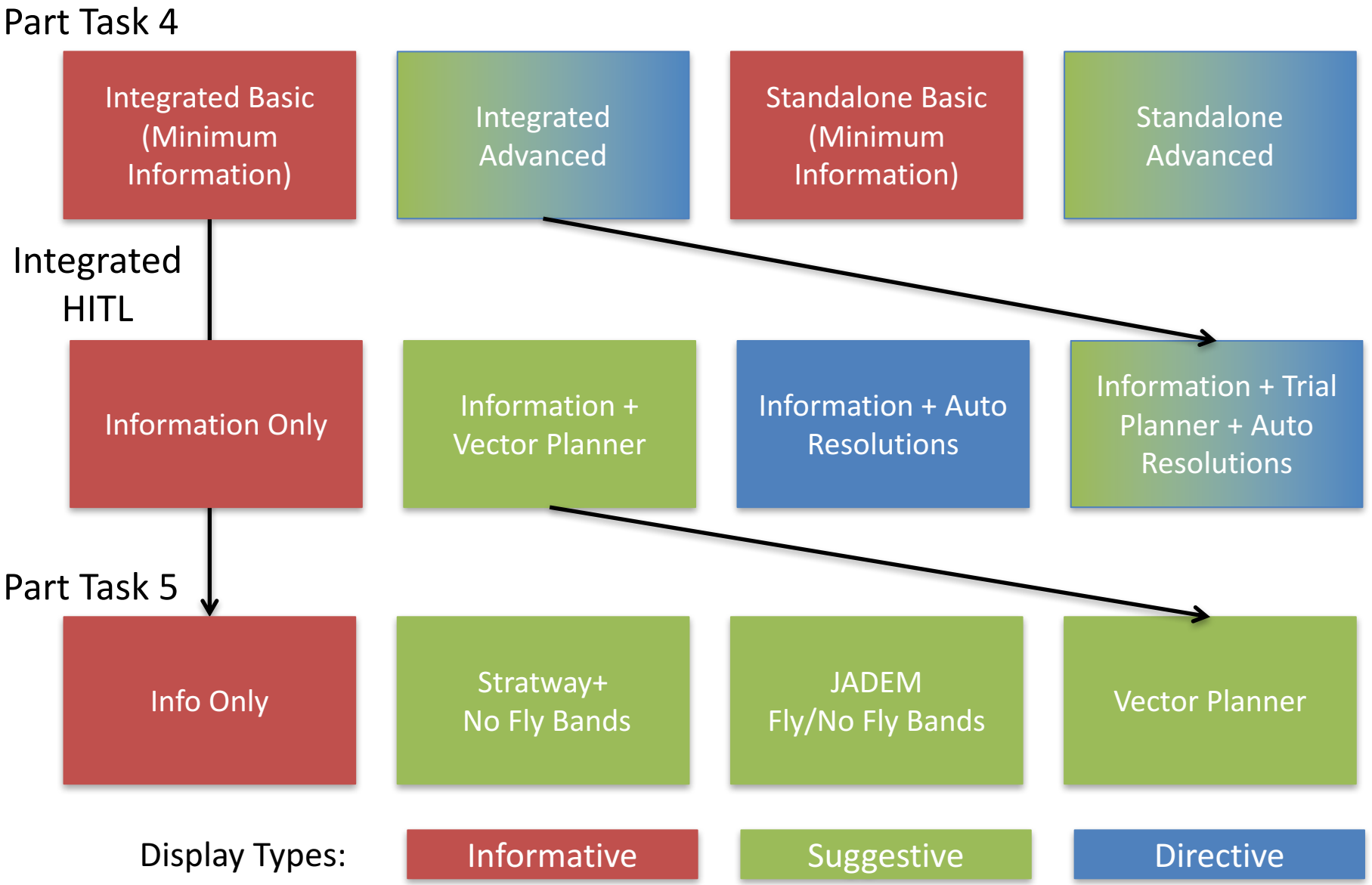
- Suggestive guidance in the form of banding resulted in safer and more timely maneuvers away from conflicts
  - Lower overall proportion of LoWC for both banding displays (none for omni bands)
  - Least severe LoWC for both banding displays; most severe with info only (where an NMAC occurred)
  - Shorter Total RTs for both banding displays
  - Pilots self-report as preferring the banding displays
- Results support decision for suggestive guidance as a minimum information requirement for DAA displays
  - Although Vector Planner display had performance between info only and banding displays, design approach not consistent with good HF principles and very poor performance compared to Omni Bands (despite same underlying algorithm)

PT5 – Results Summary

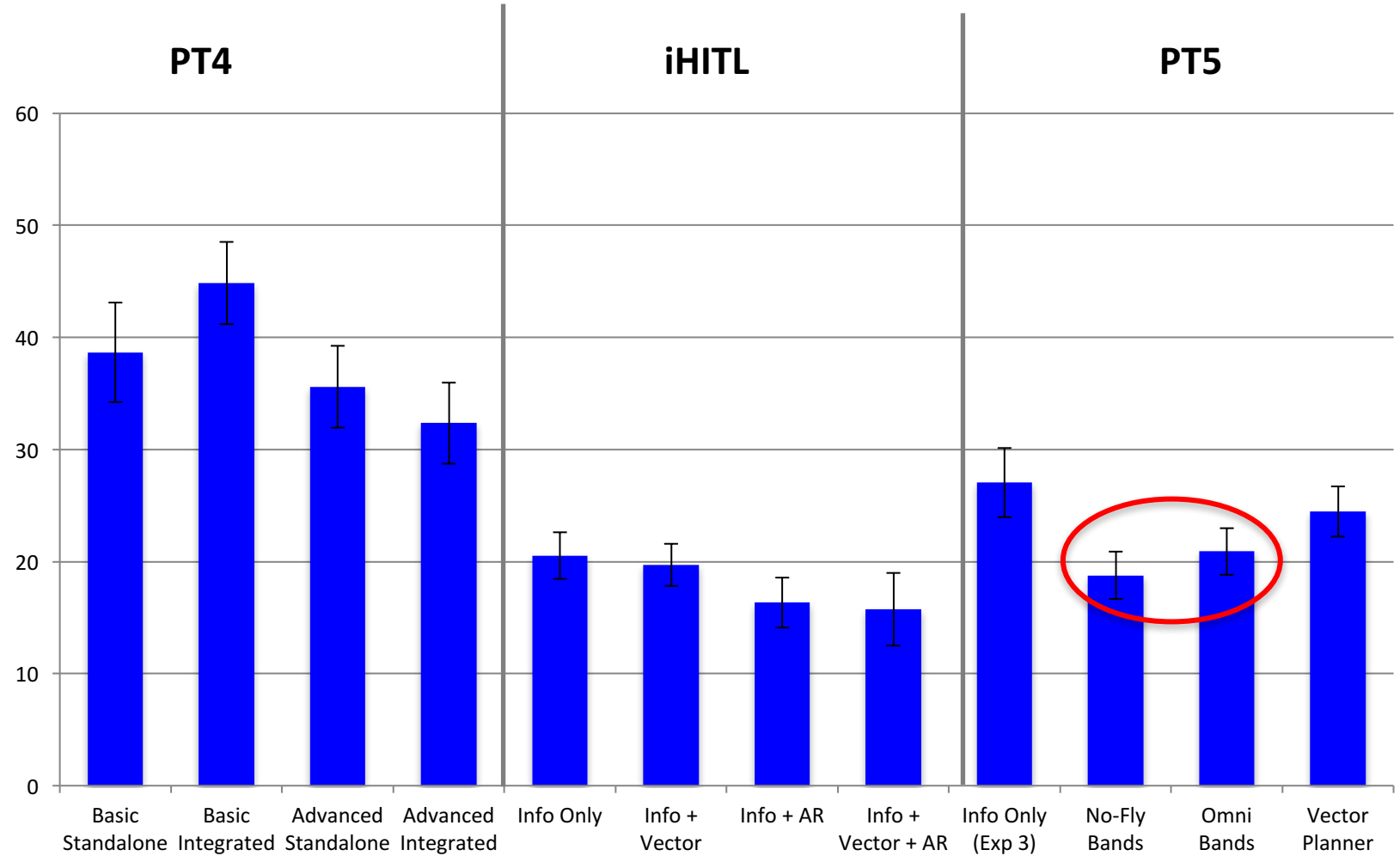
- PT5 results also inform the DAA alerting structure and thresholds:
  - Pilots responded consistently to a DAA Warning alert (no ATC coordination required) in ~ 15 seconds
  - Responded to a DAA Corrective alert (ATC coordination is required) in ~ 25 seconds, though more variability
  - Therefore, ATC coordination adds approximately 10 seconds to DAA timeline

Implications of first three HITLs on Draft DAA MOPS

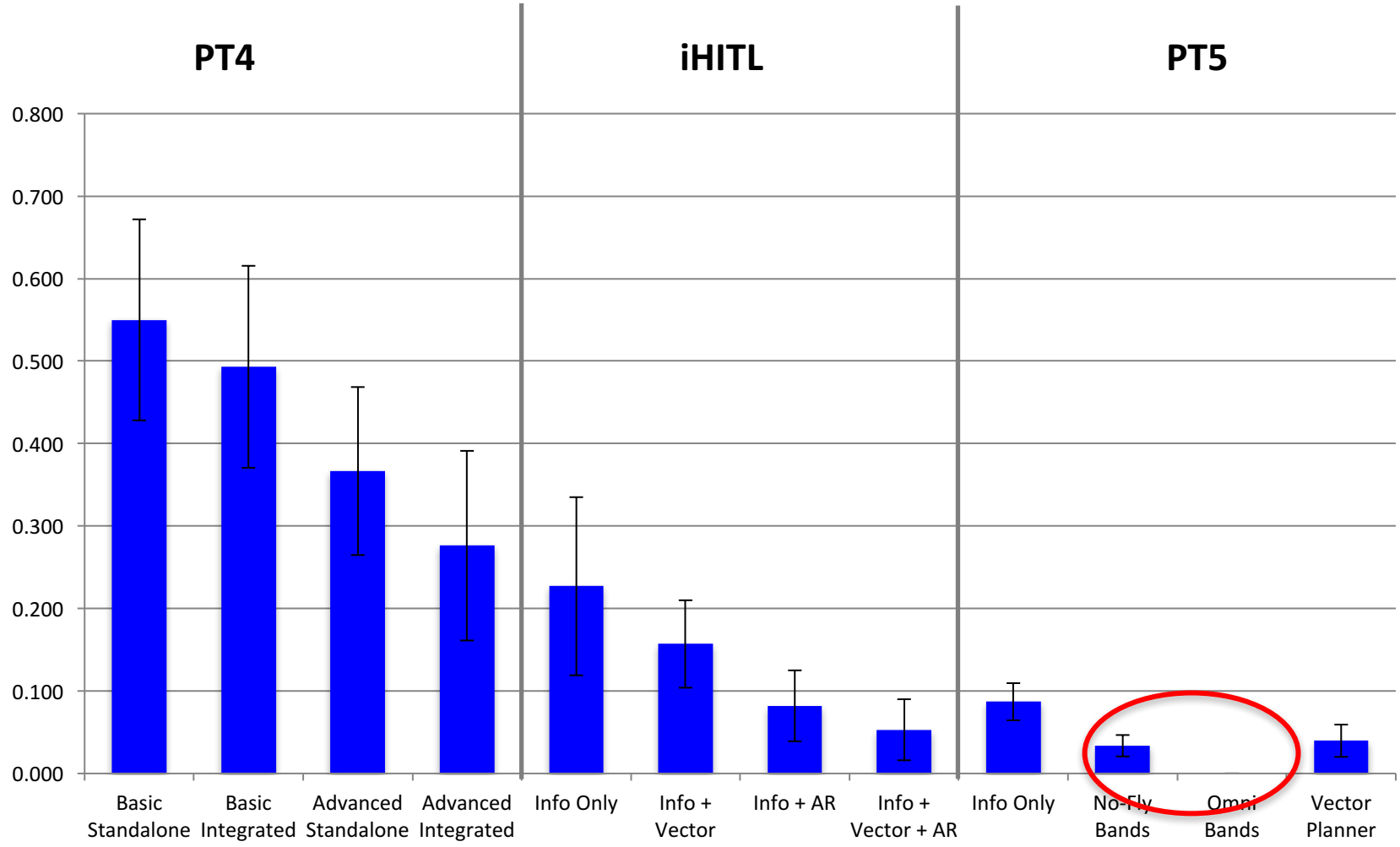
Overview Summary of HITLs



Total Response Times Across Simulations



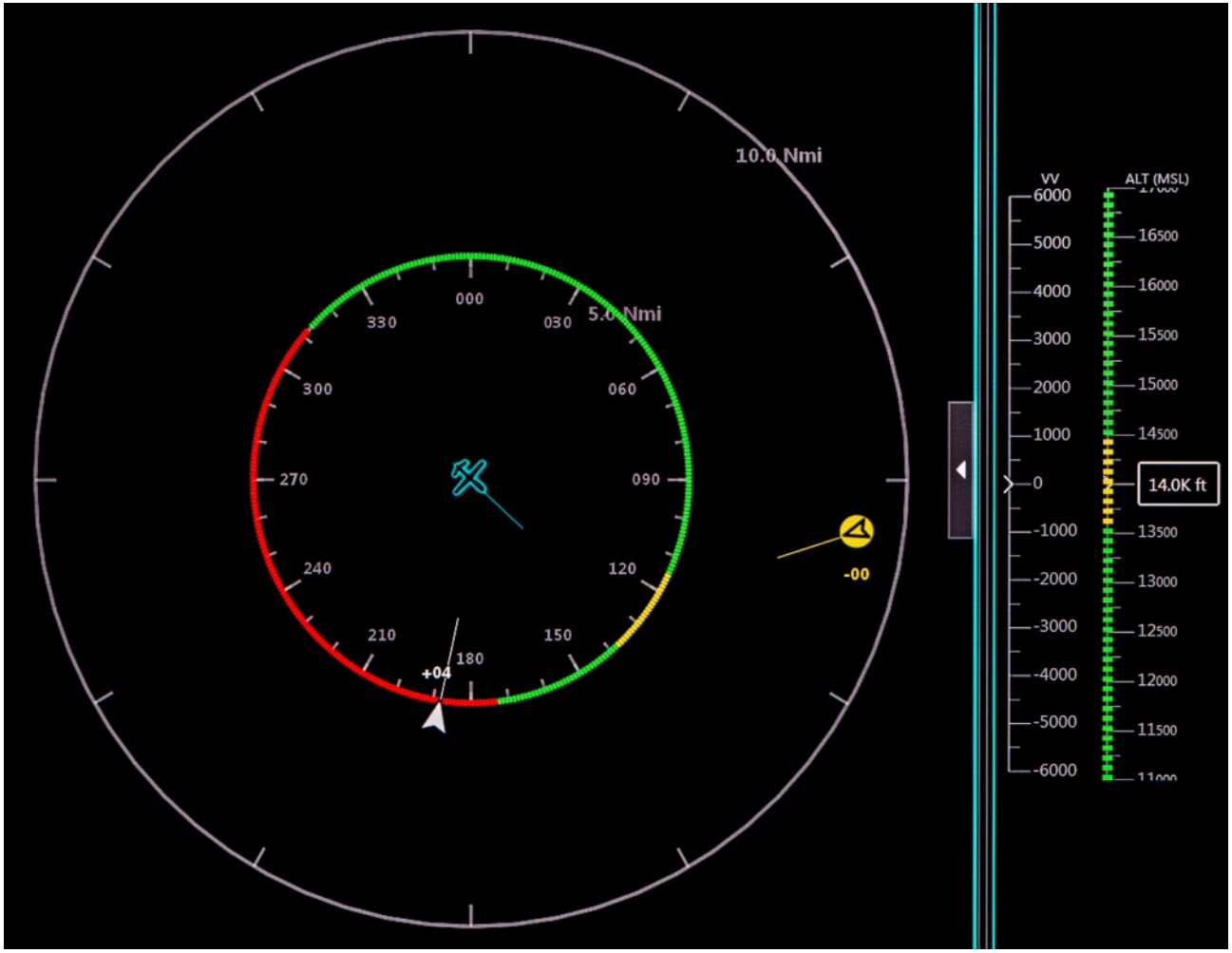
Losses of Well Clear Proportions Across Simulations



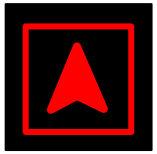
Draft MOPS Informed by HITLs

- Maneuver guidance in the form of bands
- Alerting structure with DAA Warning and Corrective alerts and their corresponding pilot actions
- Minimum thresholds for alerting levels
- Minimum surveillance range for onboard radar

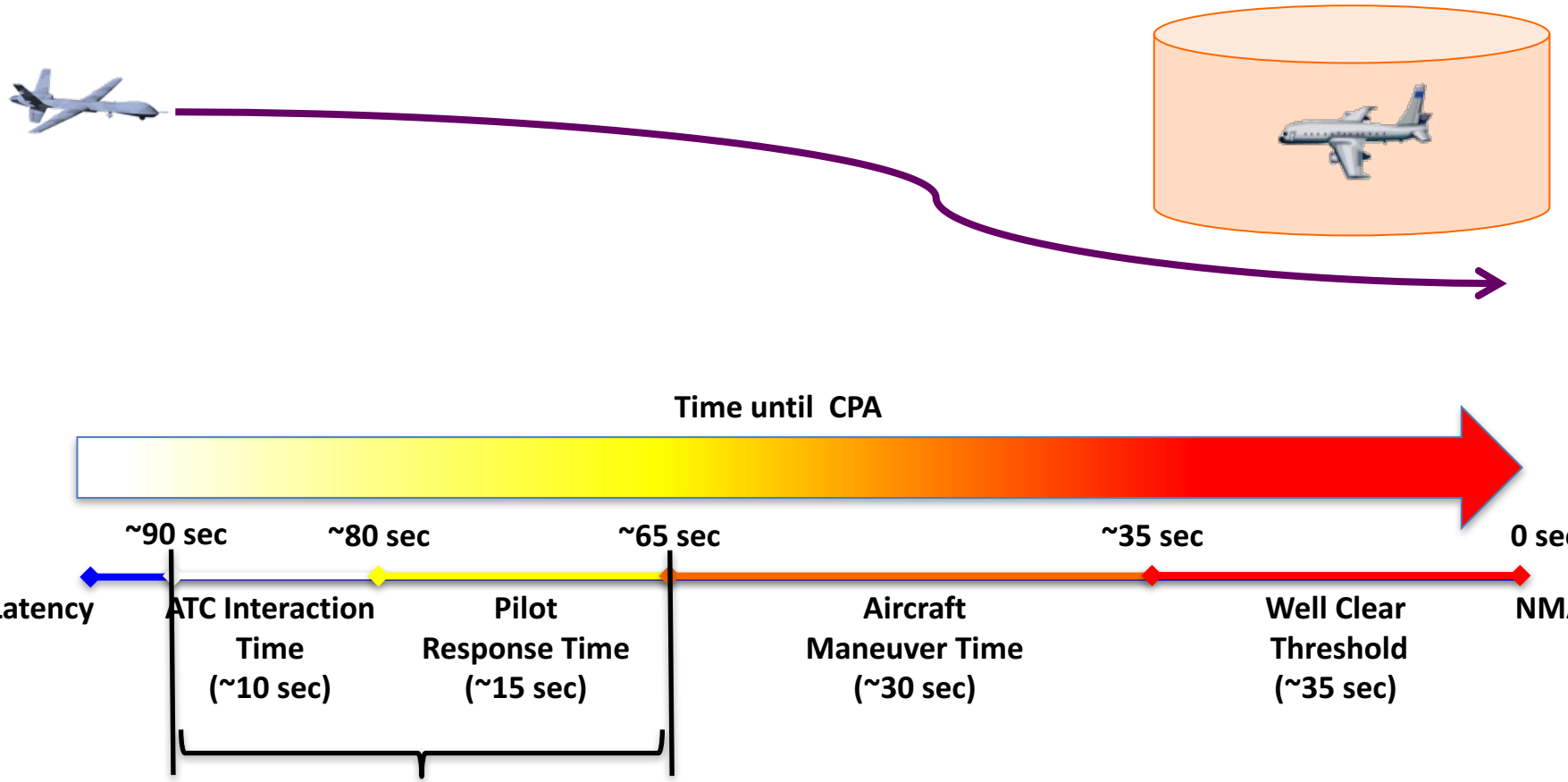
Draft MOPS Informed by HITLs: Suggestive Maneuver Guidance



Draft MOPS Informed by HITLs: Alerting Levels and Thresholds

Symbol	Name	Pilot Action	Alerting Time Threshold	Aural Alert Verbiage
	DAA Warning Alert	• ***Immediate action required*** • Notify ATC as soon as practicable after taking action	25 sec (TCPA approximate: 60 sec)	"Traffic, Maneuver Now"
	DAA Corrective Alert	• On current course, ***corrective action required*** • Coordinate with ATC to determine an appropriate maneuver	55 sec (TCPA approximate: 90 sec)	"Traffic, Avoid"
	DAA Preventive Alert	• On current course, corrective action ***should not be required*** • Monitor for intruder course changes • Talk with ATC if desired	55 sec (TCPA approximate: 90 sec)	"Traffic, Monitor"
	Guidance Traffic	• **No action required** • Traffic generating guidance bands outside of current course	X	N/A
	Remaining Traffic	• No action expected	X	N/A

Draft MOPS Informed by HITLs: Surveillance Range



V&V HITL (PT6)

PT6 – Overview

- Purpose:
  - Conduct final V&V activity in support of SC-228 DAA HMI requirements for displays, alerting and guidance
  - Determine if pilot performance w/ minimum requirements (as currently defined in the draft MOPS) comparable to previous simulations, such as Part Task 5?
- Goals:
  - Implement the minimum display, alerting and guidance requirements as close as possible in simulation
  - Test in representative simulated flight environment
    - E.g., airspace w/ ATC in-the-loop, multiple UAS missions, secondary tasks, high-fidelity surveillance models, TCAS II
  - Expected outcome/product(s): pilot performance data to validate final DAA MOPS
    - Losses of Well Clear
    - Pilot response times
    - Additional pilot behavior: TCAS compliance, type/size of maneuvers, ATC coordination

PT6 – Experimental Design

- Mixed Factorial
  - Display Configuration (within-subjects)
    - Standalone DAA display (decoupled from moving map/TSD)
    - Integrated DAA display (collocated with moving map)
  - Ownship Equipage (between-subjects)
    - TCAS II-equipped
    - No TCAS II

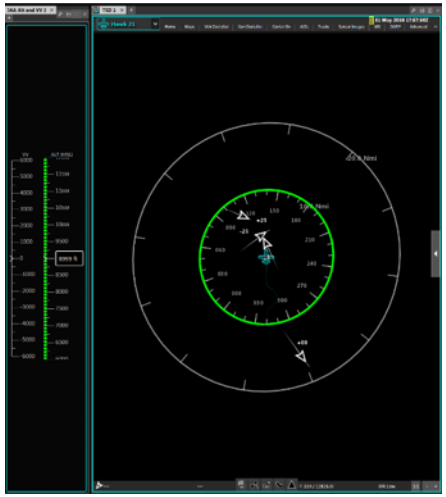
PT6 – Experimental Design

Symbol	Name	Pilot Action	Buffered Well Clear Criteria	Time to Loss of Well Clear	Aural Alert Verbiage
	TCAS RA	• ***Immediate action required*** • Comply with RA sense and vertical rate • Notify ATC as soon as practicable after taking action	*DMOD = 0.55 nmi *ZTHR = 600 ft *modTau = 25 sec	0 sec (+/- 5 sec) (TCPA approximate: 25 sec)	"Climb/Descend"
	DAA Warning Alert	• ***Immediate action required*** • Notify ATC as soon as practicable after taking action	DMOD = 0.75 nmi HMD = 0.75 nmi ZTHR = 450 ft modTau = 35 sec	25 sec (TCPA approximate: 60 sec)	"Traffic, Maneuver Now" x2
	Corrective DAA Alert	• On current course, ***corrective action required*** • Coordinate with ATC to determine an appropriate maneuver	DMOD = 0.75 nmi HMD = 0.75 nmi ZTHR = 450 ft modTau = 35 sec	55 sec (TCPA approximate: 90 sec)	"Traffic, Avoid"
	Preventive DAA Alert	• On current course, corrective action **should not be required** • Monitor for intruder course changes • Talk with ATC if desired	DMOD = 0.75 nmi HMD = 1.0 nmi ZTHR = 700 ft modTau = 35 sec	55 sec (TCPA approximate: 90 sec)	"Traffic, Monitor"
	Guidance Traffic	• **No action required** • Traffic generating guidance bands outside of current course	Associated w/ bands outside current course	X	N/A
	Remaining Traffic	• **No action required** • No coordination required	Within surveillance field of regard	X	N/A

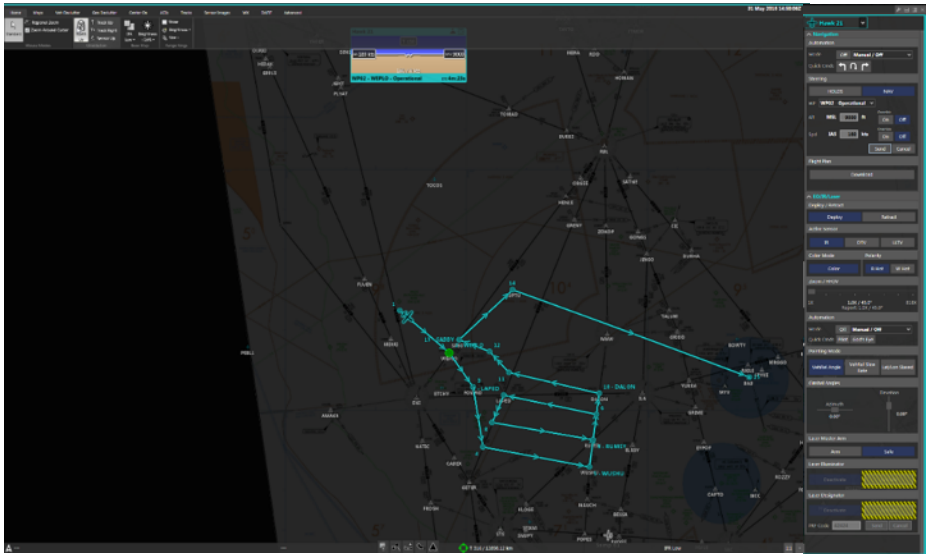
* These values show the Protection Volume (**not well clear volume**) at MSL 5000-10000ft (TCAS Sensitivity Level 5)

PT6 – Display Conditions

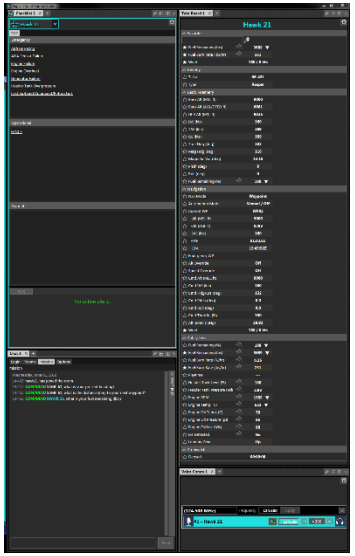
Standalone Configuration



DAA Display



TSD



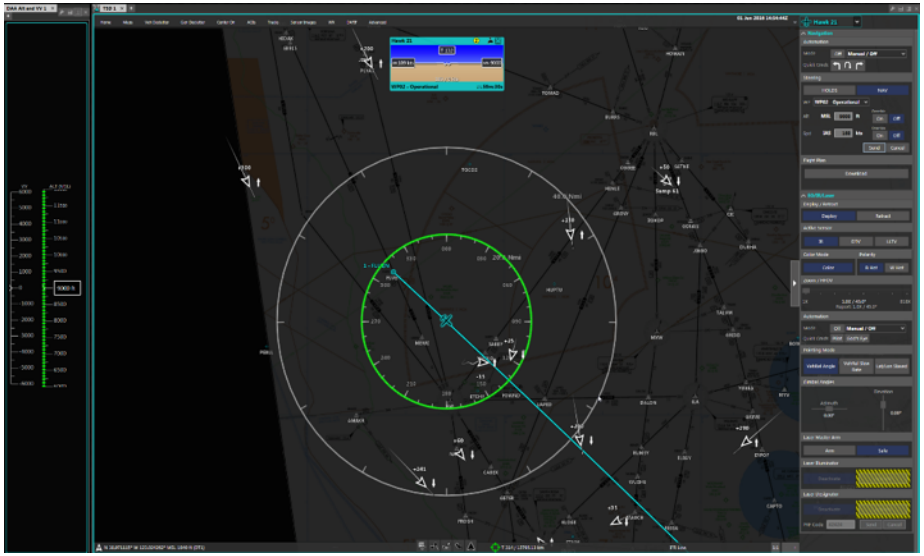
Side Panel

Notes:

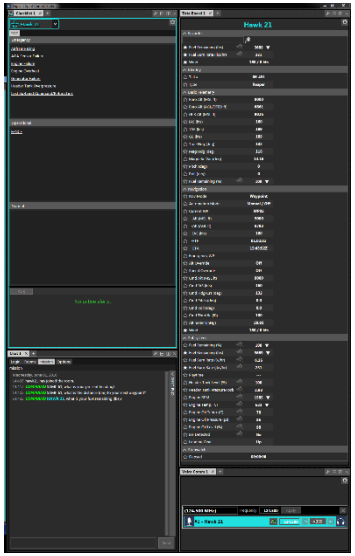
- Pilot could **only make uploads via TSD**; DAA Display only served as a traffic reference
- Pilots trained on how to adjust orientation on both DAA & TSD displays
  - North Up vs. Track Up, and whether orientations matched, was up to pilot discretion

PT6 – Display Conditions

Integrated Configuration



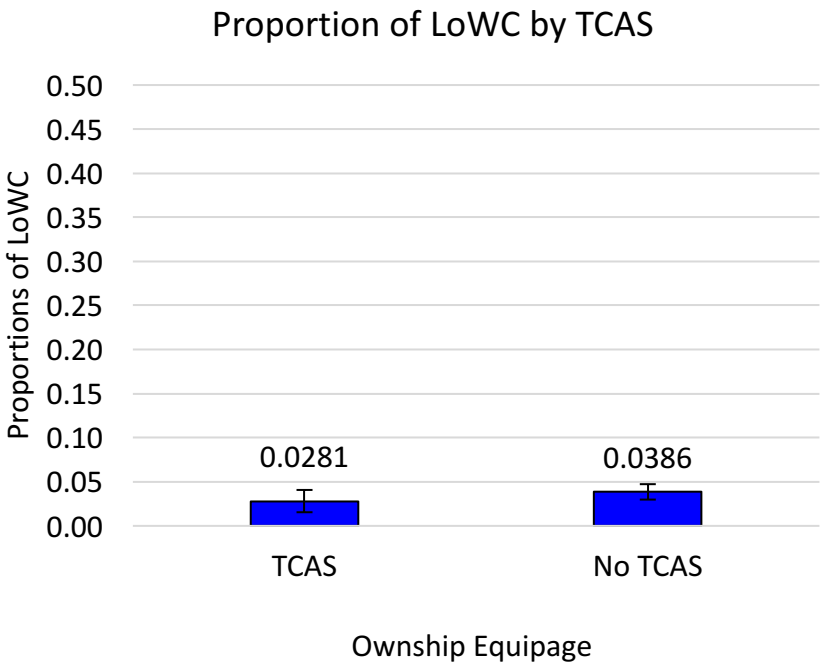
TSD w/ DAA Display

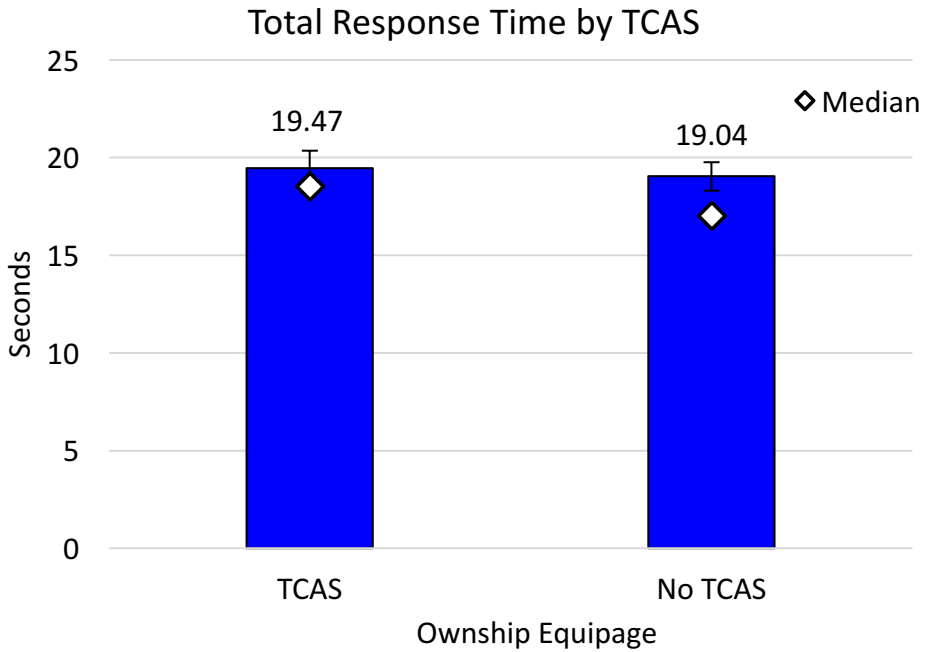


Side Panel

PT6 – TCAS II Effects

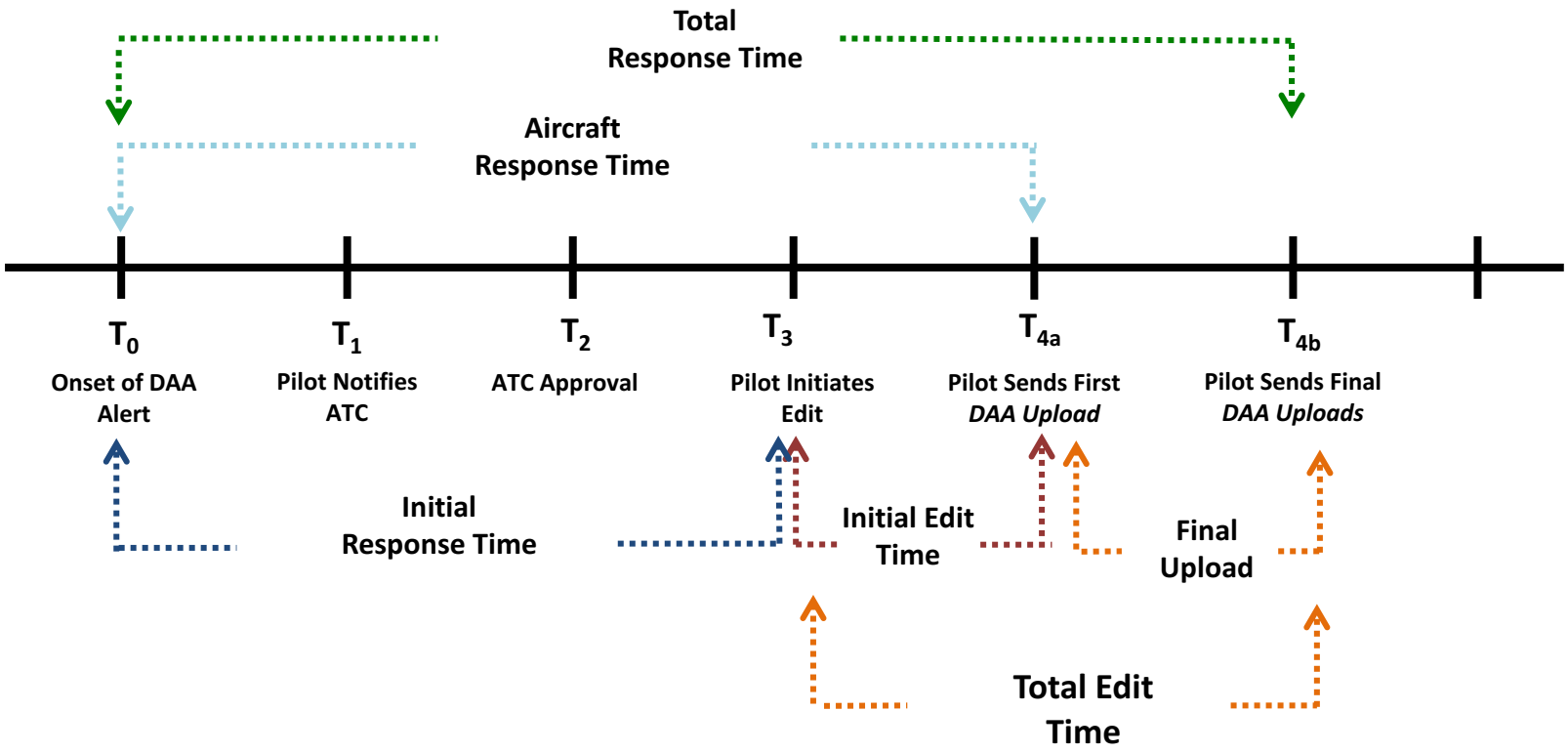
- TCAS II equipage was split between first half and second half of data collection
  - No significant main effect on proportion of LoWC
  - No significant main effect on total response time
- *Remaining results are collapsed across the TCAS variable*





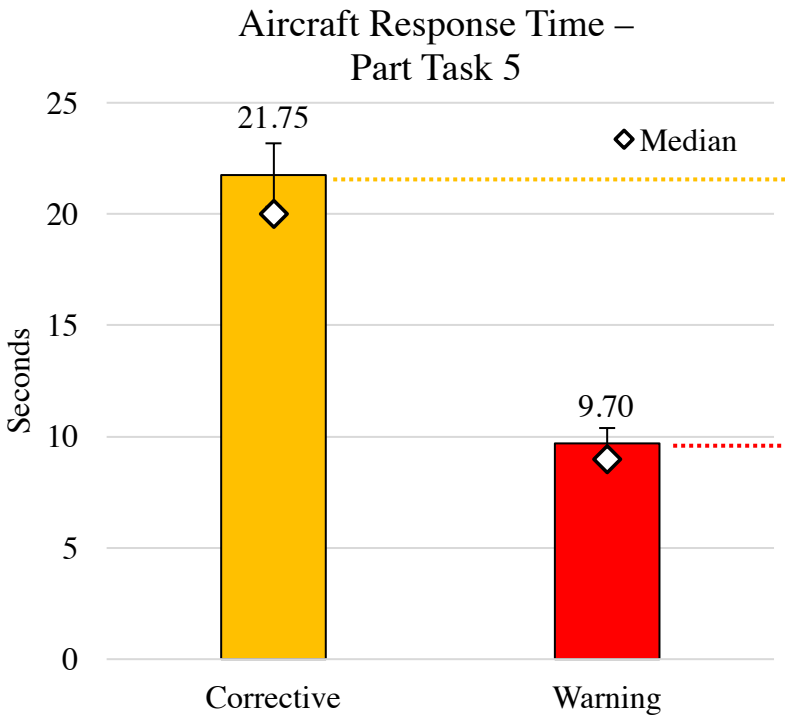
PT6 – Response Time Results

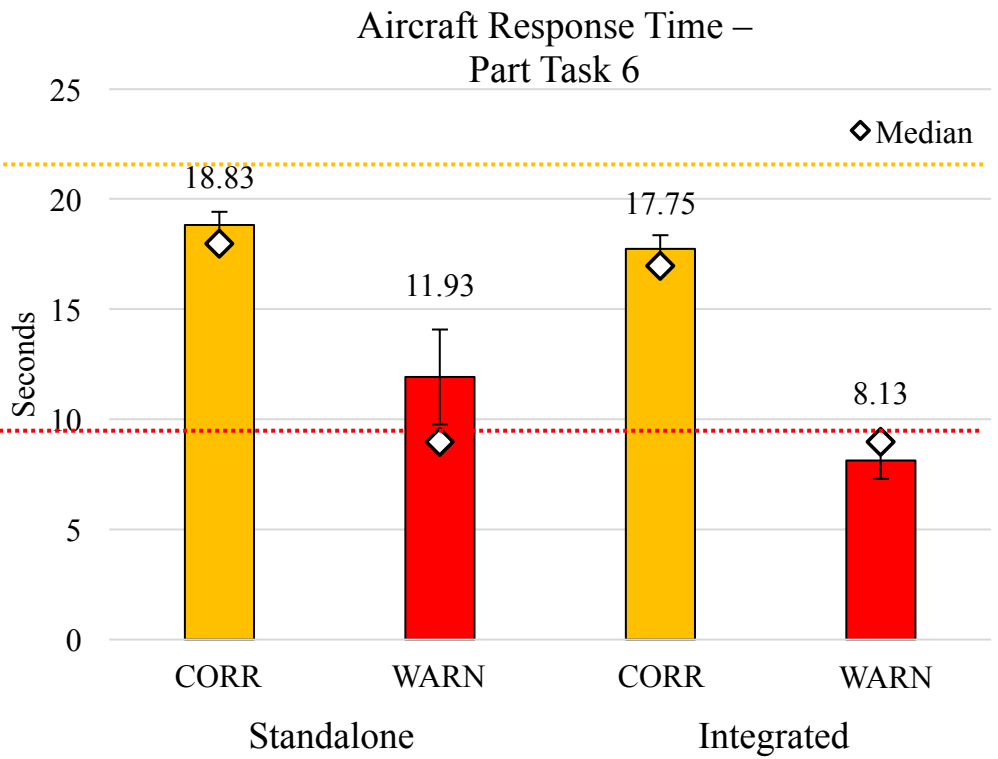
- PT6 to PT5 comparison uses aircraft response time instead of total response time
  - Difference is whether we are measuring at the first vs final upload



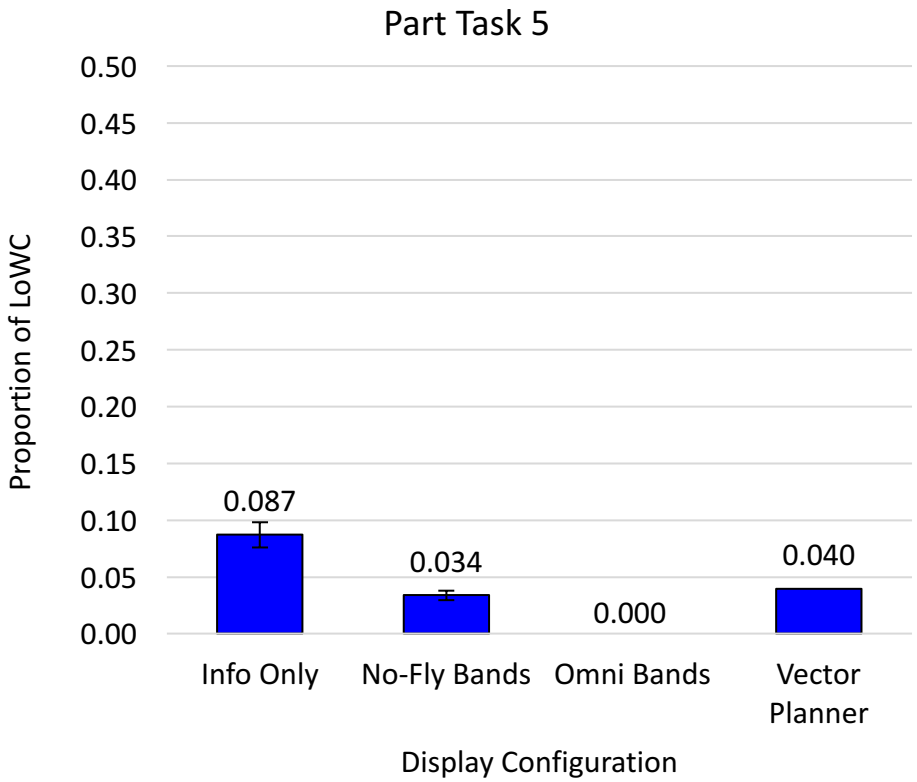
PT6 – Aircraft Response Time

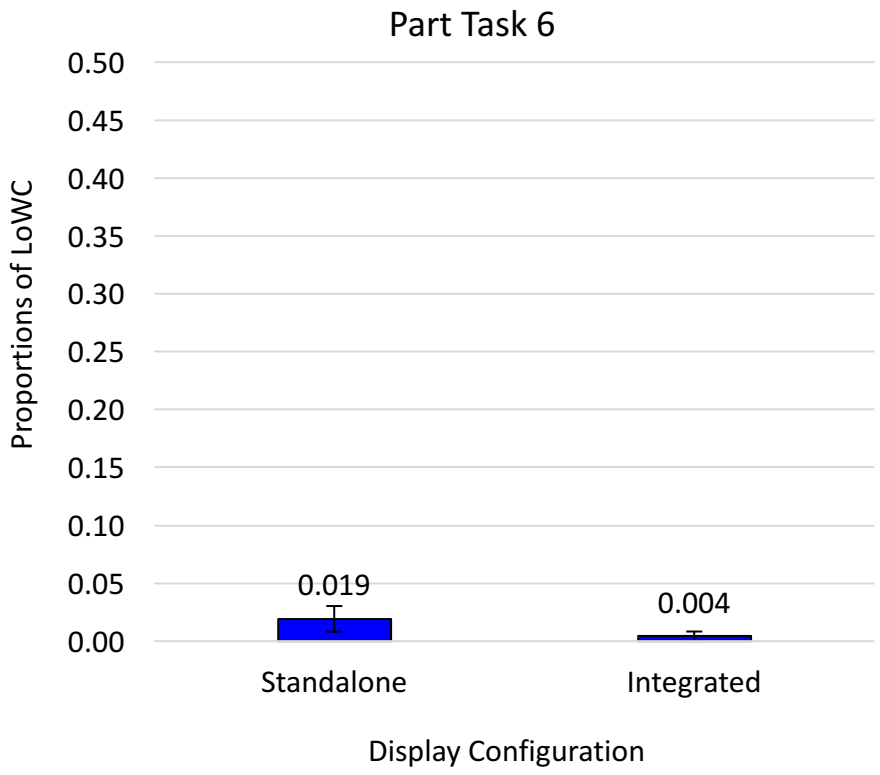
- Pilots sent their *first* upload to their aircraft **1 sec faster** in the Integrated display configuration (statistically significant; $p < .05$)
  - More pronounced difference between displays when separated by alert level
    - Pilots sent final upload **5.5 sec faster** (~30%) in response to DAA Warning alerts in Integrated display configuration
- Comparable to PT6 results, although response to Warning in Standalone configuration is slower in PT6





PT5 –Losses of Well Clear





- There was not a significant main effect of Display Configuration on Proportion of Losses of Well Clear, $p < .05$
- Proportion of LoWC where pilot was at fault (i.e., had enough time to respond) lower in PT6 than all conditions in PT5 *except for Omni Band*

PT5 – Results Summary

- Overall pilot performance was consistent with previous simulations when using minimum display, alerting & guidance requirements
  - On some measured response metrics performance was slightly better
  - Proportions of LoWC virtually identical
  - Standalone display resulted in little to no performance differences compared to the Integrated display configuration

❖ **Data supported display, alerting & guidance requirements as previously drafted**

Summary of Contributions to Phase 1 MOPS

Summary of NASA HITL Contributions to SC-228

- Suggestive DAA guidance requirements
- Alerting logic and thresholds
- Integrated or standalone*
- Pilot response timeline
  - Derived RADAR Requirements
- V&V of alerting, guidance and display draft MOPS

PT4, iHITL, PT5, PT6 HITLs

- TCAS/DAA interoperability concept
  - Requirements for DAA guidance and alerting
- Well Clear Recovery guidance logic/display

DAA-TCAS Interoperability HITL

- Alerting and guidance logic for special cases
  - E.g., no altitude, no bearing
- Alerting and guidance displays for special cases

Special Cases Mini HITL

Questions?