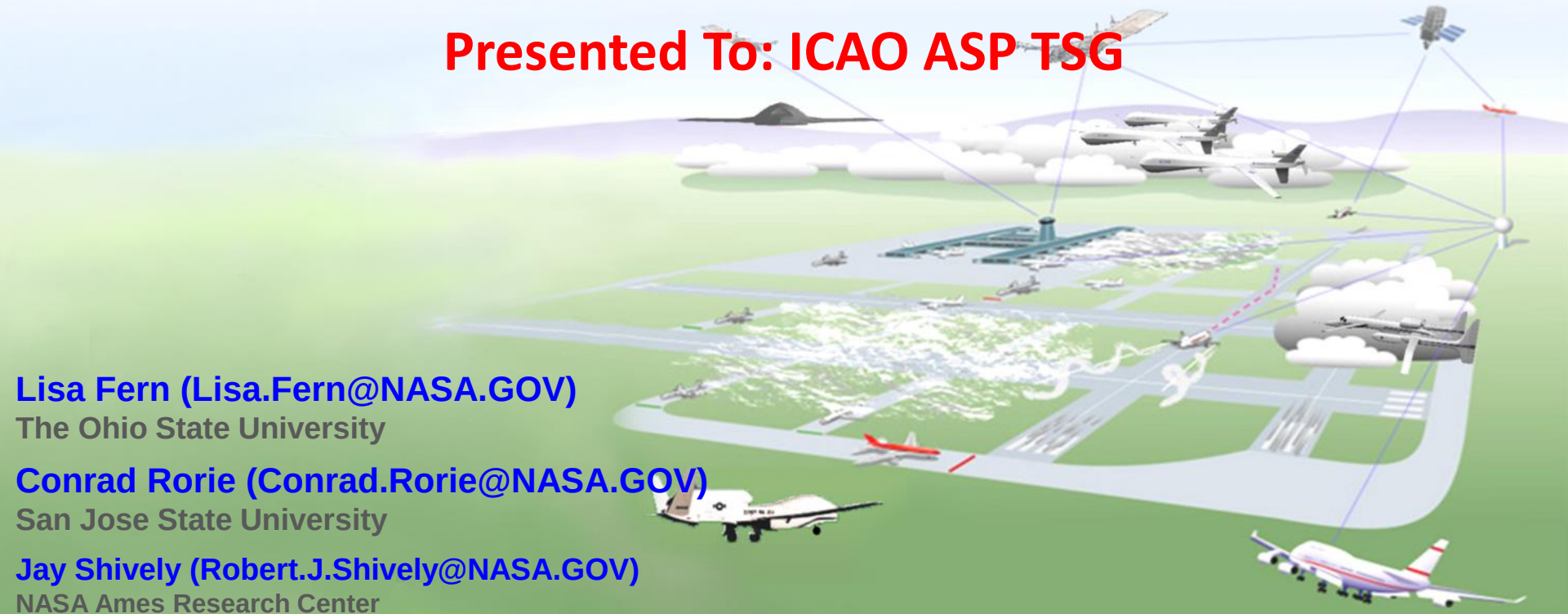
National Aeronautics and Space Administration

UAS Integration into the NAS: Detect and Avoid Display Evaluations in Support of SC-228 MOPS Development

Presented To: ICAO ASP TSG



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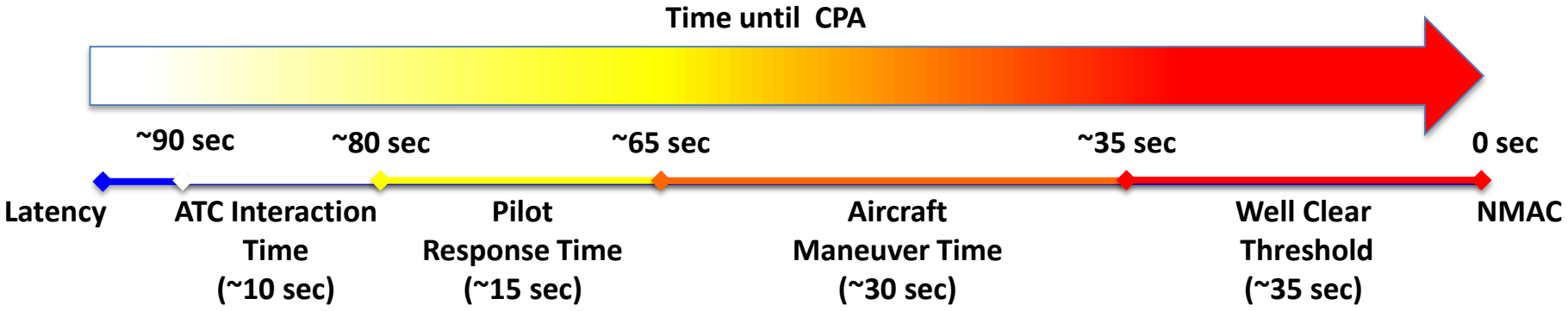
Self-Separation Timeline



Background

- Goal: Provide data on the effect of various Detect and Avoid (DAA) display features with respect to pilot performance of the self-separation function in order to determine the minimum information requirements for DAA displays
  1. What is the pilot contribution to the self-separation timeline in terms of expected response time to detect, determine and execute a maneuver in response to a potential loss of well clear?
  2. What configuration of display elements meets a minimum acceptable level of performance? What, if any, level of pilot maneuver guidance is required to support this performance?

Background

- Display Types:
  - Informative: Provides essential information of a hazard that the remote pilot may use to develop and execute an avoidance maneuver. ***No maneuver guidance or decision aiding is provided to the pilot***.
  - Suggestive: ***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: ***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.

Background

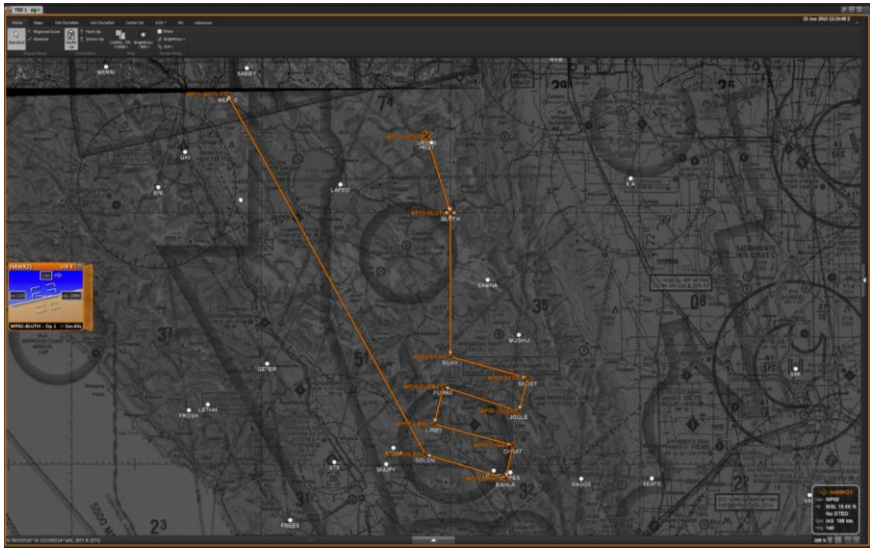
- Approach: Conduct a series of iterative human in the loop experiments, in a representative simulation environment, with different display configuration to objectively measure pilot performance on maintaining well clear
  - Key metrics: pilot response time, losses of well clear, severity of losses of well clear
  - Three simulations have been conducted: PT4, iHITL, PT5
    - Displays are modified/improved/changed based on data/observations
    - Displays are carried through to new HITLs to create anchors or linkages to previous data for comparison
    - New displays are developed for test
    - Test/simulation environment/protocols also updated and improved between HITLs

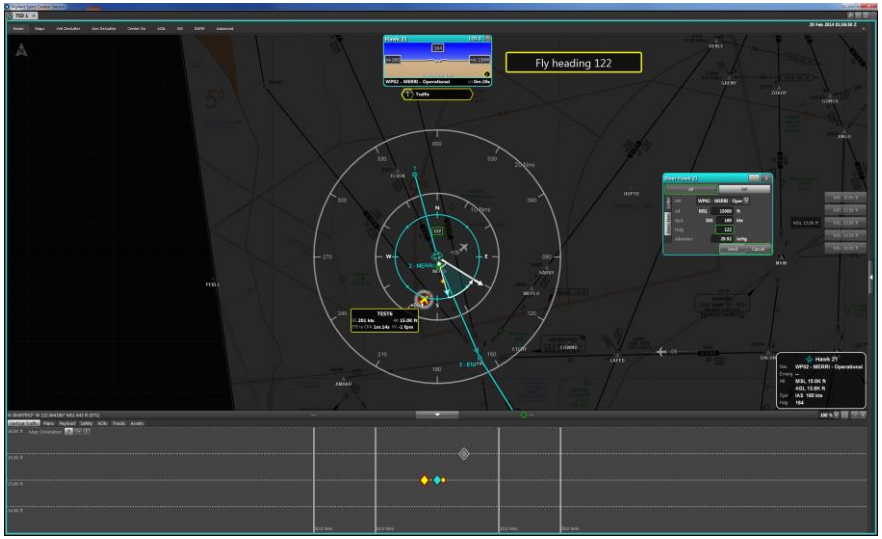
Simulation Environment

- 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

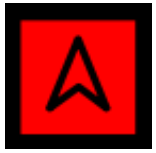




Simulation Environment: DAA System

- 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 (MACS)
    - Determine which aircraft to show on traffic display(s) based on surveillance parameters
  - Receive trajectory information from UAS ownship (VSCS)
  - Queries all intruders for potential conflicts with ownship
  - Assigns intruders alert levels based on given thresholds
  - Host self-separation and collision avoidance algorithms which can provide conflict resolution guidance

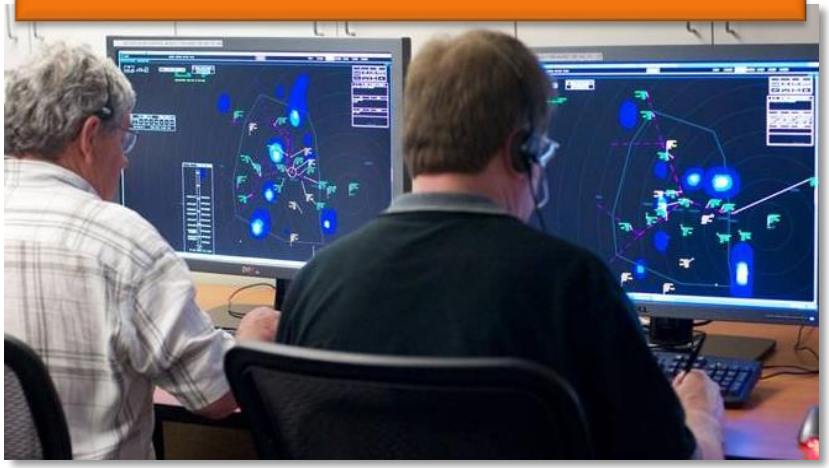
Simulation Environment: Draft MOPS Alerting Structure

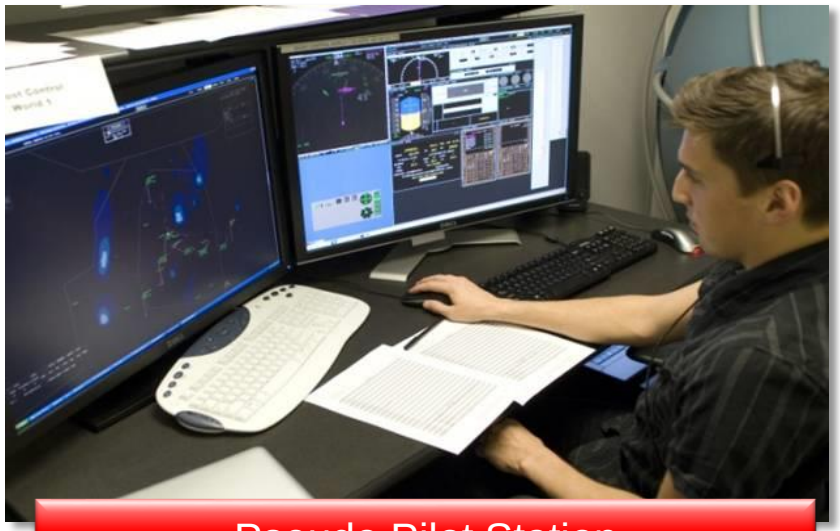
Symbol	Name	Pilot Action	Buffered Well Clear Criteria	Time to Loss of Well Clear	Aural Alert Verbiage
	Self Separation Warning Alert	• ***Immediate action required*** • Notify ATC as soon as practicable after taking action	DMOD = 0.75 nmi HMD = 0.75 nmi ZTHR = 450 ft modTau = 35 sec	25 sec (TCPA approximate: 60 sec)	"Traffic, Maneuver Now"
	Corrective Self Separation 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	75 sec (TCPA approximate: 110 sec)	"Traffic, Separate"
	Preventive Self Separation 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	75 sec (TCPA approximate: 110 sec)	"Traffic, Monitor"
	Self Separation Proximate Alert	• Monitor target for potential increase in threat level	DMOD = 0.75 nmi HMD = 1.5 nmi ZTHR = 1200 ft modTau = 35s	85 sec (TCPA approximate: 120 sec)	N/A
	None (Target)	• No action expected	Within surveillance field of regard	X	N/A

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

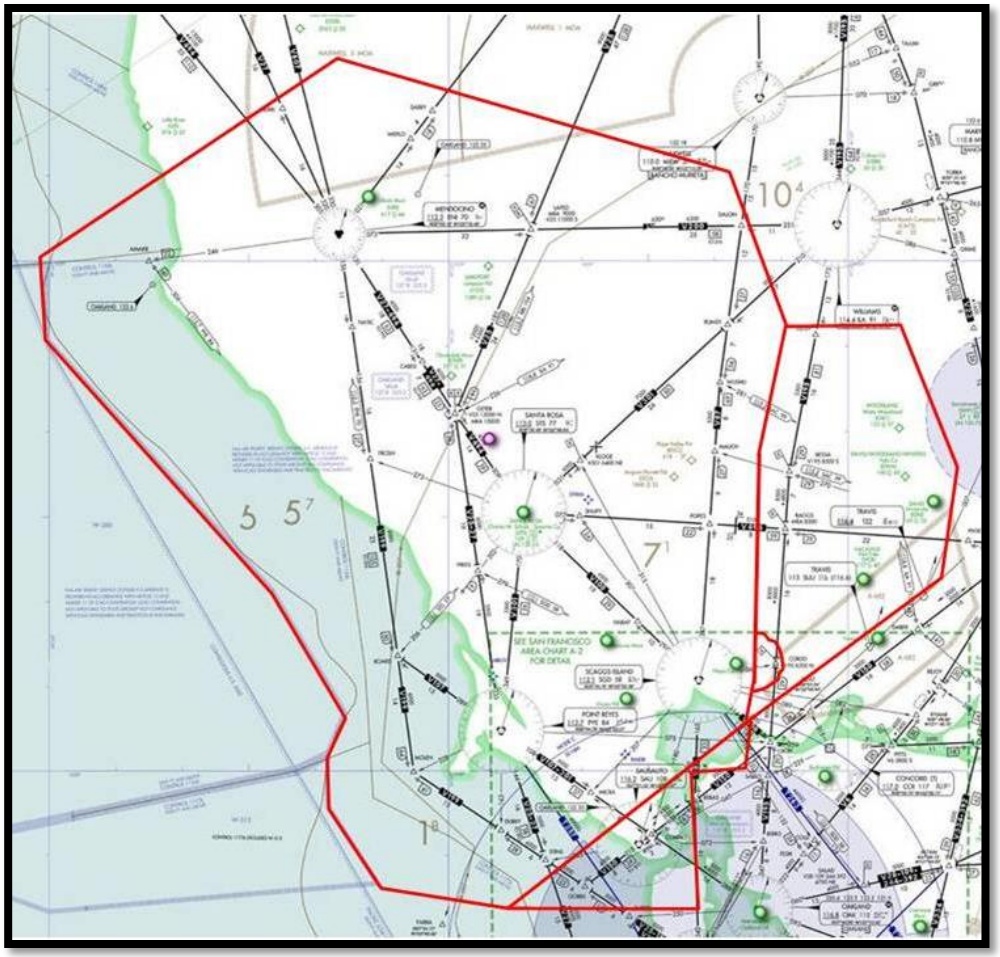
Air Traffic Control Station





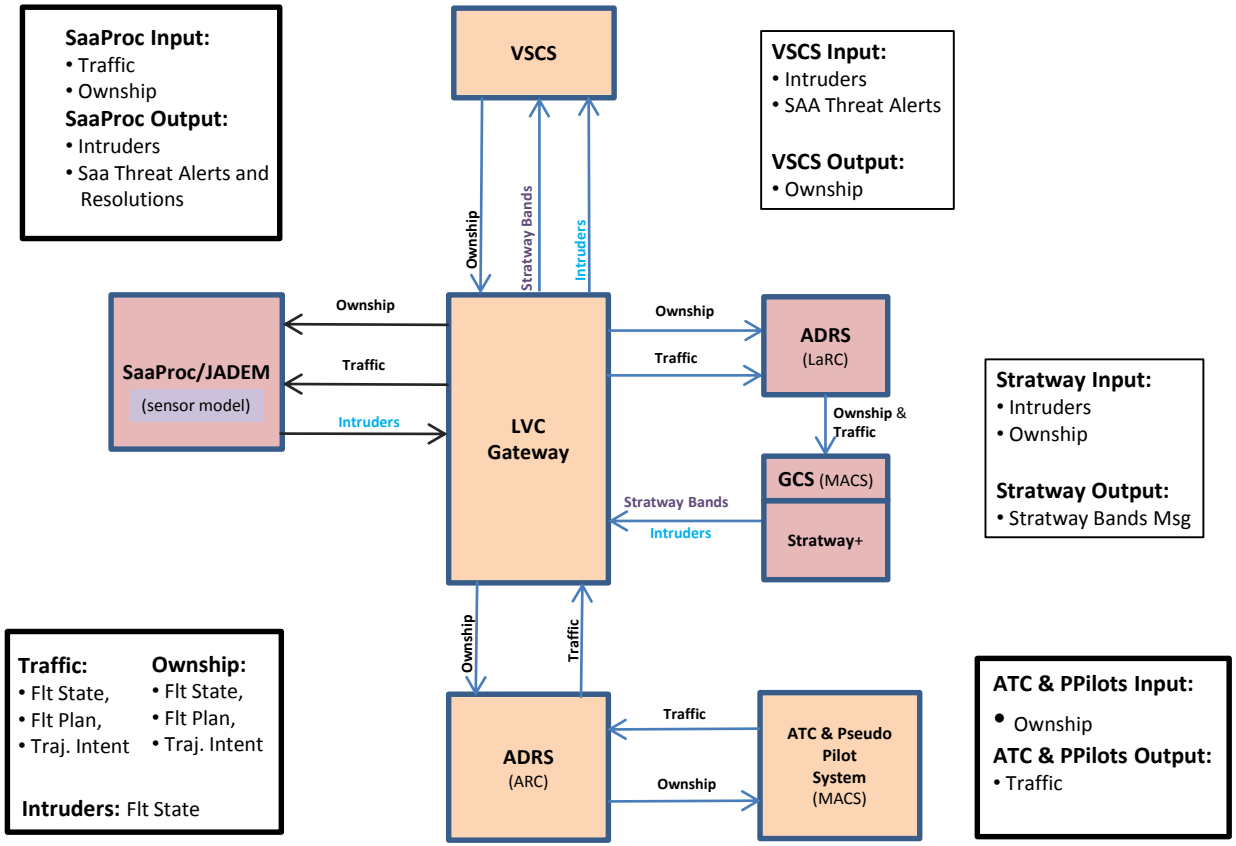
Pseudo Pilot Station

Simulation Environment: Multi Aircraft Control Station (MACS)



- Oakland Center ZOA 40/41
  - Class A & E
  - Current day IFR and VFR traffic flows
- UAS mission scenario derived from FAA CONOPS scenarios (combination of “Loiter for Surveillance” and “Grid Pattern”)

Simulation Environment: LVC Architecture



Background

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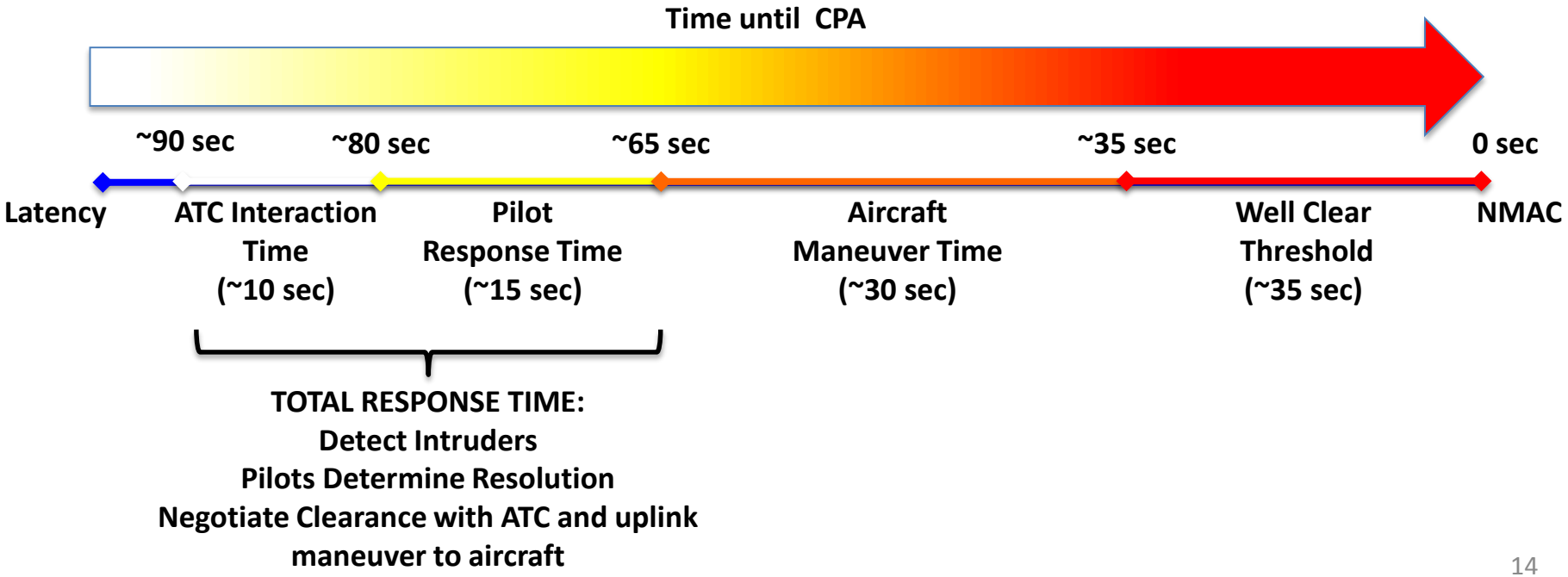
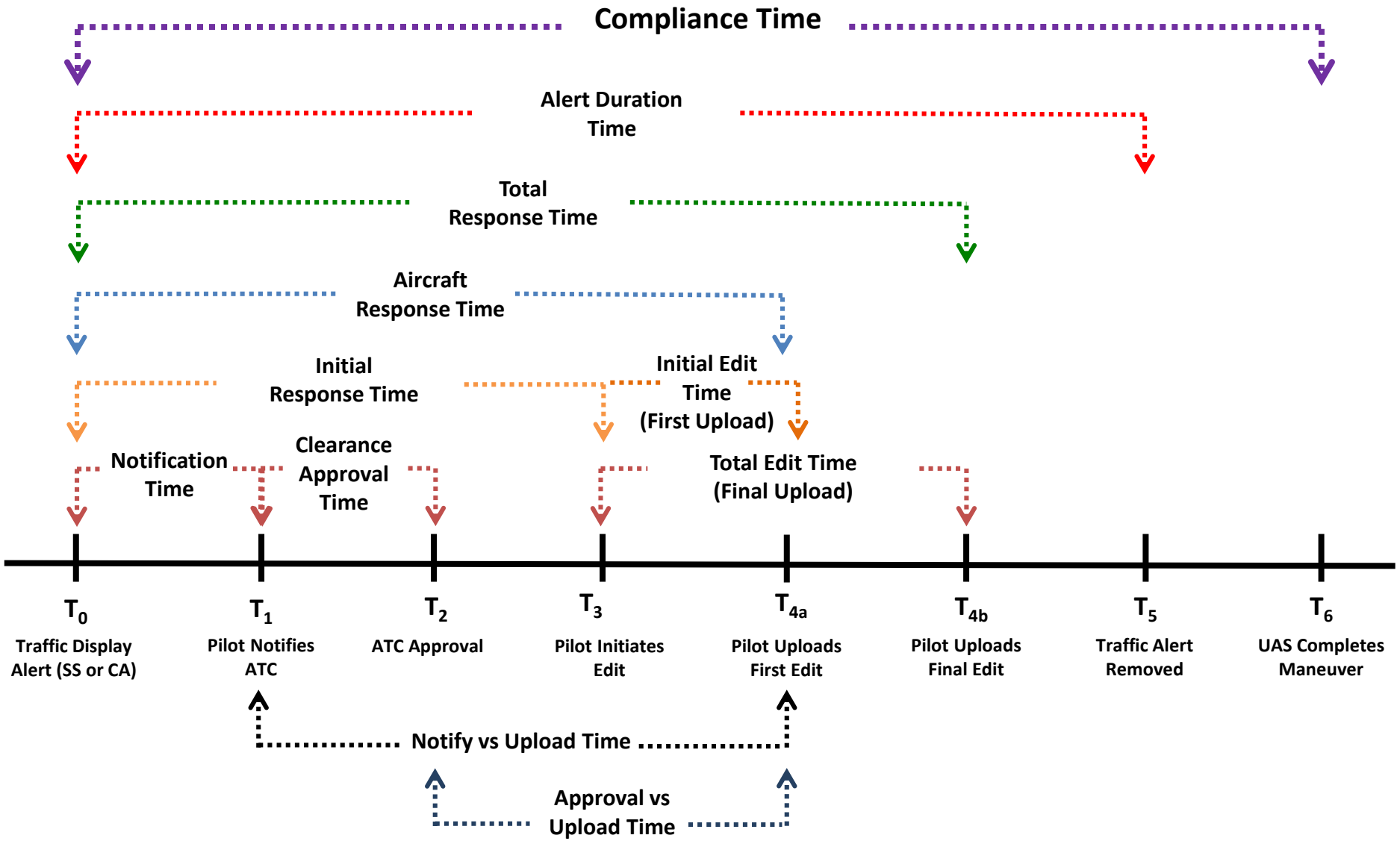
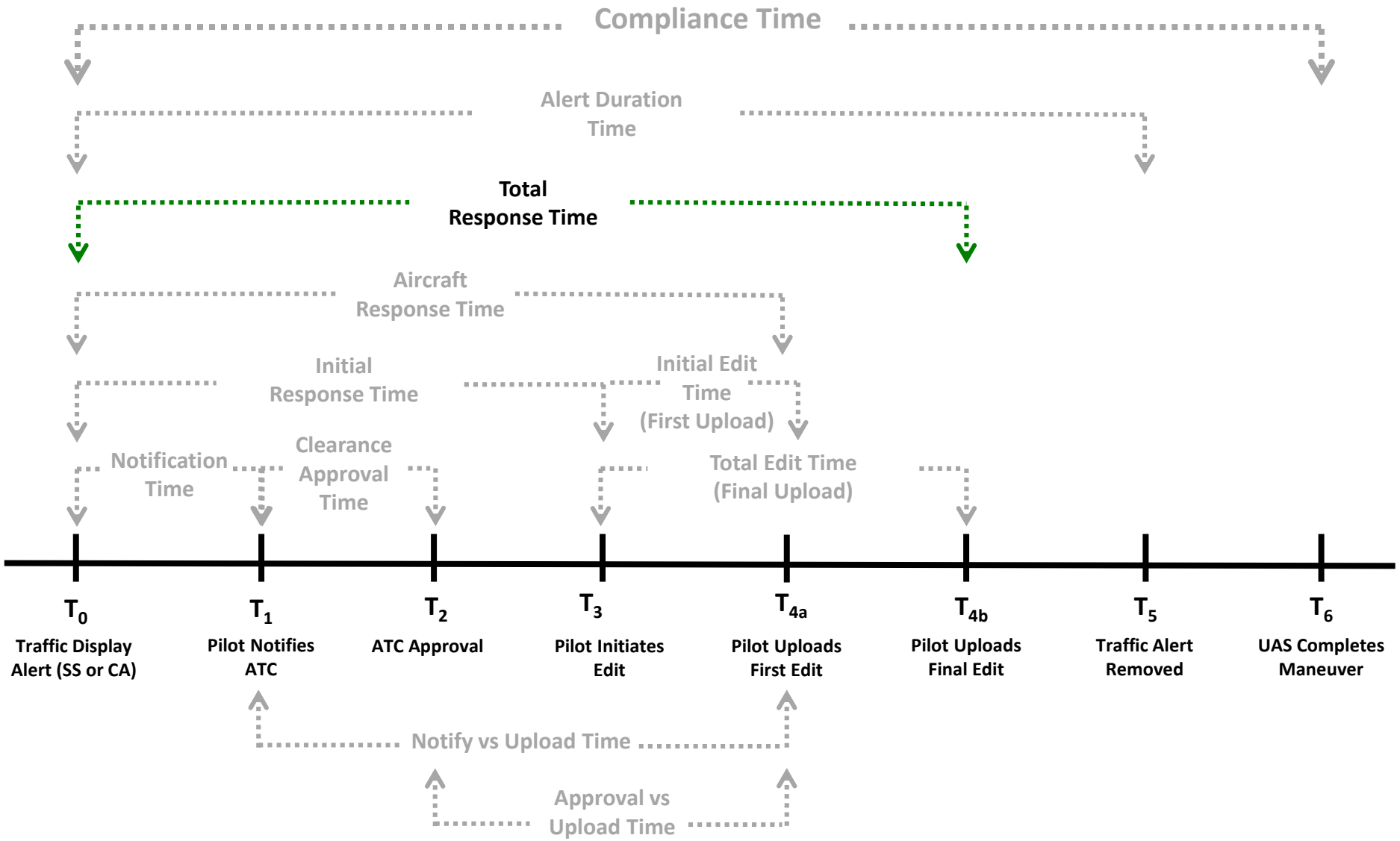
Self-Separation Timeline



Self-Separation Timeline



Self-Separation Timeline



PT4 – Experimental Design

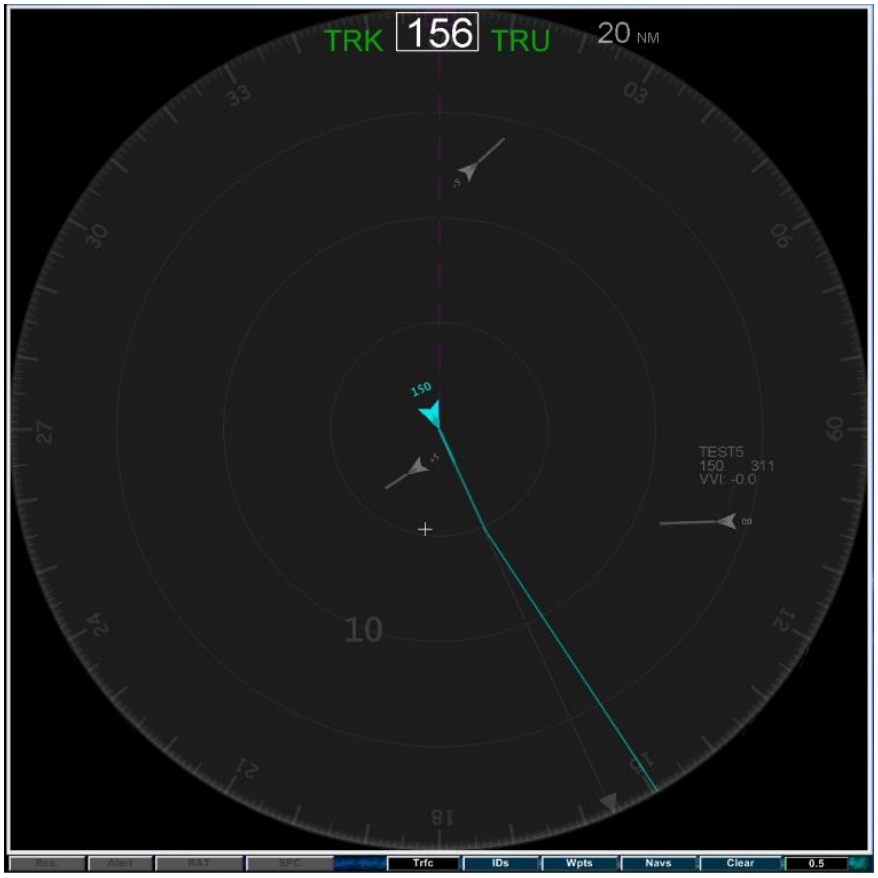
- Goal: Evaluate candidate Detect and Avoid (DAA) displays and algorithms with respect to self-separation and collision avoidance.
  - What are the appropriate alerting thresholds for self separation?
  - What are the minimum information requirements for DAA displays?
  - Is there a performance difference 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 – Information Level

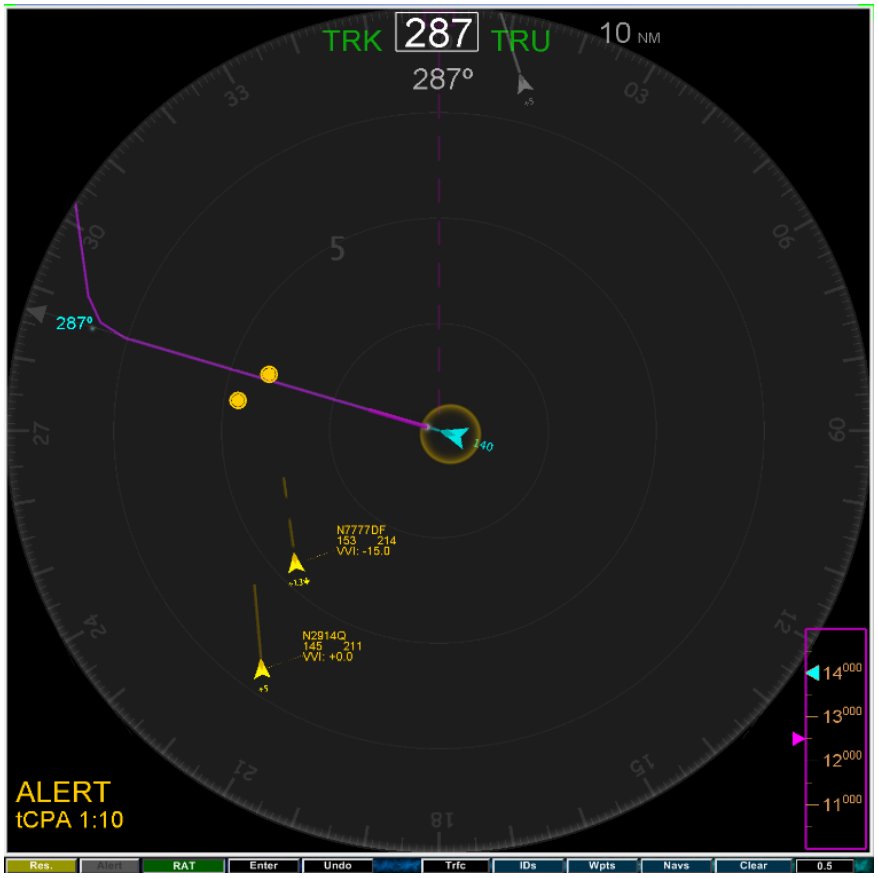
- Display Information Level: Basic versus Advanced
  1. Basic presents minimum information requirements only
     - Implementation identical as possible between Standalone and Integrated displays
     - Based on separate literature/requirements reviews by NASA and AFRL HMI teams
     - Vetted with FAA tech center (based on study they were running)
     - Similar to DO-317B (was a source document)
     - Alerting considered part of the min set
  2. Advanced information elements:
     - Implementation different between Standalone and Integrated displays
     - Additional alerting information (predictive CA)
     - Time to and location of predicted CPA (intruder and ownship)
     - Pilot guidance
       - Trial/vector planner (suggestive)
       - Maneuver recommendations (directive)
     - Vertical situation display (Integrated only)

PT4 – Standalone Displays

Basic

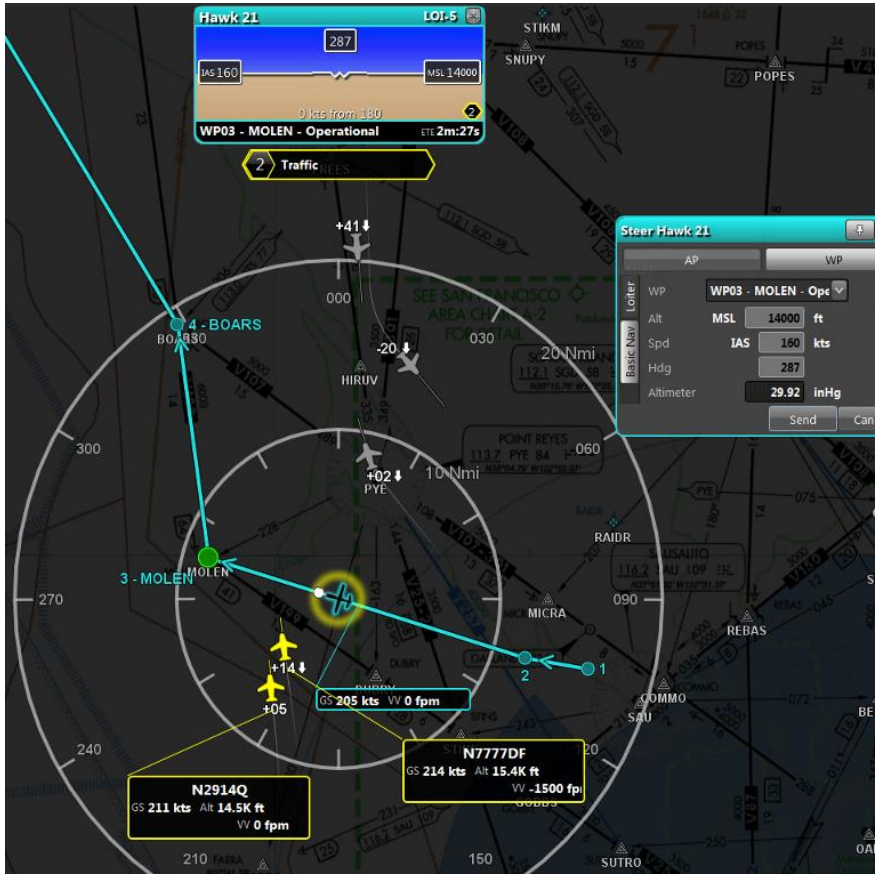


Advanced



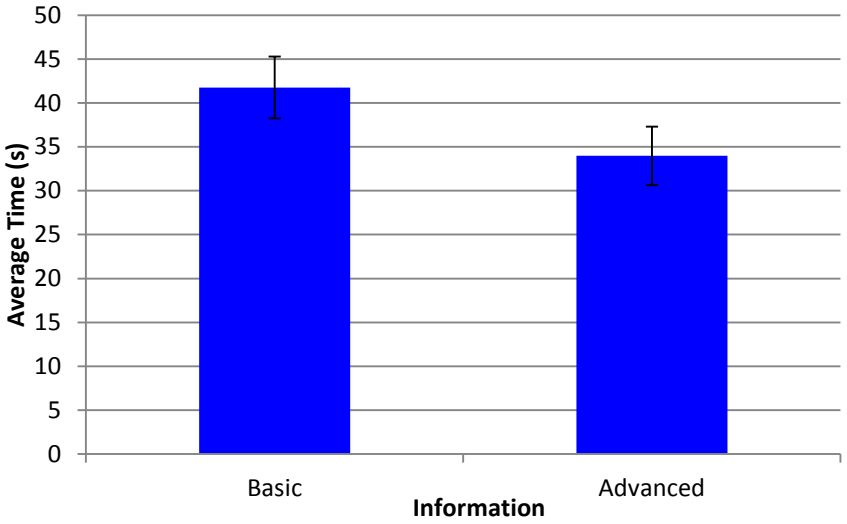
PT4 – Integrated Displays

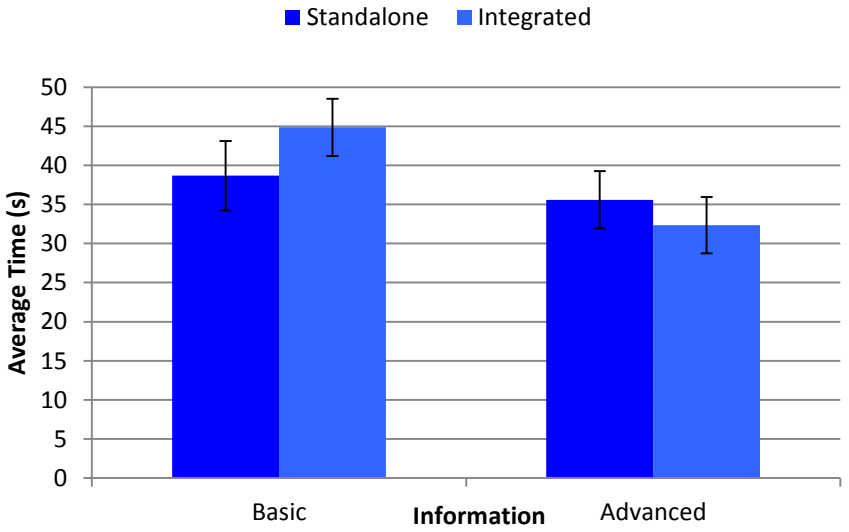
Basic



Advanced

PT4 – Total Response Time Results

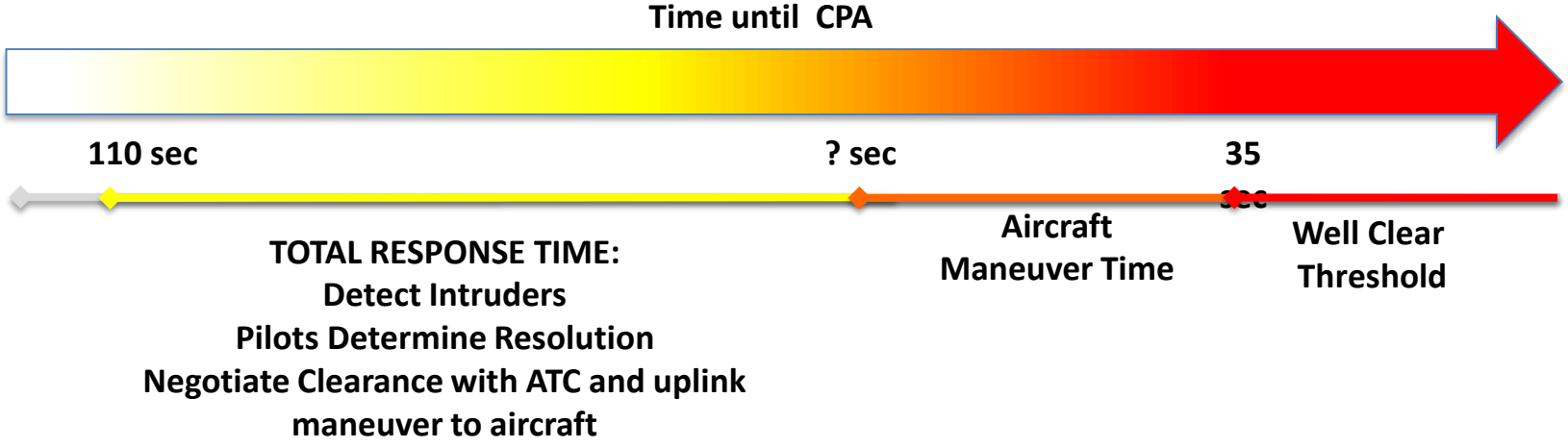




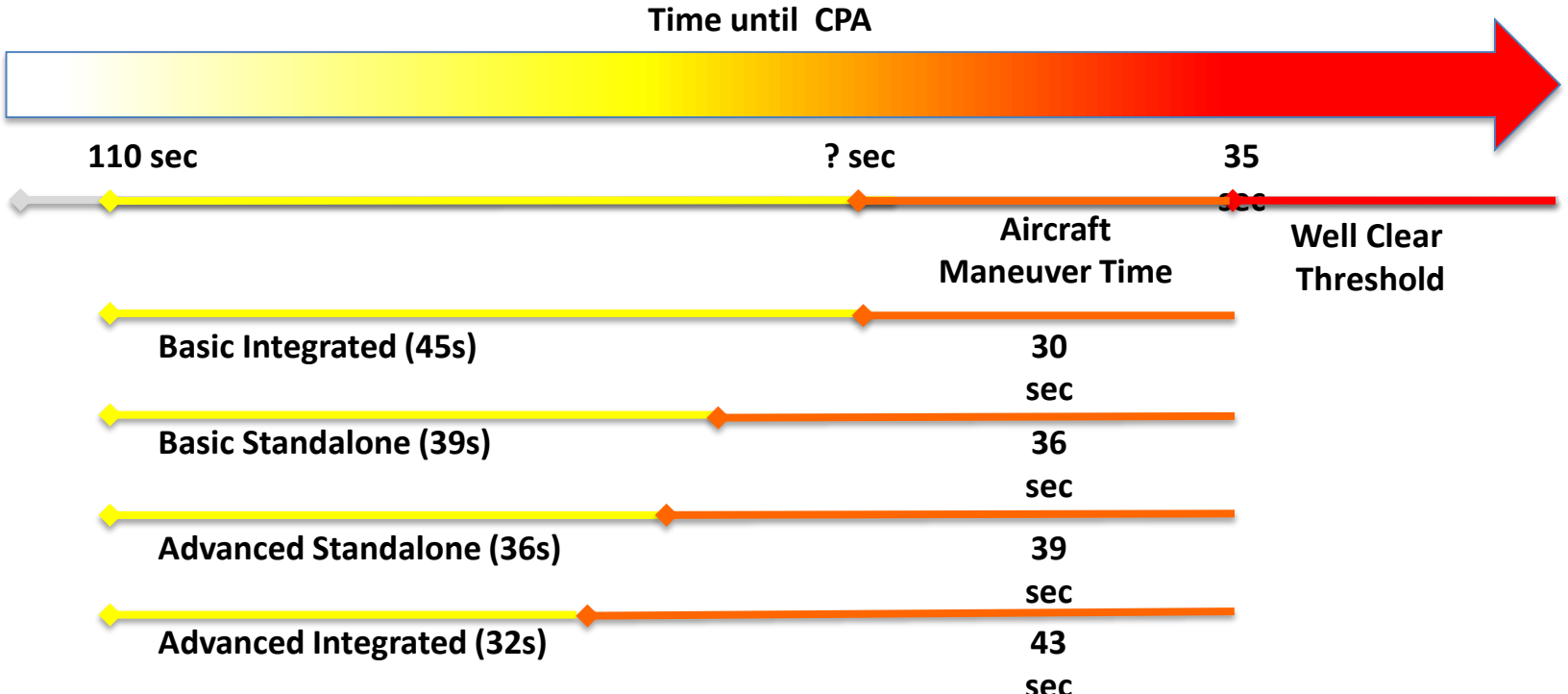
- There was a significant main effect of Information on Total Response Time, $p < .05$
  - Advanced was significantly faster (by 13.79 seconds on average) compared to Basic
- Pilots took an average of **37.87 seconds** to complete their final edit in response to SS/CA alerts (from first alert appearance)
  - Basic = 47.77 sec
  - Advanced = 33.98 sec

- There was not a significant interaction of Information by Display for Total Response Time, $p > .05$
- Pilots took an average of **37.87 seconds** to complete their final edit in response to SS/CA alerts (from first alert appearance)
  - Basic Standalone = 38.68 sec
  - Basic Integrated = 44.86 sec
  - Advanced Standalone = 35.60 sec
  - Advanced Integrated = 32.35 sec

Self-Separation Timeline

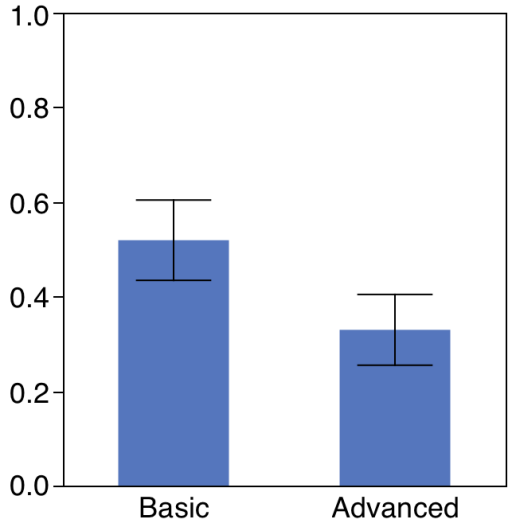


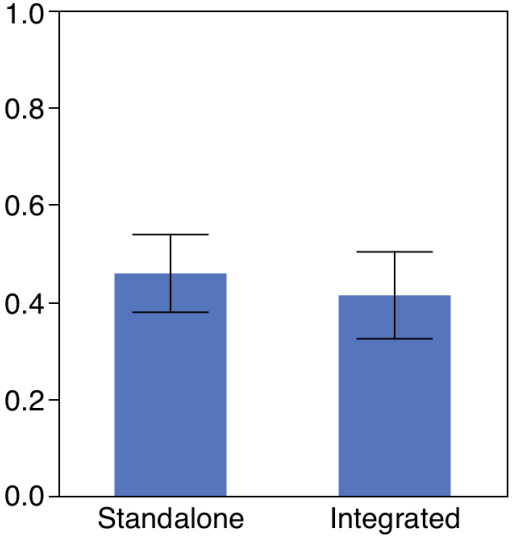
PT4 – Response Time Results

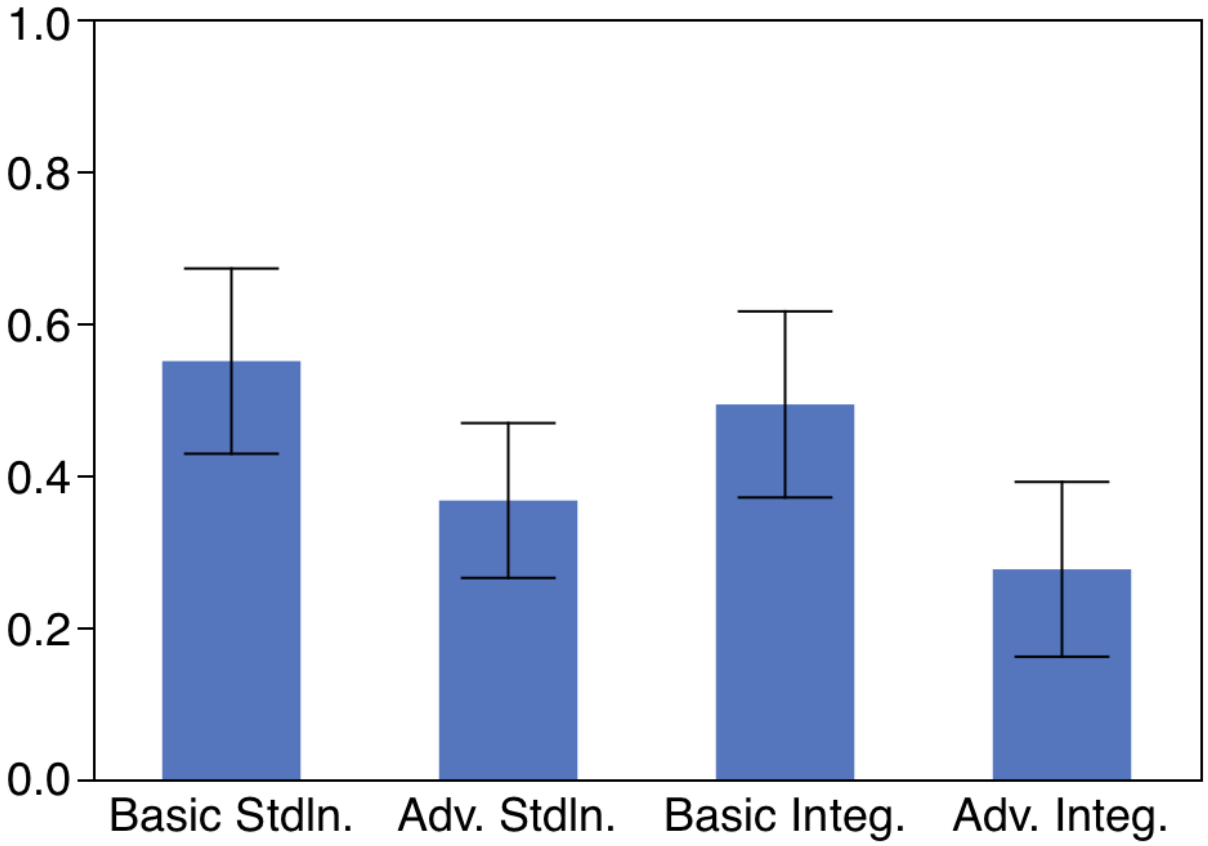


PT4 – Losses of Well Clear

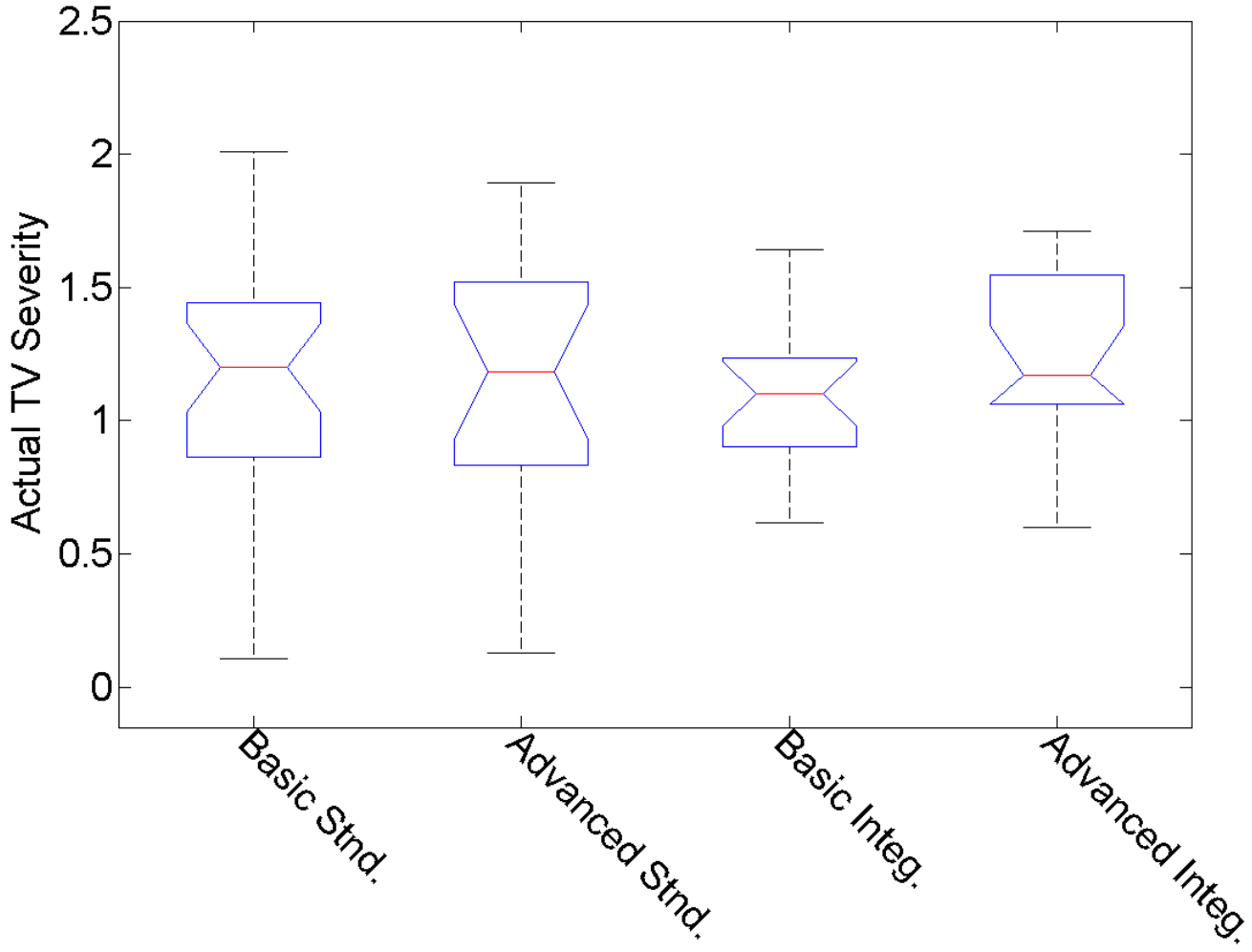
Proportion of Losses of Well Clear







PT4 – WCV Severity



PT4 – Results Summary

- Consistent advantage seen for Advanced over Basic displays in pilot response times
  - Overall, the Advanced displays had a faster Total Response Time (from initial alert appearance to the final maneuver upload) compared to Basic (14s faster, on average)
- There were no significant differences between the Standalone and Integrated condition
- No significant differences in number of, or severity of, losses of well clear, however:
  - Advanced had lower rates of LoWC than basic
  - No difference between Standalone and Integrated in rates of LoWC
  - Severity of well clear about the same across all displays

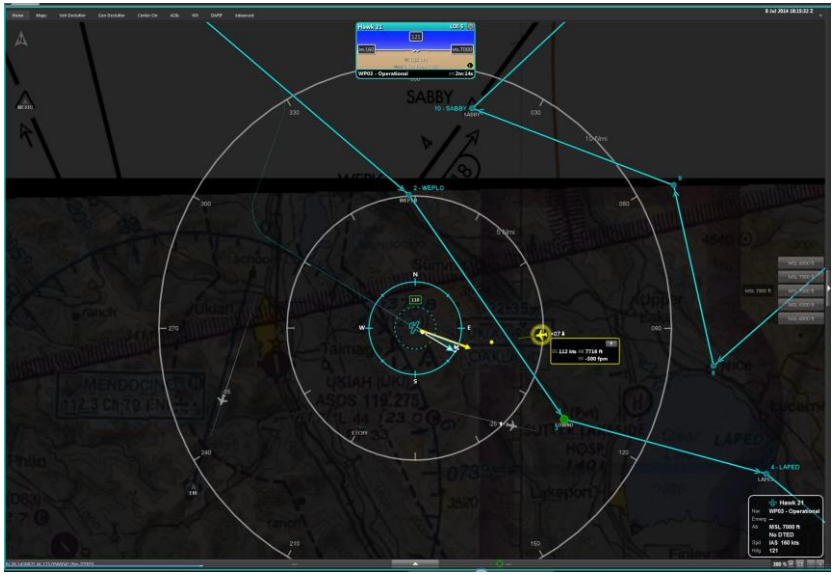
iHITL – Experimental Design

- Goals:
  1) Determine the individual contributions of the various PT4 advanced display features to pilots' response times and ability to maintain well clear
  2) Introduce non-cooperative intruders to examine effect of different sensor ranges on pilots 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
- Embedded Variable
  - *Intruder Equipage* (manipulated within each scenario)
    - Transponder-equipped (detected via UAS's ADS-B)
    - No Transponder (detected via UAS's on-board RADAR)

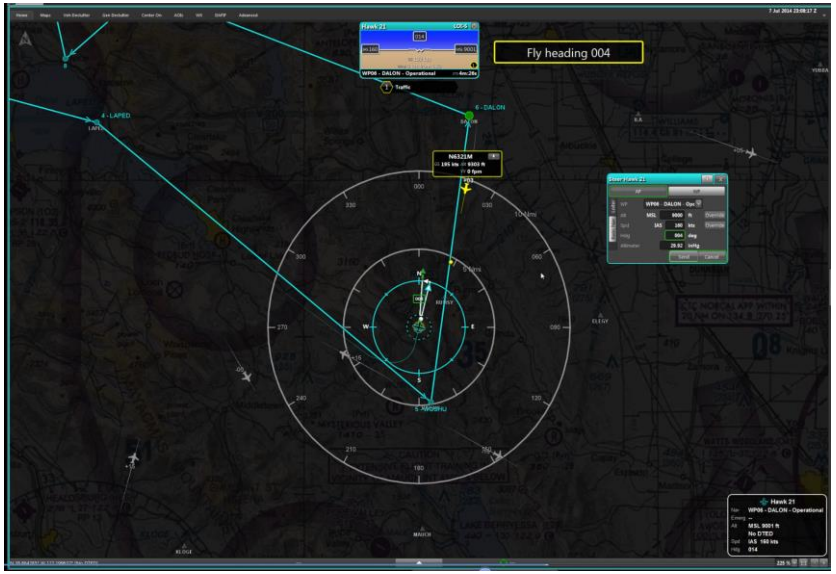
iHITL – Display Conditions

D1

D2



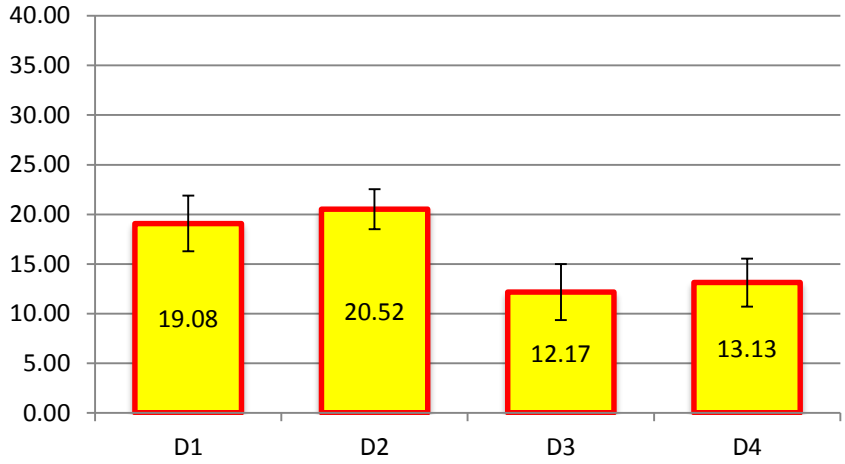
D3



D4

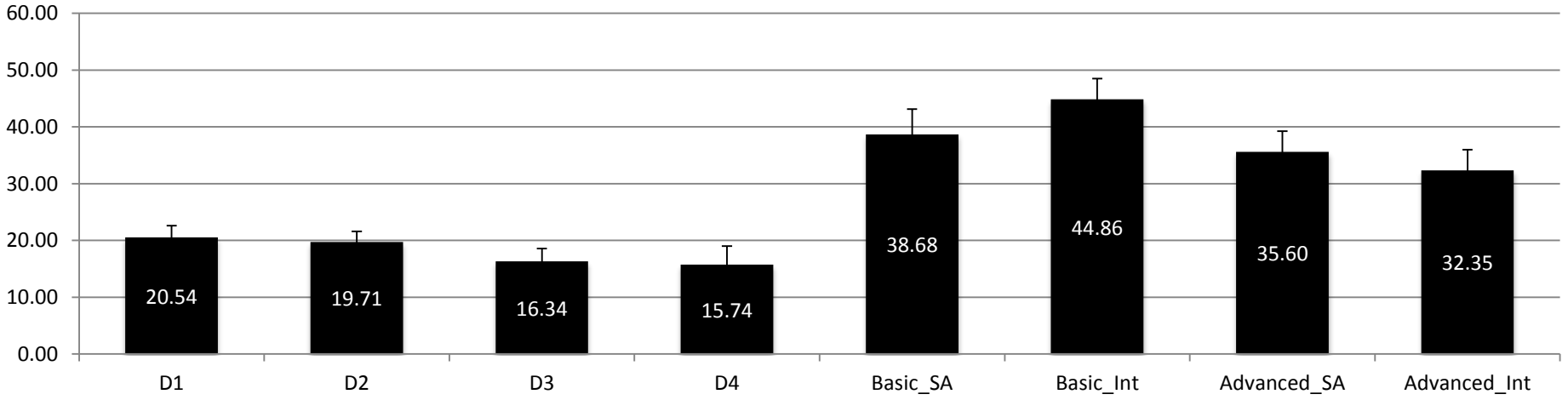
iHITL – Total Response Time Results

Predictive SS Alerts

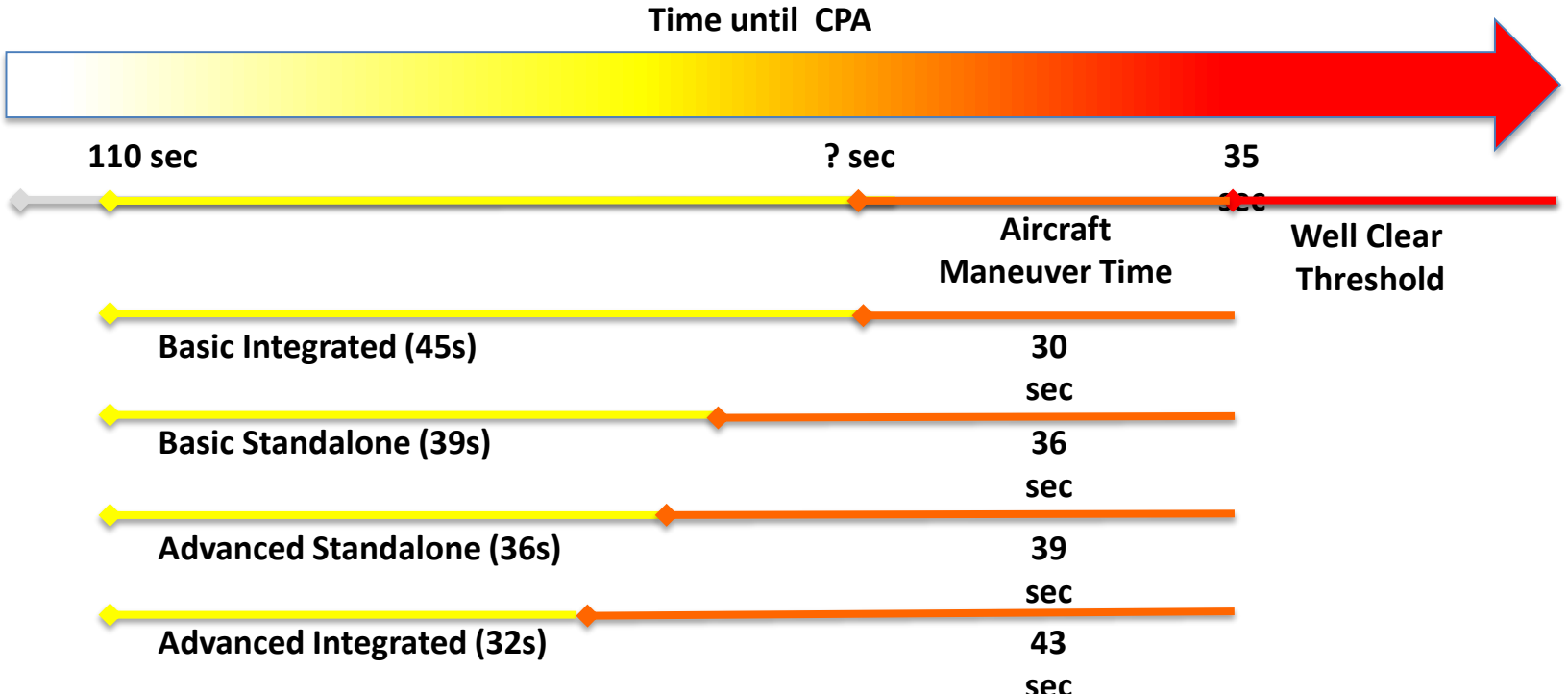


- Predictive SS = encounters that are predicted to lose well clear at any point during the encounter
- There was a near significant effect of Display on Total Response Time for Predictive SS alerts, p = .056
- Pilots took an average of **16.22 seconds** to complete their final edit in response to Predictive SS alerts (from first alert appearance)

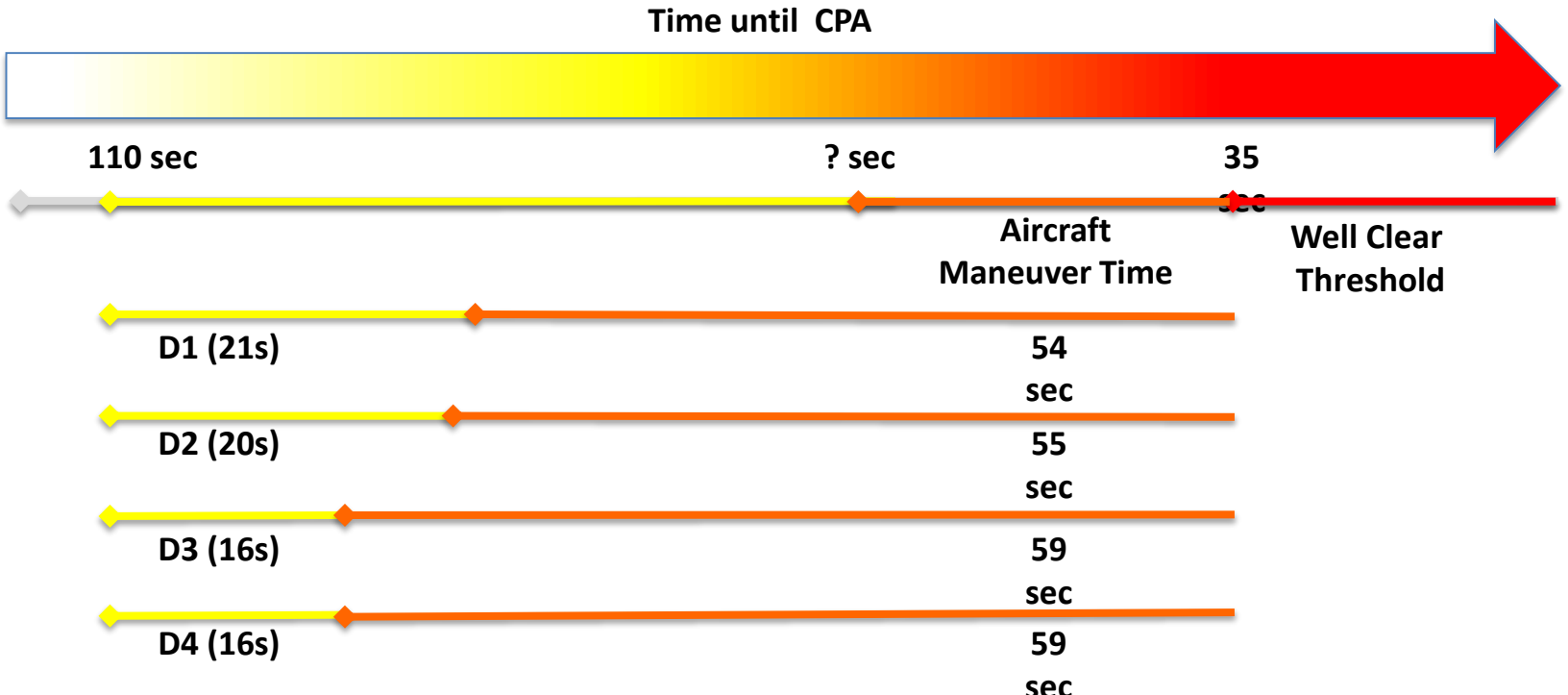
IHITL and PT4 Display Comparison (All Encounters)



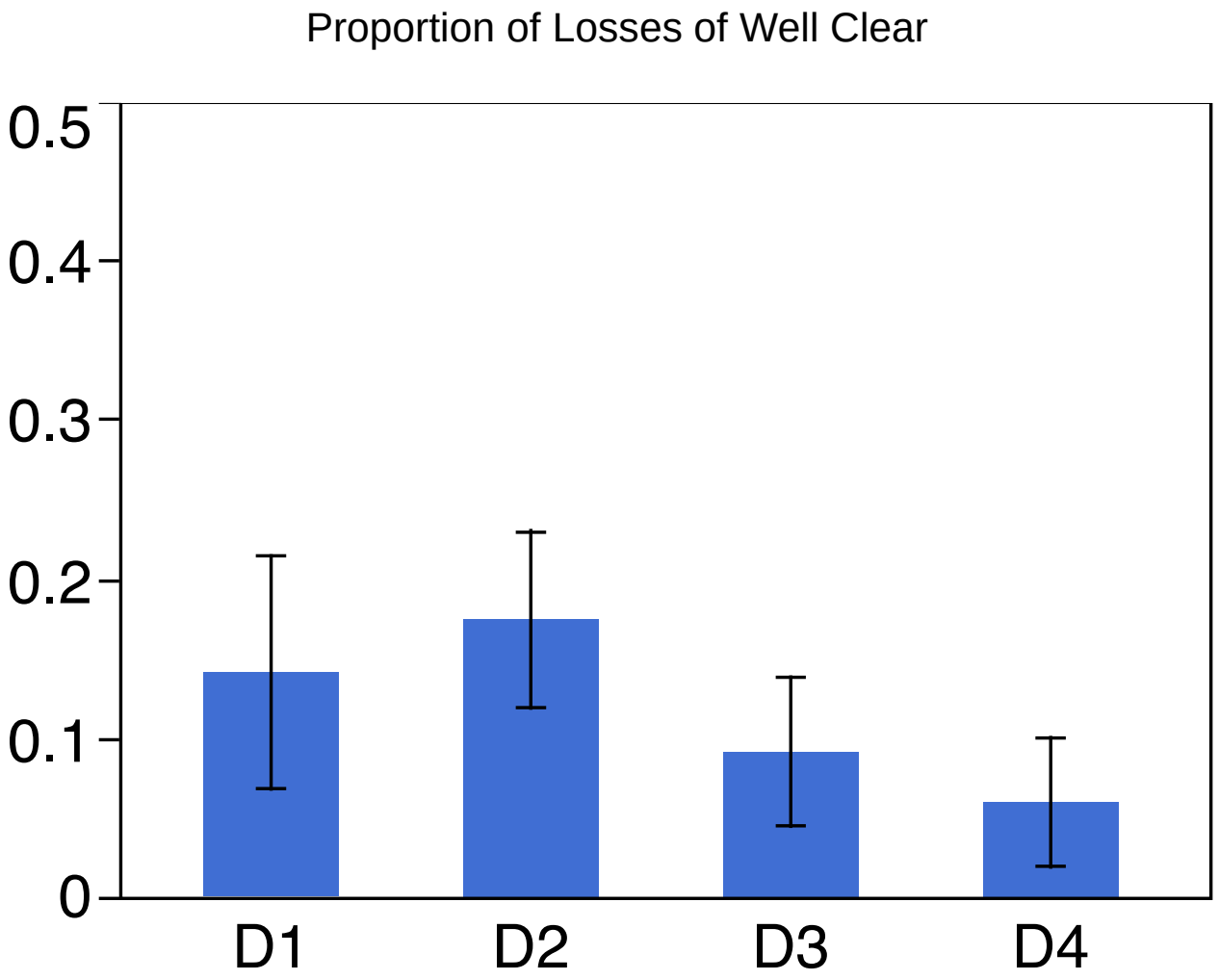
PT4 – Response Time Results



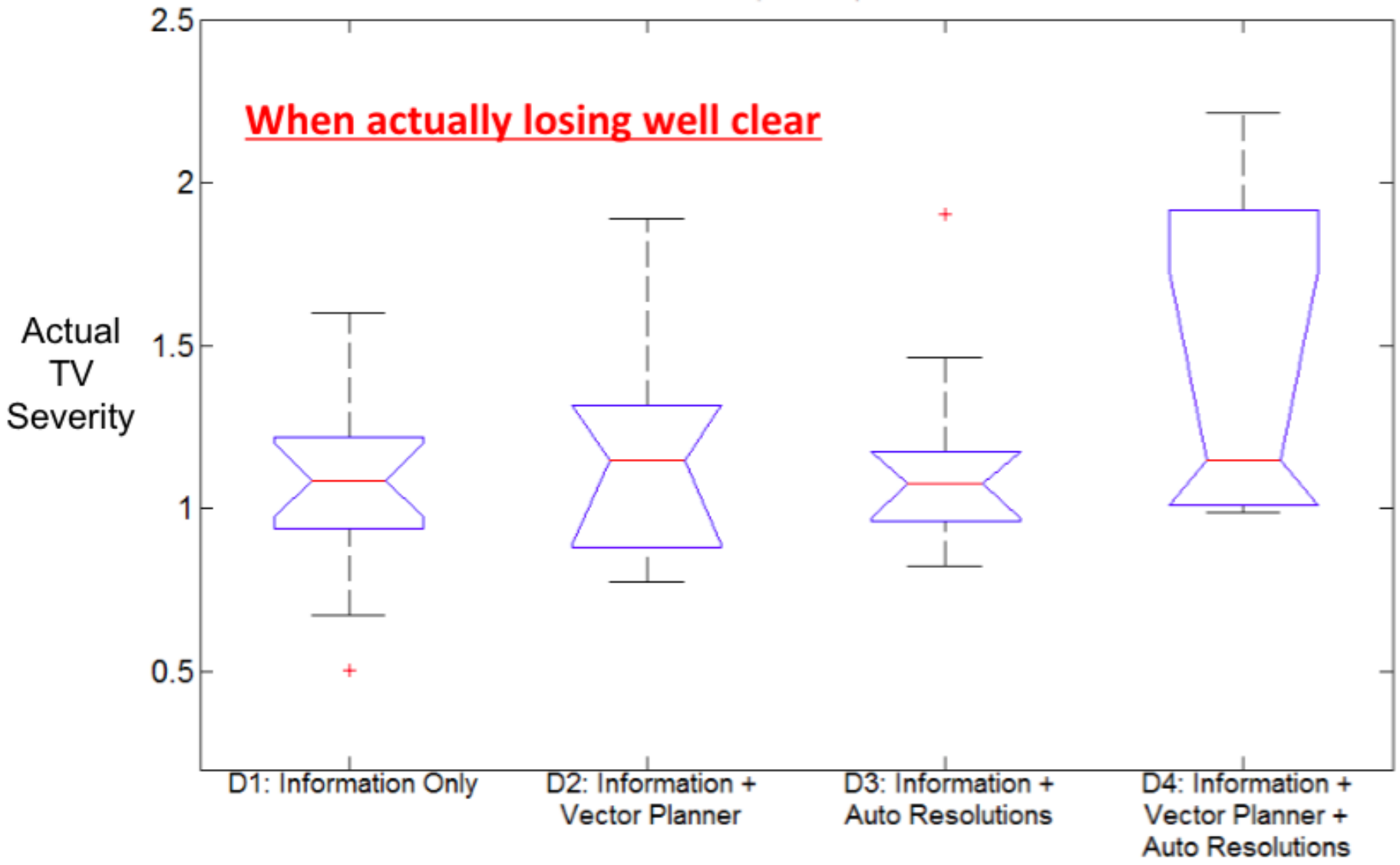
iHITL – Response Time Results



iHITL – Losses of Well Clear



iHITL – LoWC Severity



iHITL – Results Summary

- Total Response Time:
  - No significant differences between displays
  - Trend shows **Directive Only** and **Suggestive + Directive** as faster than Information Only and Suggestive Only
- Well Clear Metrics:
  - No significant differences between displays
  - **Information** and **Suggestive Only** (D1 and D2) display conditions had 2.5X as many LoWCs than the **Suggestive + Directive** combined (D4)
  - Severity data shows evidence of trends toward performance benefits with **Suggestive + Directive** compared to other three displays

PT5 – Overview

- Goal: Continue evaluation of candidate Detect and Avoid (DAA) displays and algorithms with respect to self-separation 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
    - PT4: Advanced better than Basic (but issues; well clear & display training, pop-ups)
    - iHITL: No significant differences between Advanced information features from PT4, but trends favoring combined **Suggestive + Directive (D4)** guidance
    - Maneuver Study (AFRL): Banding display showed faster response time compared to informative and directive displays; banding and advanced informative had least losses of well clear (neither results statistically significant)

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
- Embedded Variable
  - *Intruder Equipage* (manipulated within each scenario)
    - Transponder-equipped (detected via UAS's ADS-B)
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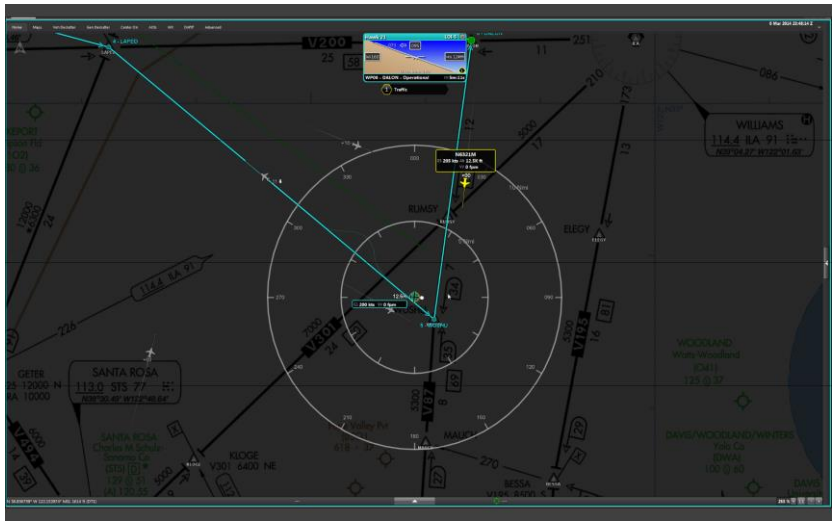
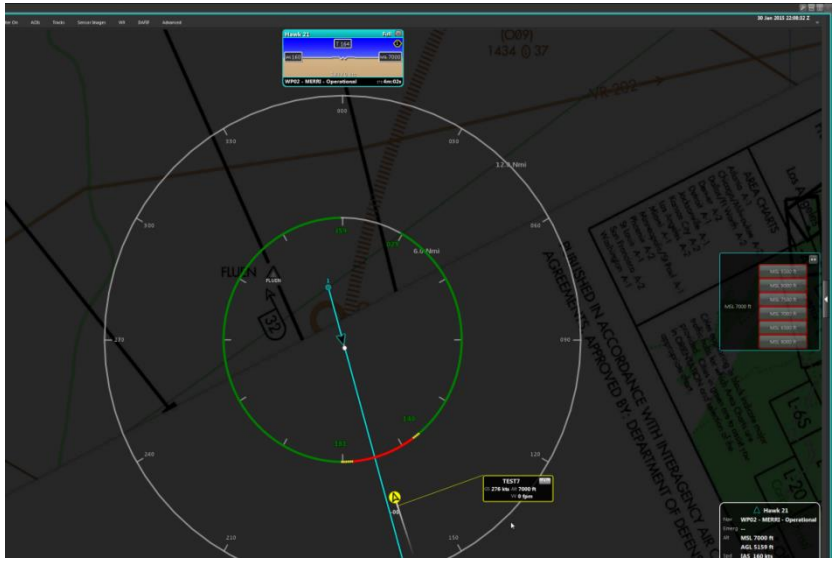
PT5 – Display Conditions

D1



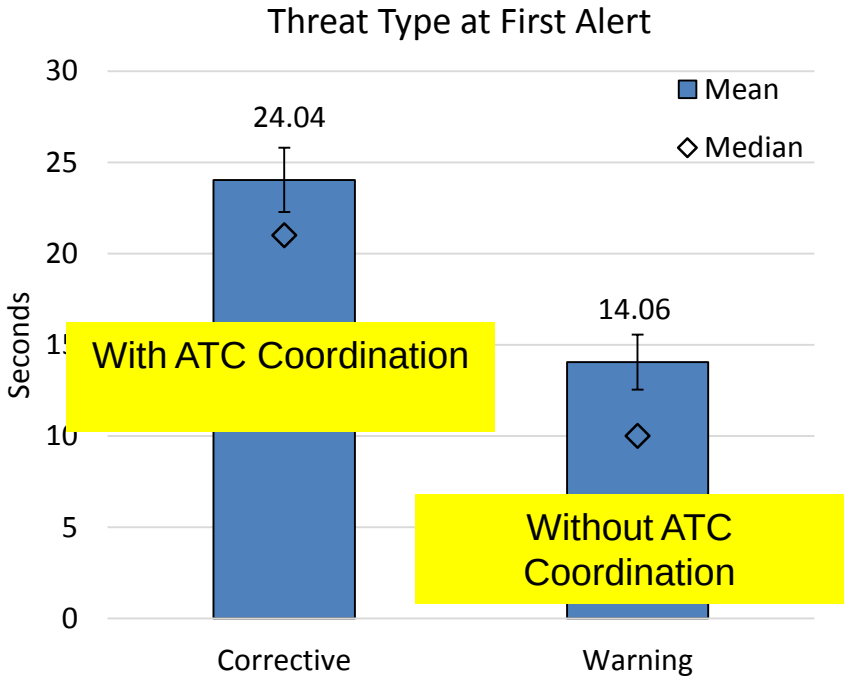
D2

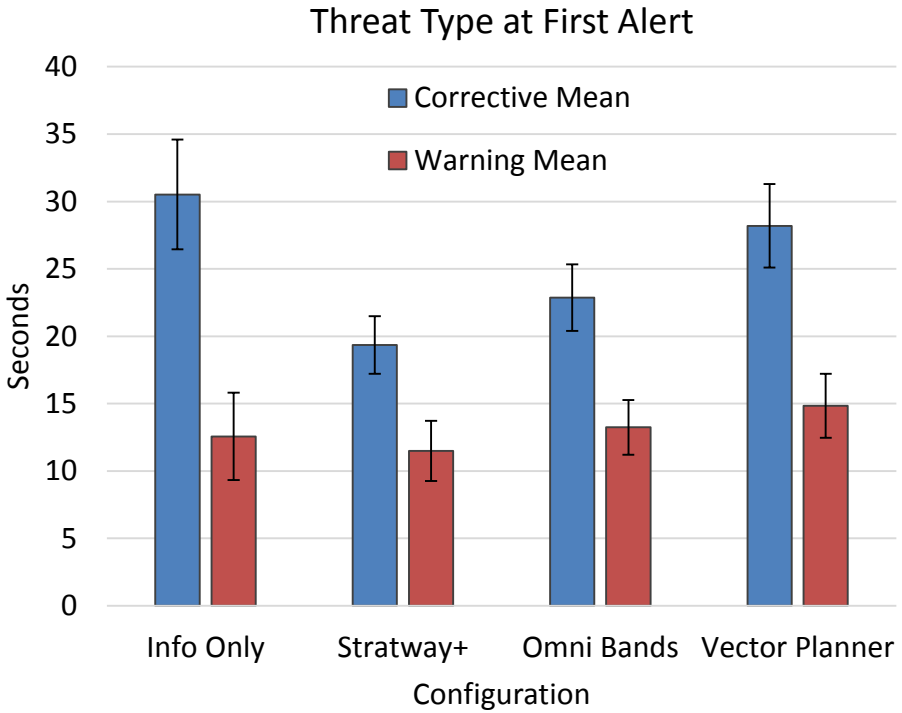
D3



D4

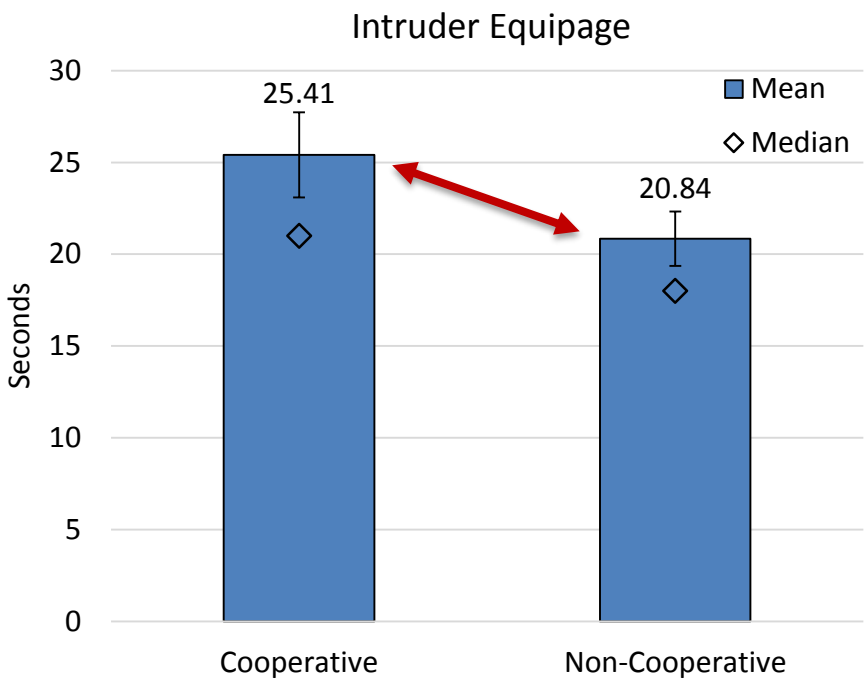
PT5 – Total Response Time Results

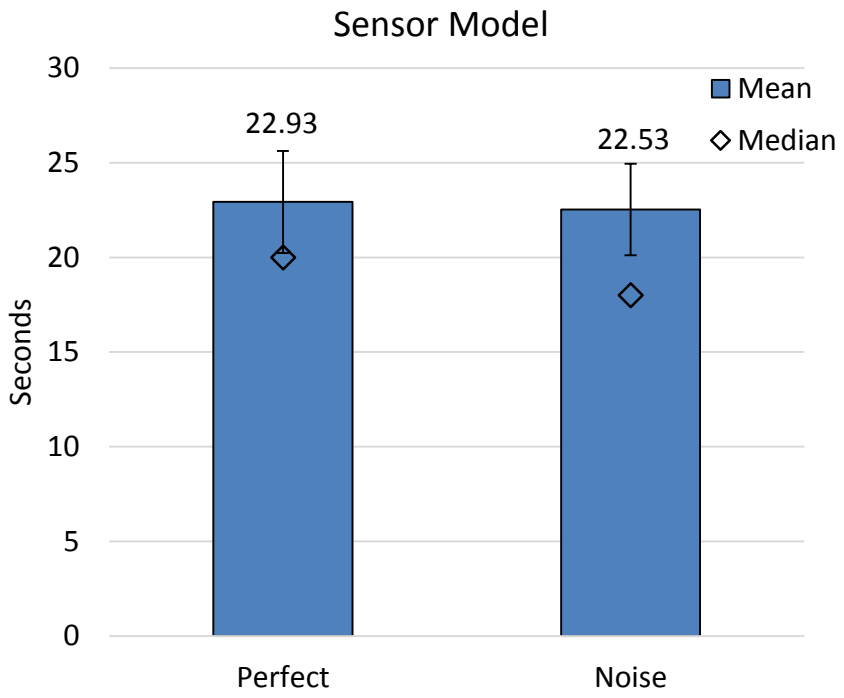




- Pilots responded, on average, **10s** faster to SS Warning Alerts than they did to Corrective SS Alerts
  - Pilots exhibited less variability between displays when responding to SS Warning Alerts than to Corrective SS Alerts
    - Range for SS Warning Alerts: 11s - 15s
    - Range for Corrective SS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

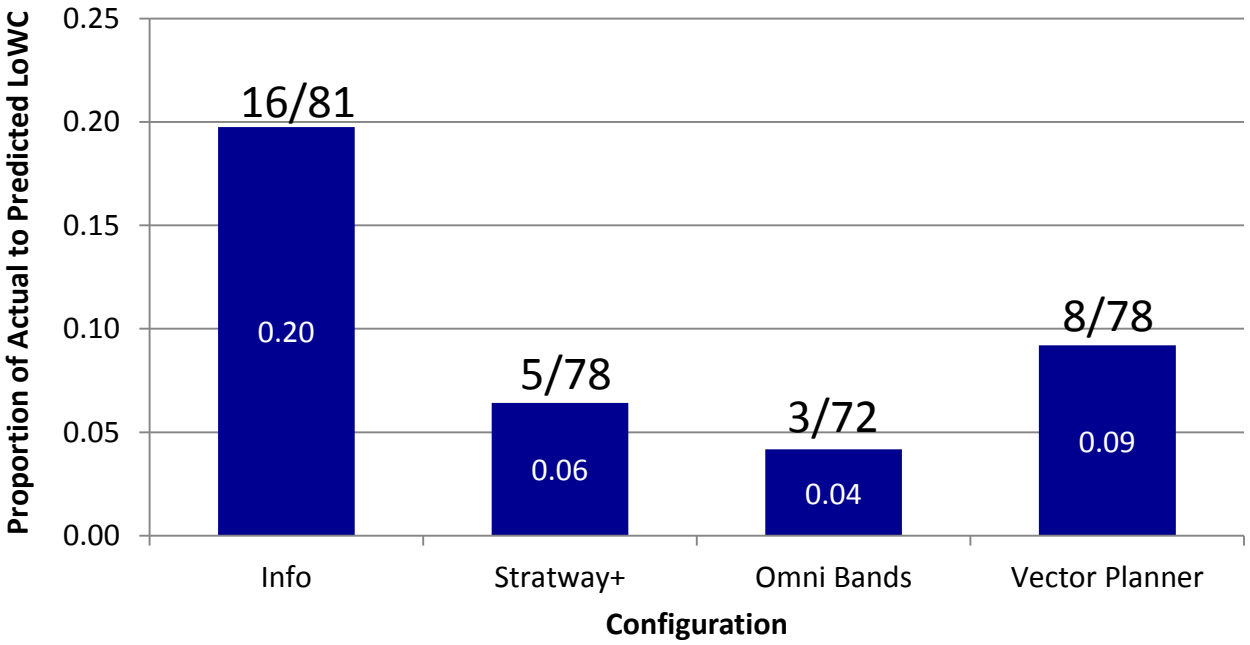
Total Response Time





- Pilots responded, on average, **4.5s** faster to non-cooperative traffic than they did to cooperative traffic, which was a significant difference (p=.008)
  - There was also less variability in pilots' responses to Non-Cooperative encounters
- Sensor model was not found to have any effect on pilot's Total RTs

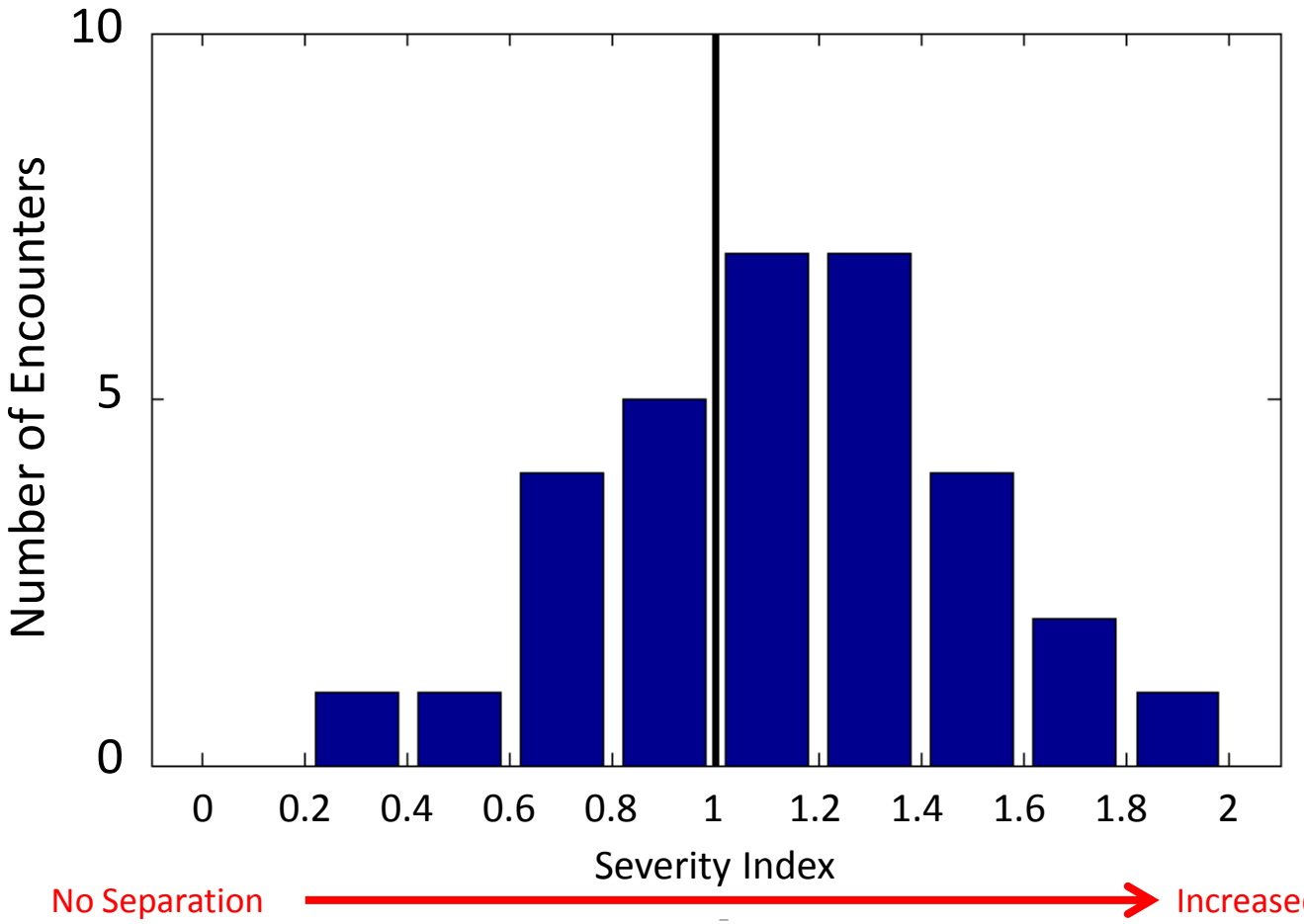
PT5 –Losses of Well Clear

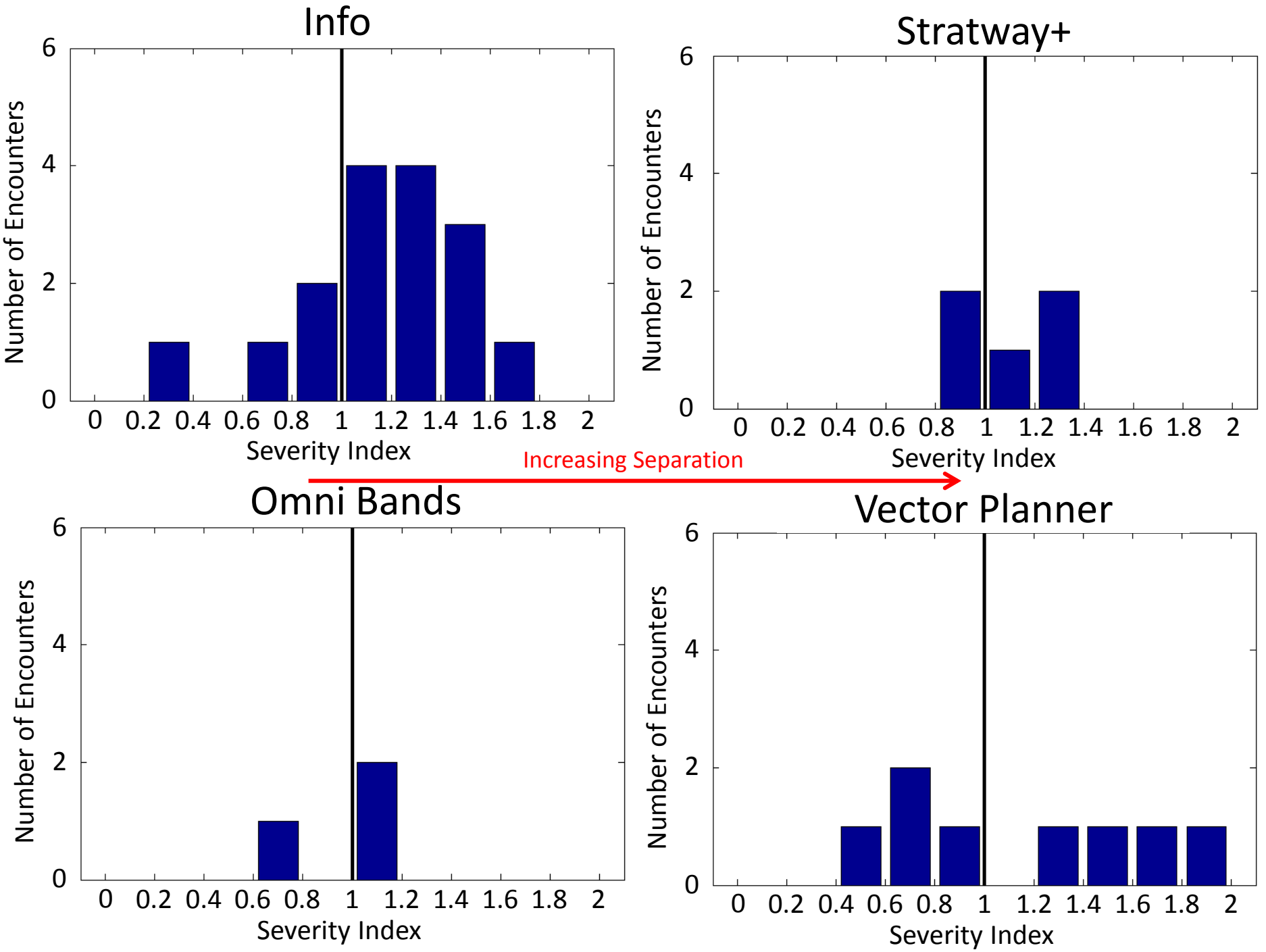


- Info Only (**19.8%**) was roughly *four times* as likely as Stratway+ (**6.5%**) and Omni Bands (**4.2%**) to result in LoWC, a significant difference ($p<.05$)
  - Info Only was roughly *two times* as likely as Vector Planner (10.3%) to lead to LoWC, which approached significance ($p=.086$)
- No significant differences seen between the three guidance displays in terms of LoWC

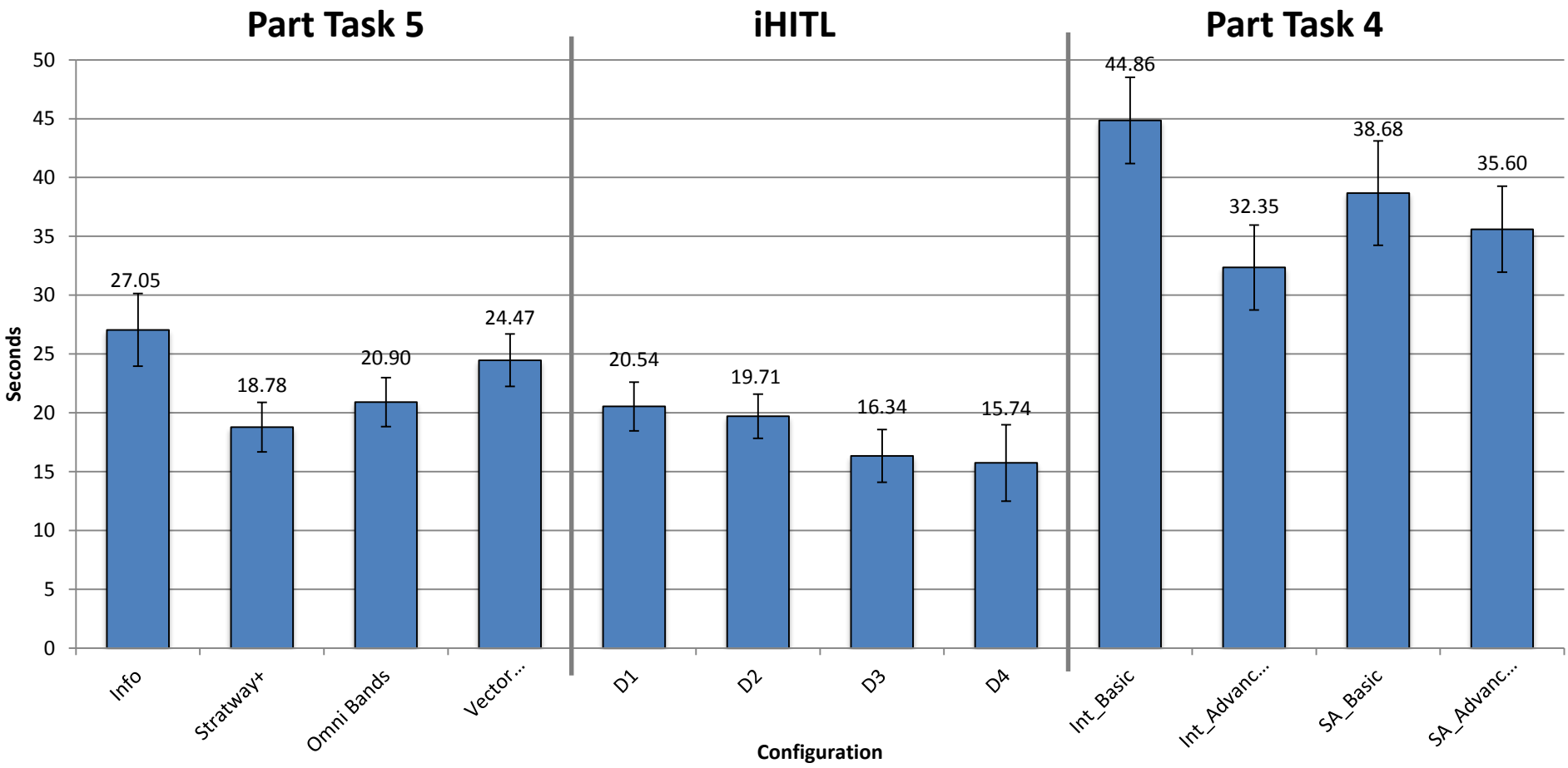
PT5 – LoWC Severity

- All Displays:
  - Actual Separation / Separation Threshold
  - Less than 1 = spatial separation was NOT maintained




Info
Stratway+
Omni Bands
Vector Planner
Number of Encounters
Severity Index
0
2
4
6
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
Increasing Separation

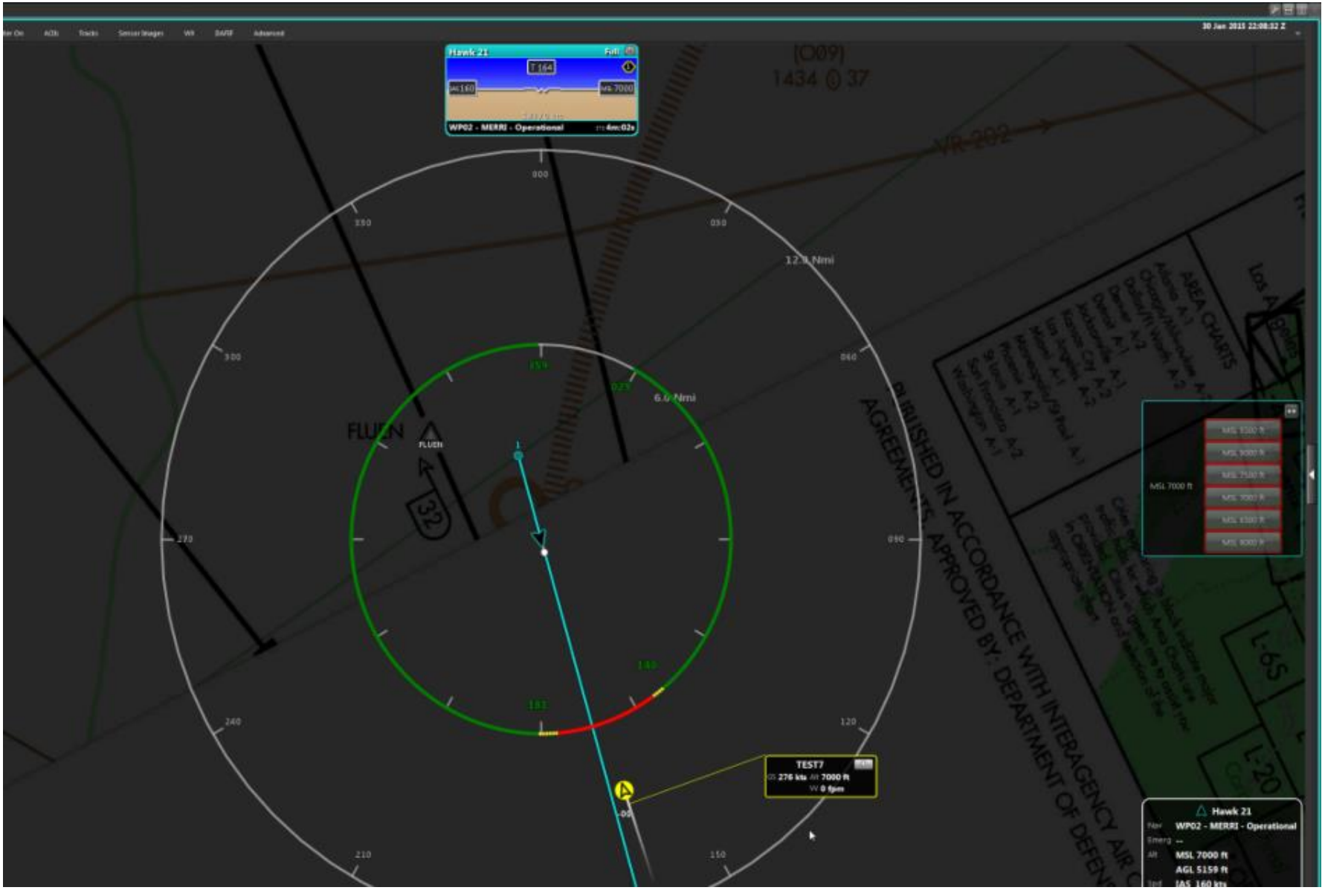
Total Response Times Across Simulations



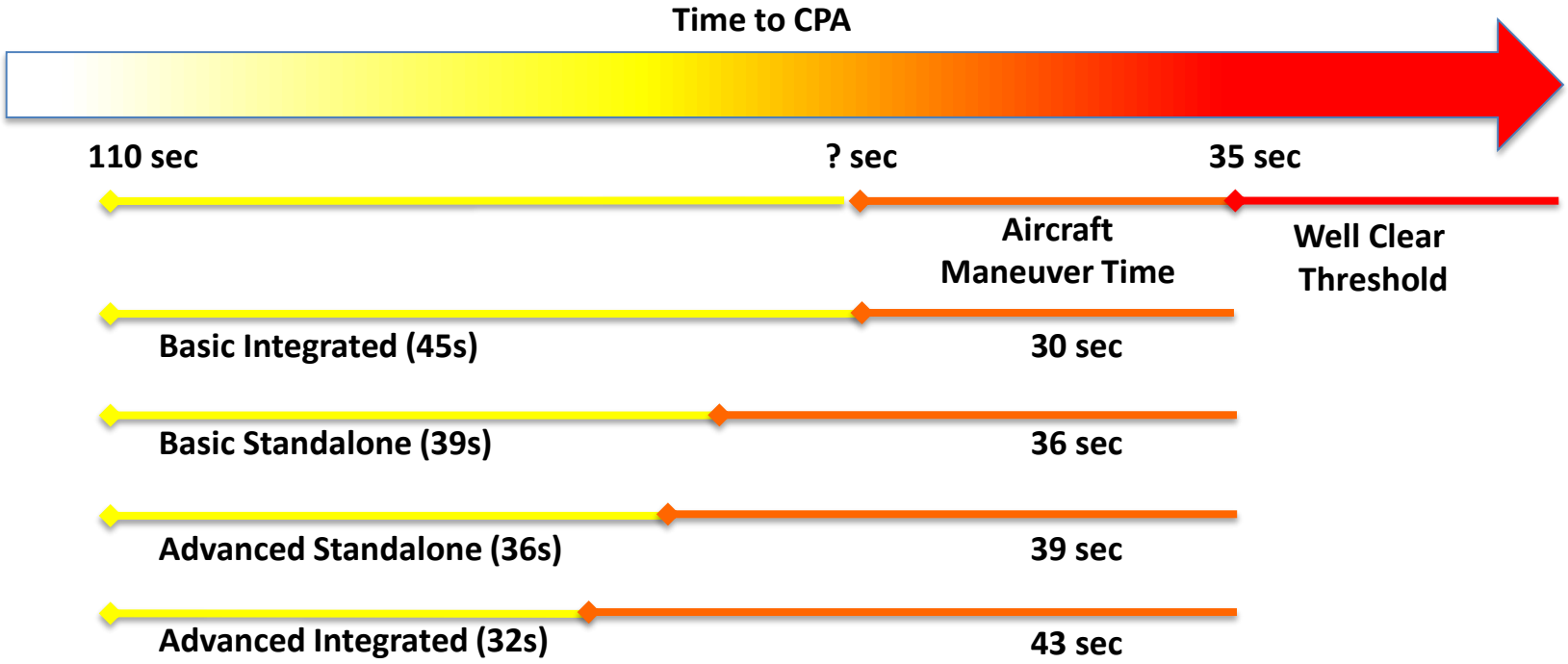
PT5 – Results Summary

- Suggestive guidance in the form of banding resulted in ***safer*** and ***more timely*** maneuvers away from conflicts
  - Fewer overall number of LoWC for both banding displays
  - Less severe LoWC for both banding displays
  - 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
- Results indicate that pilots can respond to a DAA Warning alert (no ATC coordination required) in ~ 15 seconds
- Results indicate that pilots can respond to a DAA Corrective alert (ATC coordination **is** required) in ~ 25 seconds
- ATC coordination adds approximately 10 seconds to DAA timeline

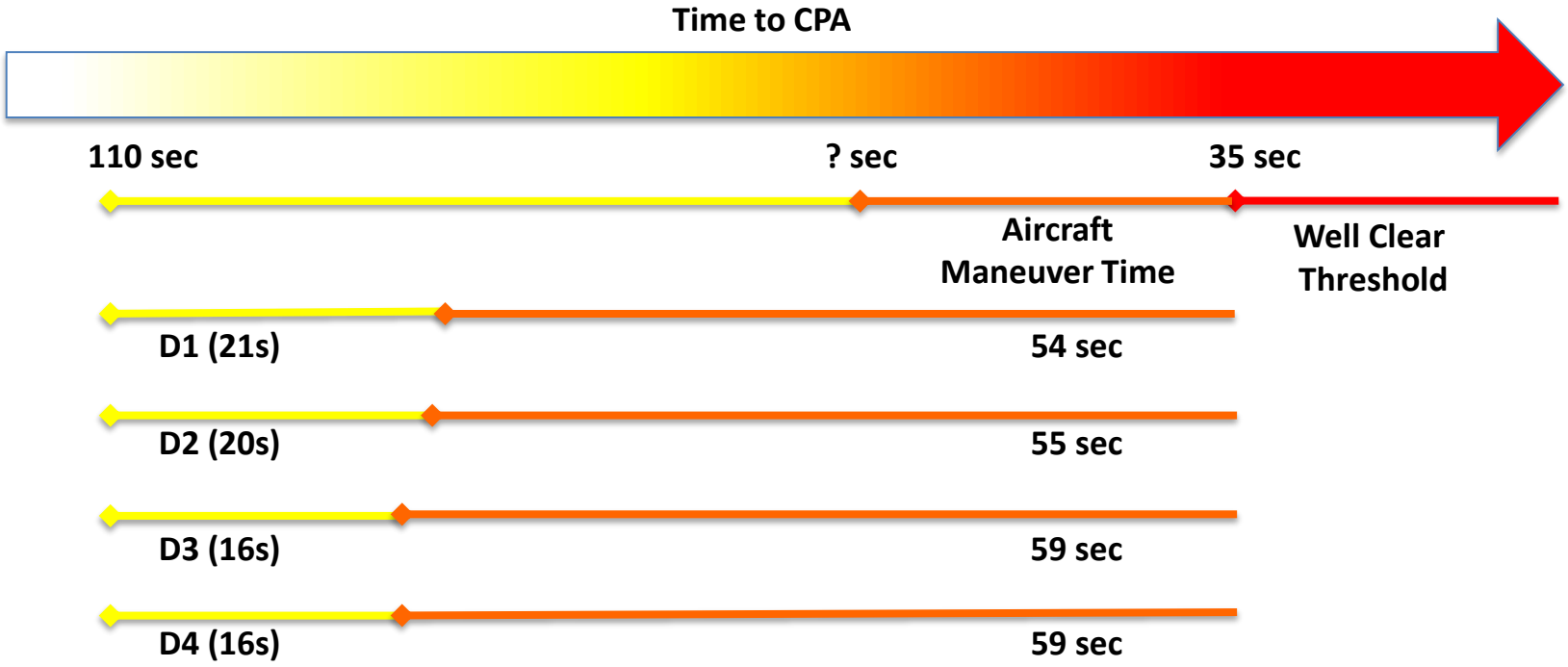
Suggestive Guidance Display – Example



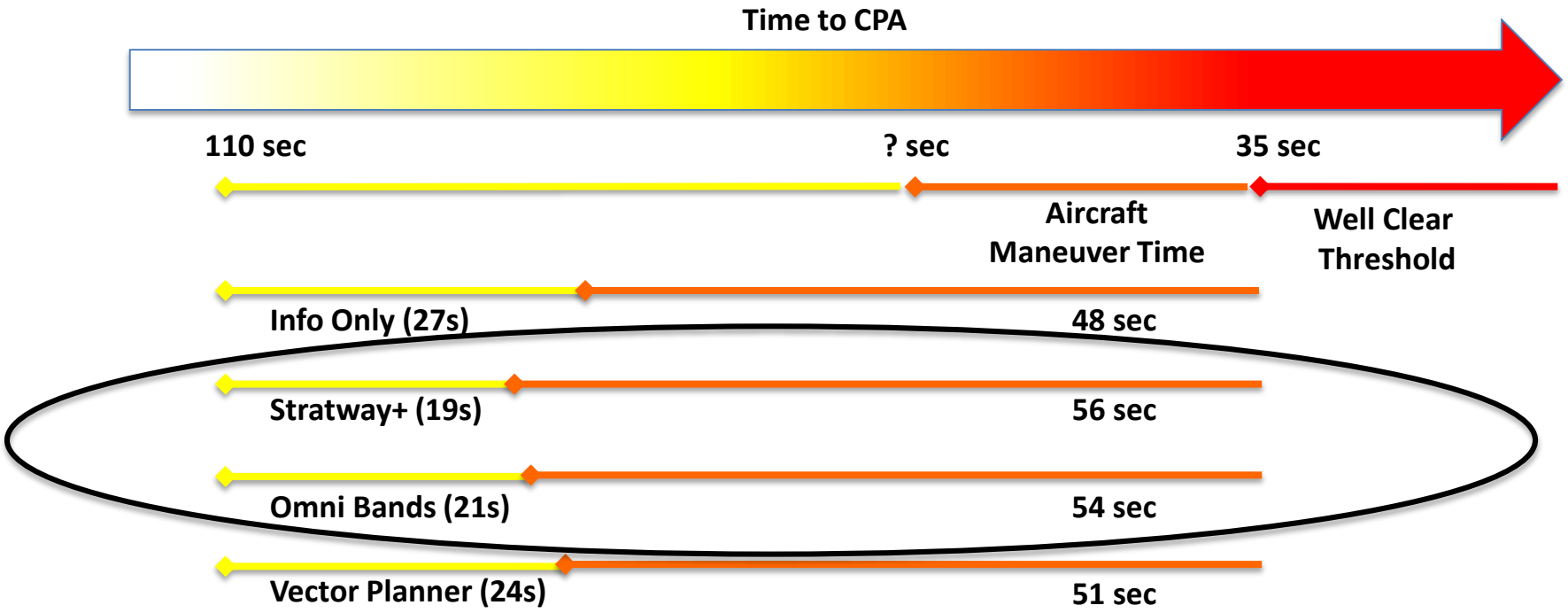
PT4 – Total Response Times



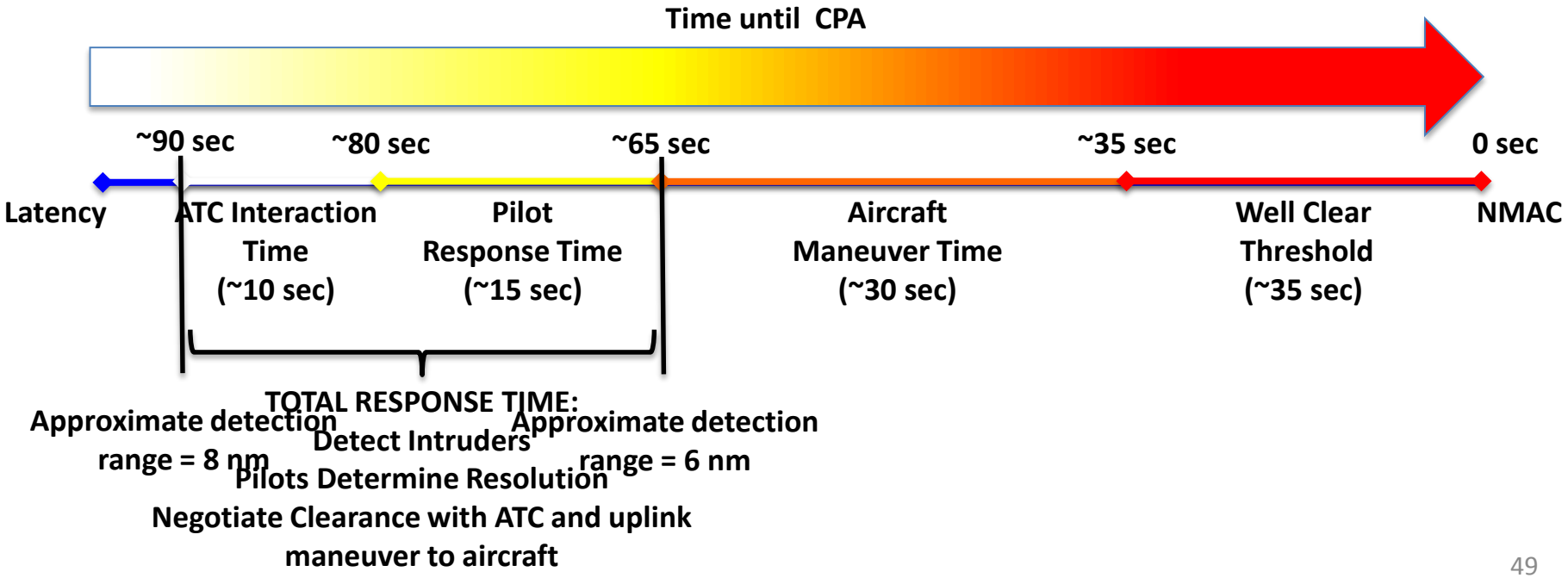
iHITL – Total Response Times



PT5 – Total Response Times



Self-Separation Timeline

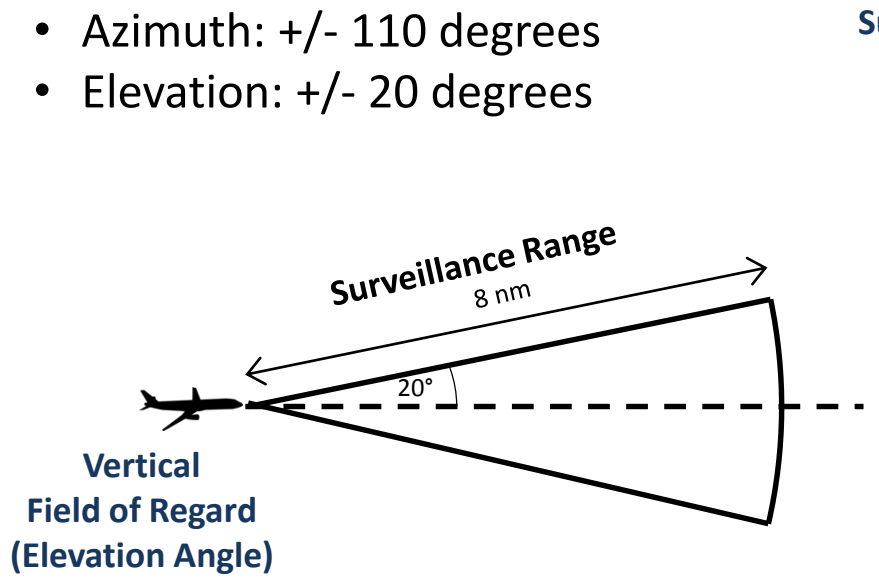


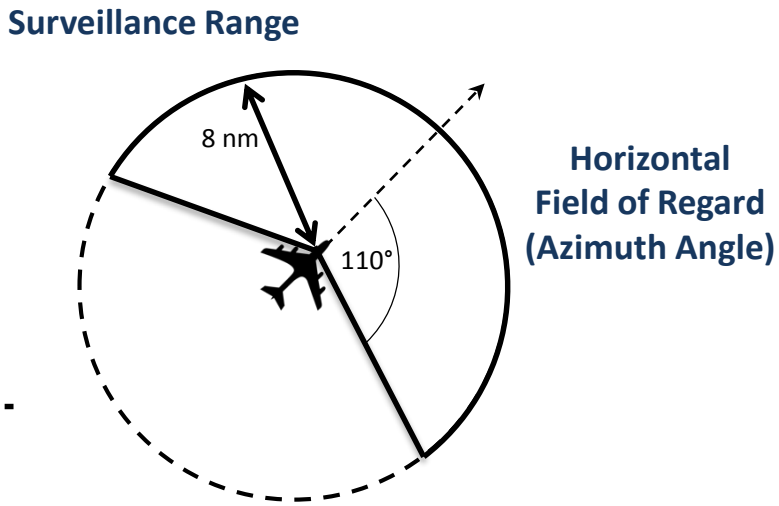
Questions?

Backup Slides

Sensor Parameters

- Sensor Ranges
  - Simulated **cooperative** sensor: ADS-R/TCAS-like ranges
    - Lateral Range: 15 nm
    - Vertical Range: +/- 5000 ft
  - Simulated **non-cooperative** sensor: based on state-of-the-art airborne RADAR
    - Lateral Range: 8 nm
    - Azimuth: +/- 110 degrees
    - Elevation: +/- 20 degrees





Parameters for Noisy Cooperative Sensor

Noisy Cooperative Sensor ("Transponder")			
	Parameter	**Value**	**Unit**
Field Of Regard	Range	15	nmi
	Azimuth	360	deg
	Elevation	+/-90	deg
Accuracy	Range Error Mean	0	nmi
	Range Error Std. Dev	0	nmi
	Range Moving Avg. Window Size	1	measures
	Azimuth Error Mean	0	deg
	Azimuth Error Std. Dev	2	deg
	Azimuth Moving Avg. Window Size	3	measures
	Altitude Quantization	100	feet
	Altitude Moving Avg. Window	6	measure

Yellow denotes the noise model variables that will used for PT5.

Parameters for Noisy Non-Cooperative Sensor

Noisy Non-Cooperative Sensor ("Airborne Radar")			
	Parameter	**Value**	**Unit**
Field Of Regard	Range	6	nmi
	Azimuth	+/-110	deg
	Elevation	+/-20	deg
Accuracy	Range Error Mean	0.008	nmi
	Range Error Std. Dev.	0.001	nmi
	Range Moving Avg. Window Size	1	measures
	Azimuth Error Mean	0	deg
	Azimuth Error Std. Dev.	2	deg
	Azimuth Moving Avg. Window Size	3	measures
	Elevation Error Mean	1	deg
	Elevation Error Std. Dev.	1	deg
	Elevation Moving Avg. Window Size	6	measure

Yellow denotes the noise model variables that will used for PT5.

Parameters for “Perfect” Cooperative Sensor

“Perfect” Cooperative Sensor (“ADS-B”)			
	Parameter	**Value**	**Unit**
Field Of Regard	Range	15	nmi
	Azimuth	360	deg
	Elevation	+/-90	deg
Accuracy	Latitude Error	0	deg
	Latitude Error Std. Dev.	0	deg
	Latitude Moving Avg. Window Size	1	measures
	Longitude Error	0	deg
	Longitude Error Std. Dev.	0	deg
	Longitude Moving Avg. Window Size	1	measures
	Altitude Error	0	deg
	Altitude Error Std. Dev.	0	deg
	Altitude Moving Avg. Window Size	1	measure

Parameters for “Perfect” Non-Cooperative Sensor

“Perfect” Non-Cooperative Sensor (“Perfect Airborne Radar”)			
	Parameter	**Value**	**Unit**
Field Of Regard	Range	6	nmi
	Azimuth	+/-110	deg
	Elevation	+/-20	deg
Accuracy	Range Error Mean	0	nmi
	Range Error Std. Dev.	0	nmi
	Range Moving Avg. Window Size	1	measures
	Azimuth Error Mean	0	deg
	Azimuth Error Std. Dev.	0	deg
	Azimuth Moving Avg. Window Size	1	measures
	Elevation Error Mean	0	deg
	Elevation Error Std. Dev.	0	deg
	Elevation Moving Avg. Window Size	1	measure