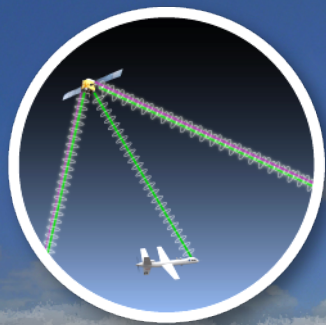
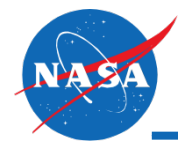


# Unmanned Aircraft Systems (UAS) Integration in the National Airspace System (NAS) Project

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





# Presentation Overview

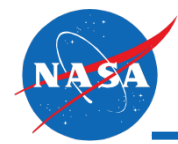
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- Background
- Simulation environment components
- Key results of first three human-in-the-loop (HITL) simulations that compared different DAA maneuver guidance and display configurations
  - Key metrics used to inform SC-228 DAA MOPS:
    - Total 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



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# Background



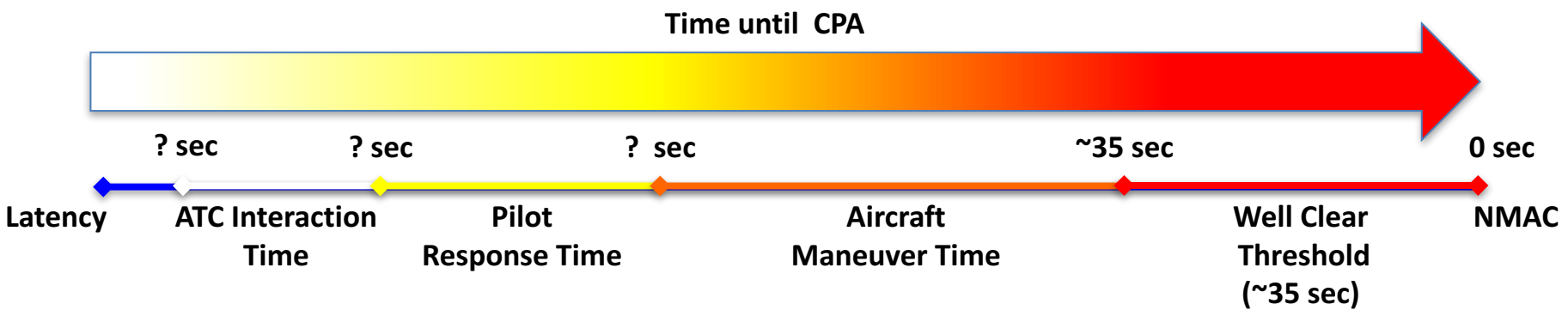
# Background

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- NASA's Unmanned Aircraft Systems Integration into the National Airspace System (**UAS-NAS**) Project has been investigating the technical barriers associated with the full integration of UAS into civil airspace
- Its research has been conducted in collaboration with RTCA Special Committee 228 (**SC-228**), responsible for developing the Minimum Operational Performance Standards (**MOPS**) for UAS
- The Human Systems Integration (HSI) Subproject's primary activity was to provide data on the effect of various Detect and Avoid (DAA) display features on pilots' performance of the remain well clear function in order to inform the minimum requirements for DAA displays, alerting and guidance
- Two key questions needed to be answered in Phase 1:
  - 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?



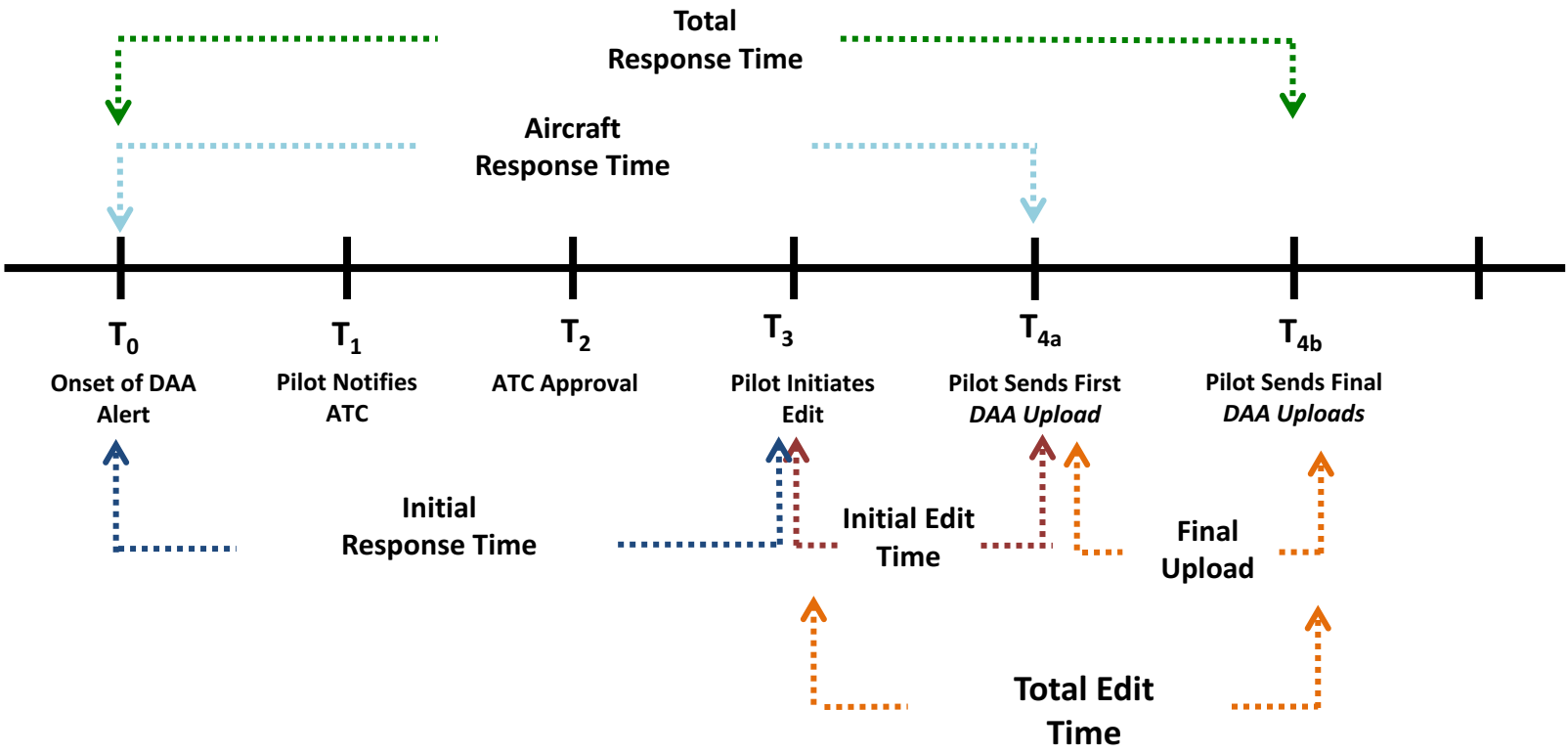
# DAA/Remain Well Clear Timeline



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



# Pilot-DAA Timeline

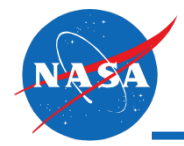




# Background

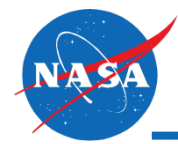
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- An early critical question for the Phase I MOPS for DAA systems was what, if any, level of DAA maneuver guidance would be required to support acceptable performance on maintaining well clear?
- Phase I MOPS assumptions specify that the pilot in command 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



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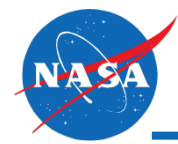
# Simulation Environment



# Simulation Environment

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- Emulation of representative environment:
  - Concept of Operations
  - 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



# Concept of Operations

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- Human Systems Integration research largely focused on operational scenario described in the Phase 1 DAA Operational Services and Environment Description (OSED), A.5.3 (page 330-333)
  - Operating on IFR flight plan in U.S. Class E airspace
    - Pilot in command is responsible for separation against VFR traffic
    - ATC gives traffic advisories when workload permits
  - Predicted loss of DAA well clear encounters with VFR (non-participating, non-cooperative) aircraft
  - Coordination with ATC when time permits



# Concept of Operations

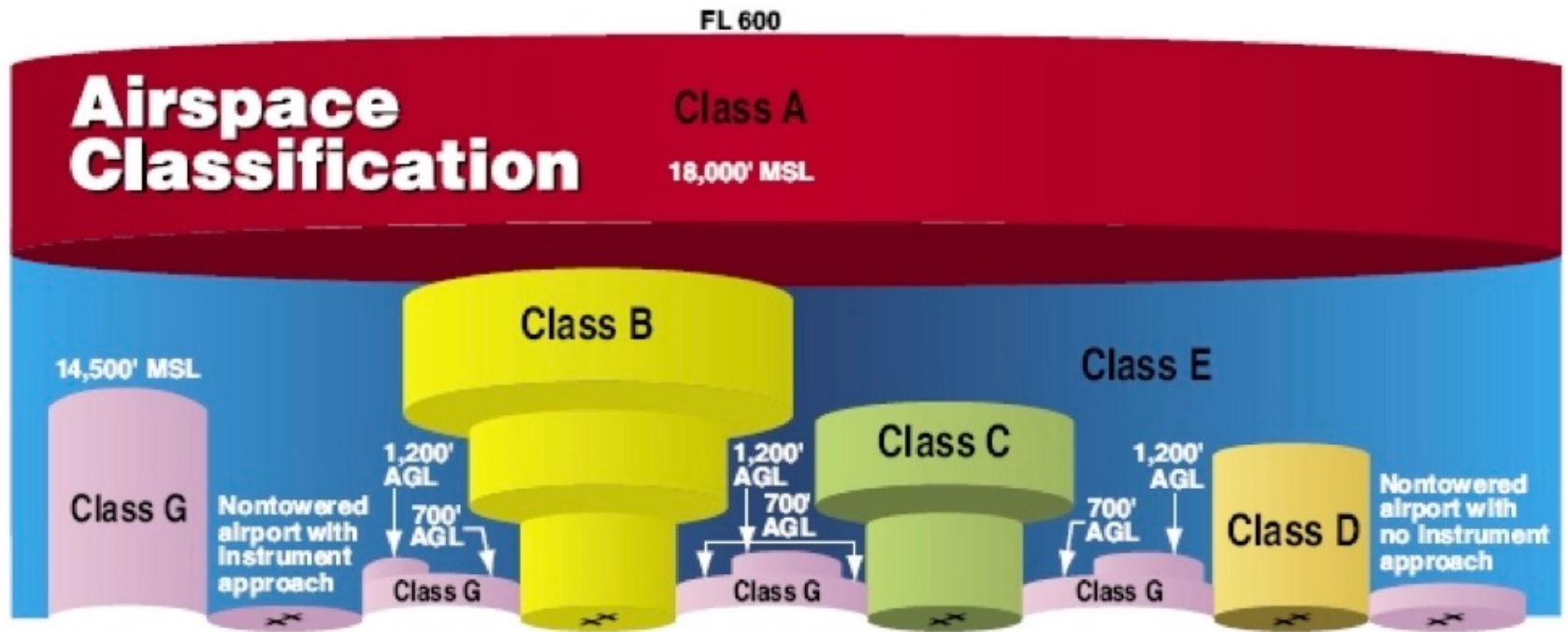


Figure A-2

Airspace Classes (faasafety.gov)

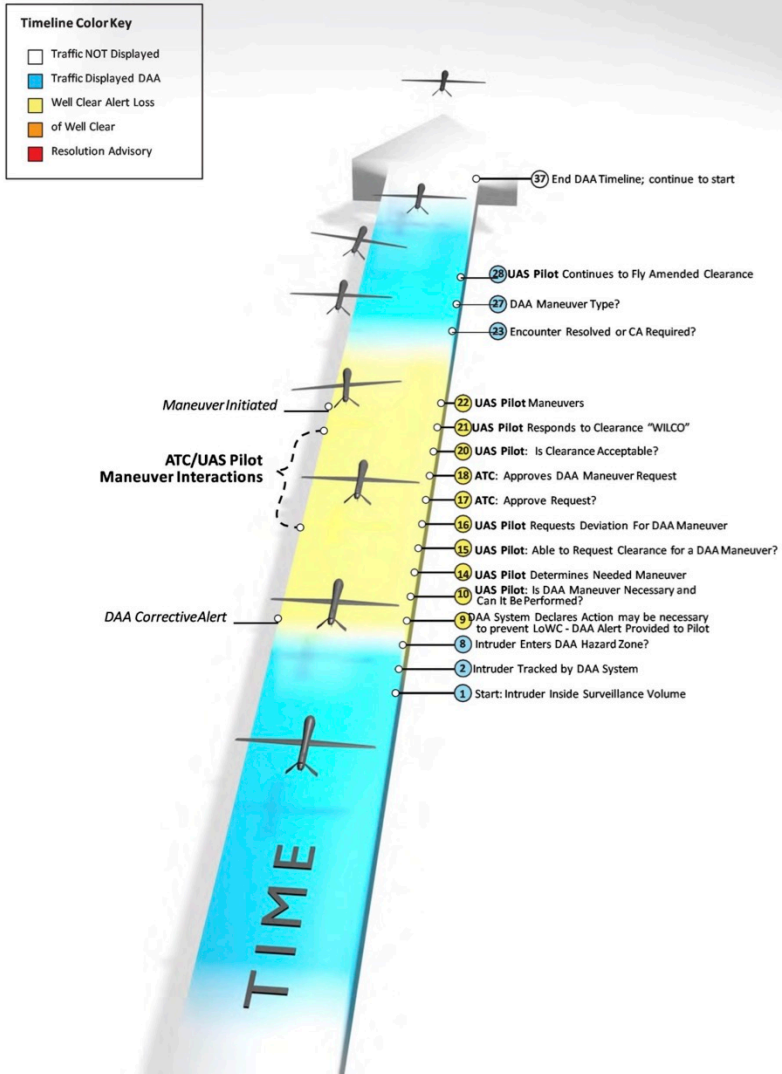


Figure A-18 Scenario A.5.3.a/b – Timeline for UAS PIC Calls Out VFR Traffic

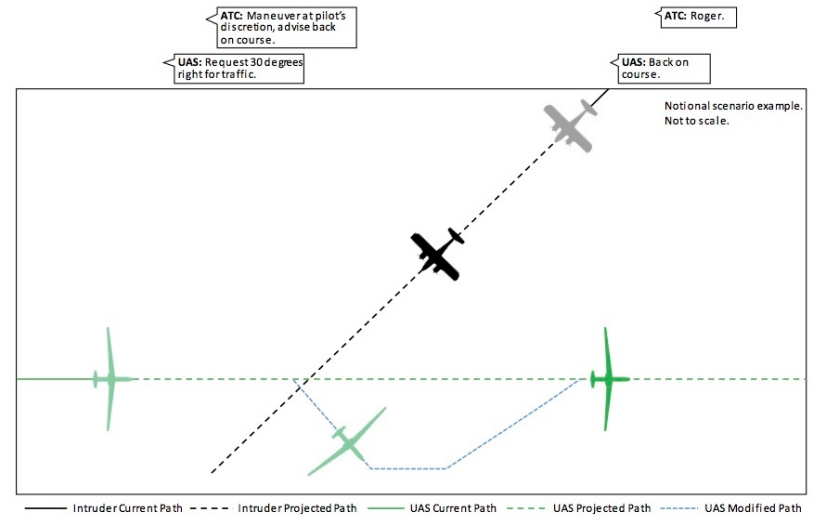


Figure A-16 Scenario A.5.3.a – UAS PIC Calls Out Co-altitude VFR Traffic to ATC

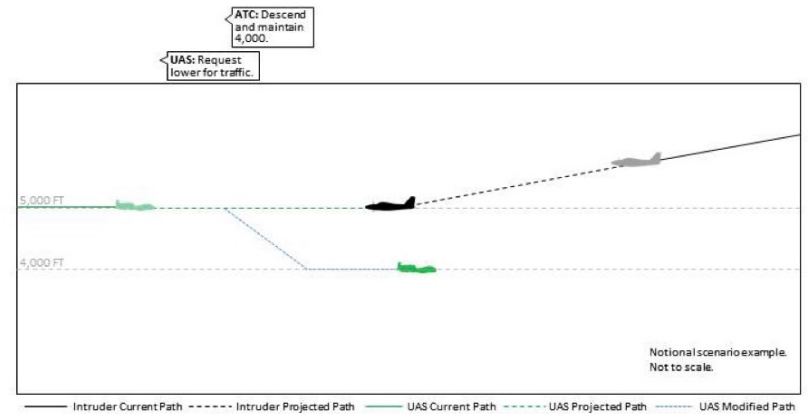
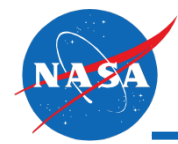
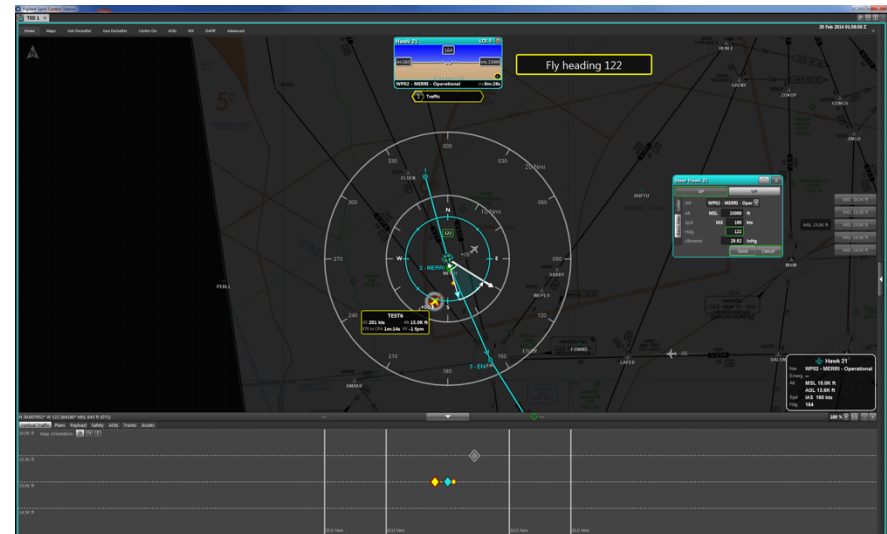


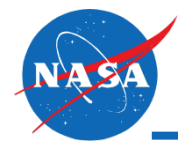
Figure A-17 Scenario A.5.3.b – UAS PIC Calls Out Descending VFR Traffic to ATC



# Simulation Environment: Ground Control Station (GCS)

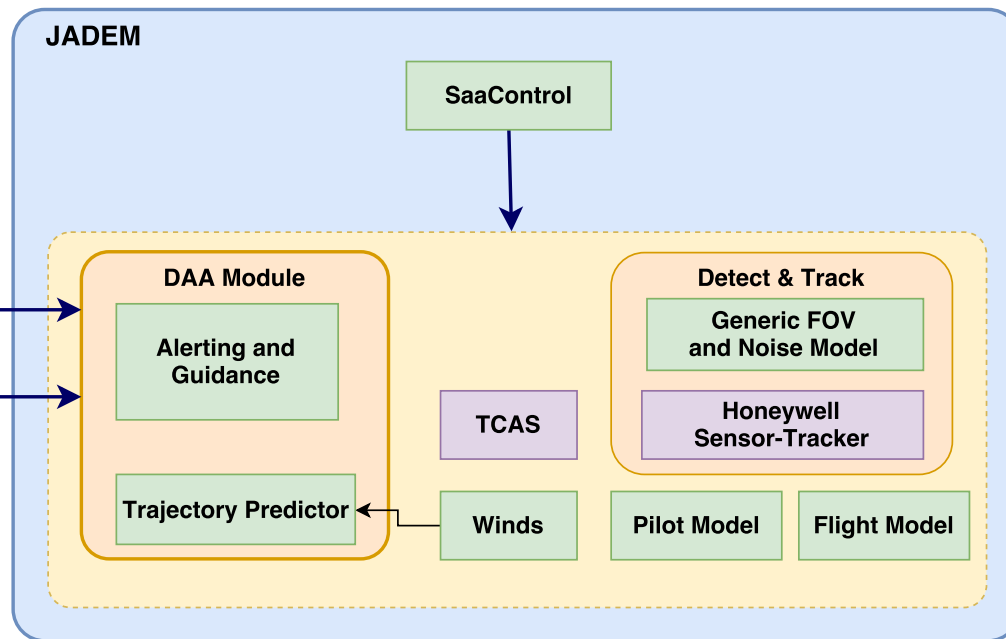
- The Vigilant Spirit Control Station (VSCS) developed by the Air Force Research Laboratory (AFRL)
- Main Features:
  - Robust, flexible interface
  - Realistic control and navigation displays
  - System status and health monitoring
  - STANAG 4586 Compliant
  - Multi-UAS control with VSCS has been tested 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



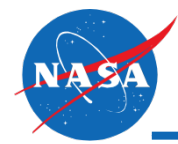


# Simulation Environment: DAA System

- 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



DAA Module can be driven by  
Real time aircraft states  
Recorded world VFR and IFR data  
Encounter models  
Test scenarios



# 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



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# Human-in-the-Loop (HITL) Experiment Summaries



# Experiment 1 – Experimental Design

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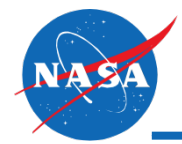
- Goal: Evaluate candidate Detect and Avoid (DAA) displays and algorithms with respect to traffic avoidance and collision avoidance.
  - What are the minimum information requirements for DAA displays?
  - Is there a performance difference between integrated and standalone displays?
  - What advanced display features improve pilot performance on maintaining DAA well clear from other traffic?
- Experimental Design: Mixed Factorial Design
  - 2 (Display: Standalone, Integrated)
  - X 2 (Information: Basic, Advanced)
  - = 4 DAA Display Concepts:
    - Standalone Basic
    - Standalone Advanced
    - Integrated Basic
    - Integrated Advanced



# Experiment 1 – Display Configurations

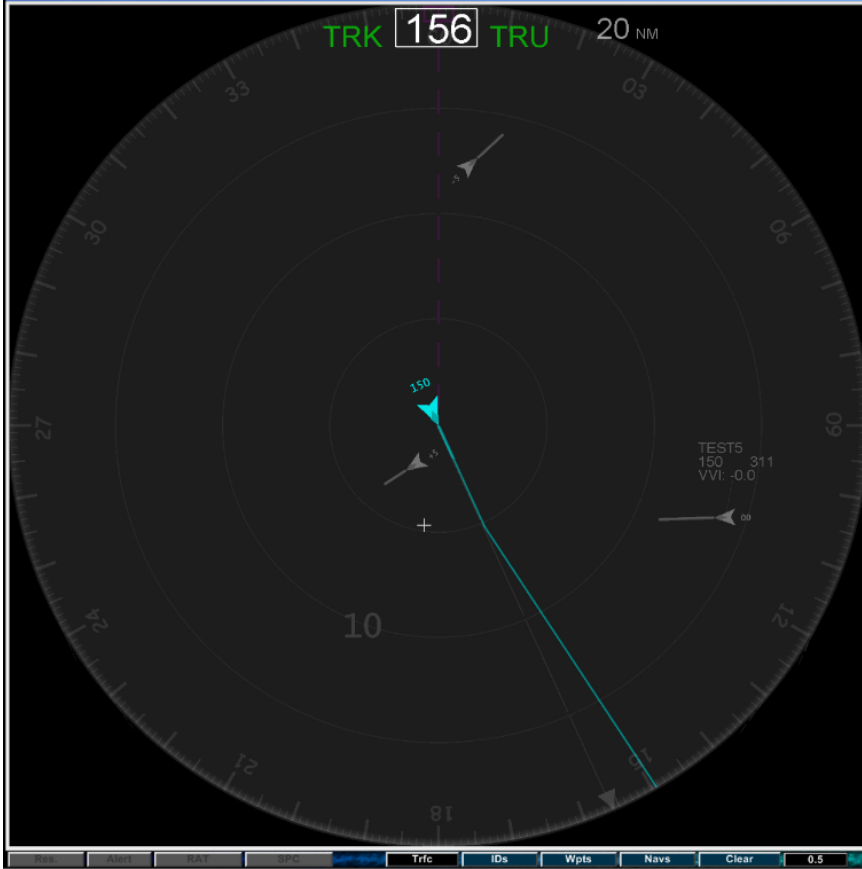
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- Display Location Level: Standalone versus Integrated
  - Standalone: display located on own monitor, separate from primary moving map display
  - Integrated: display integrated with primary moving map display
- Display Information Level: Basic versus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

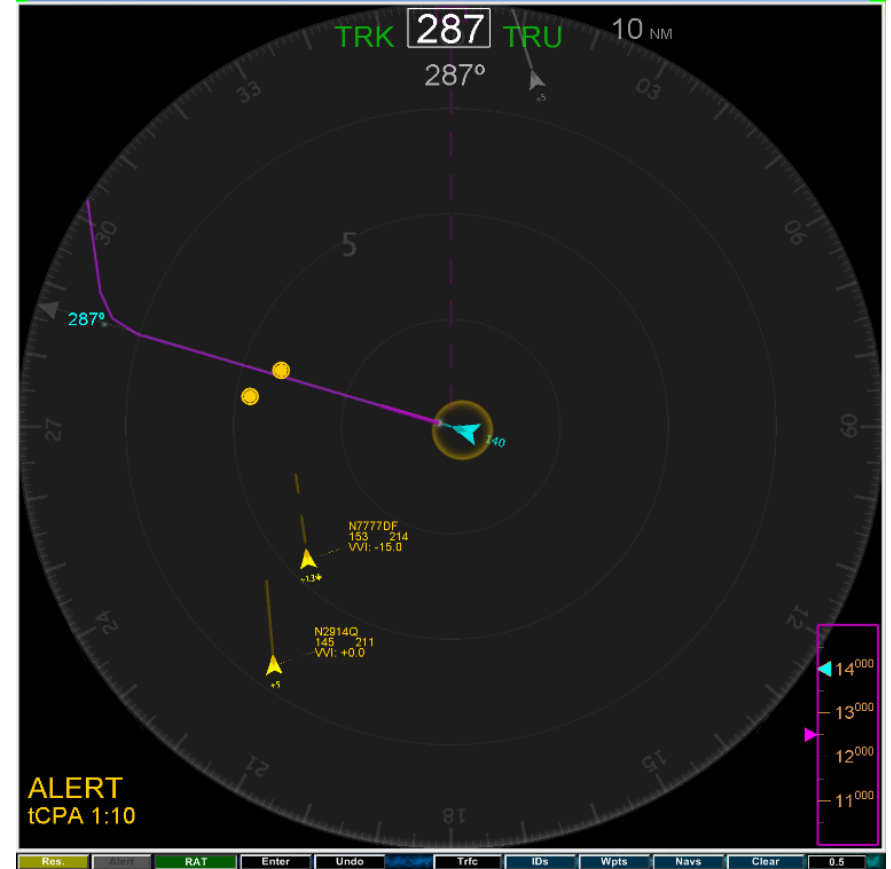


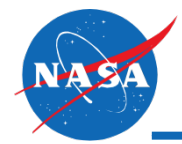
# Experiment 1 – Standalone Displays

## Basic



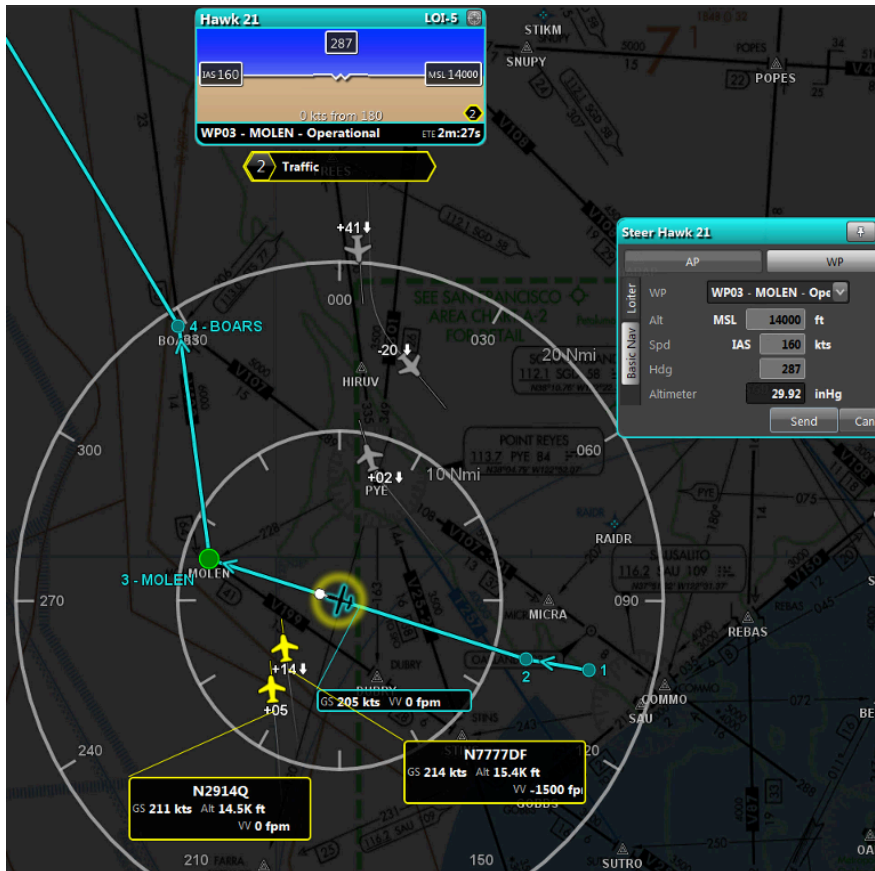
## Advanced





# Experiment 1 – Integrated Displays

## Basic

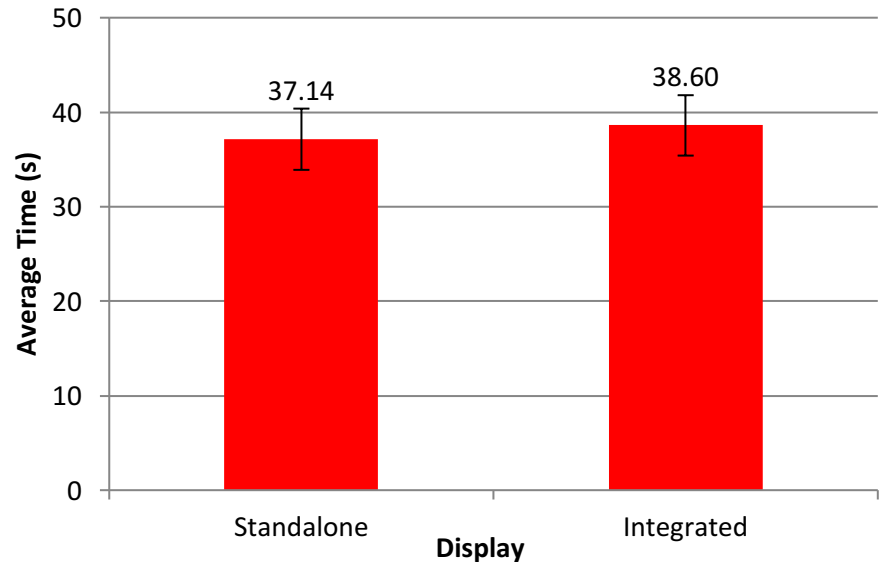
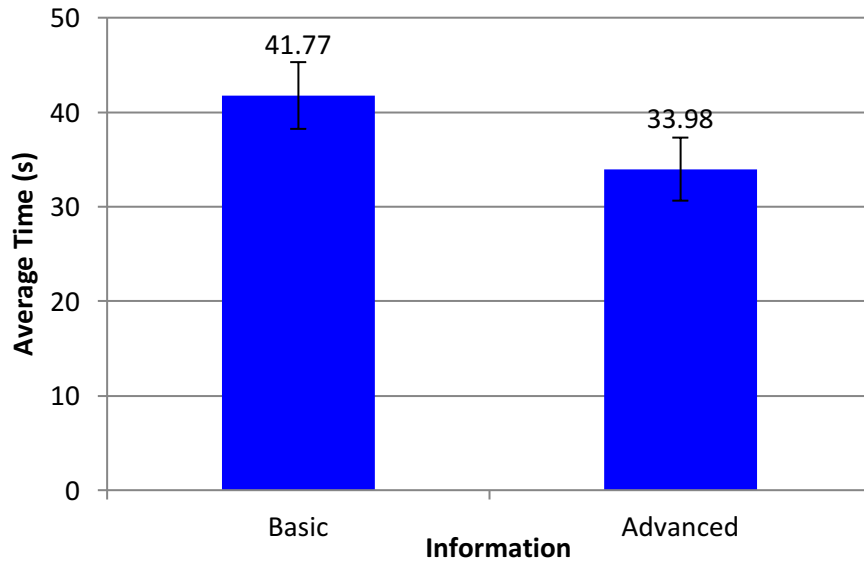


## Advanced



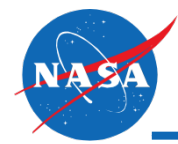


# Experiment 1 – Total Response Time Results

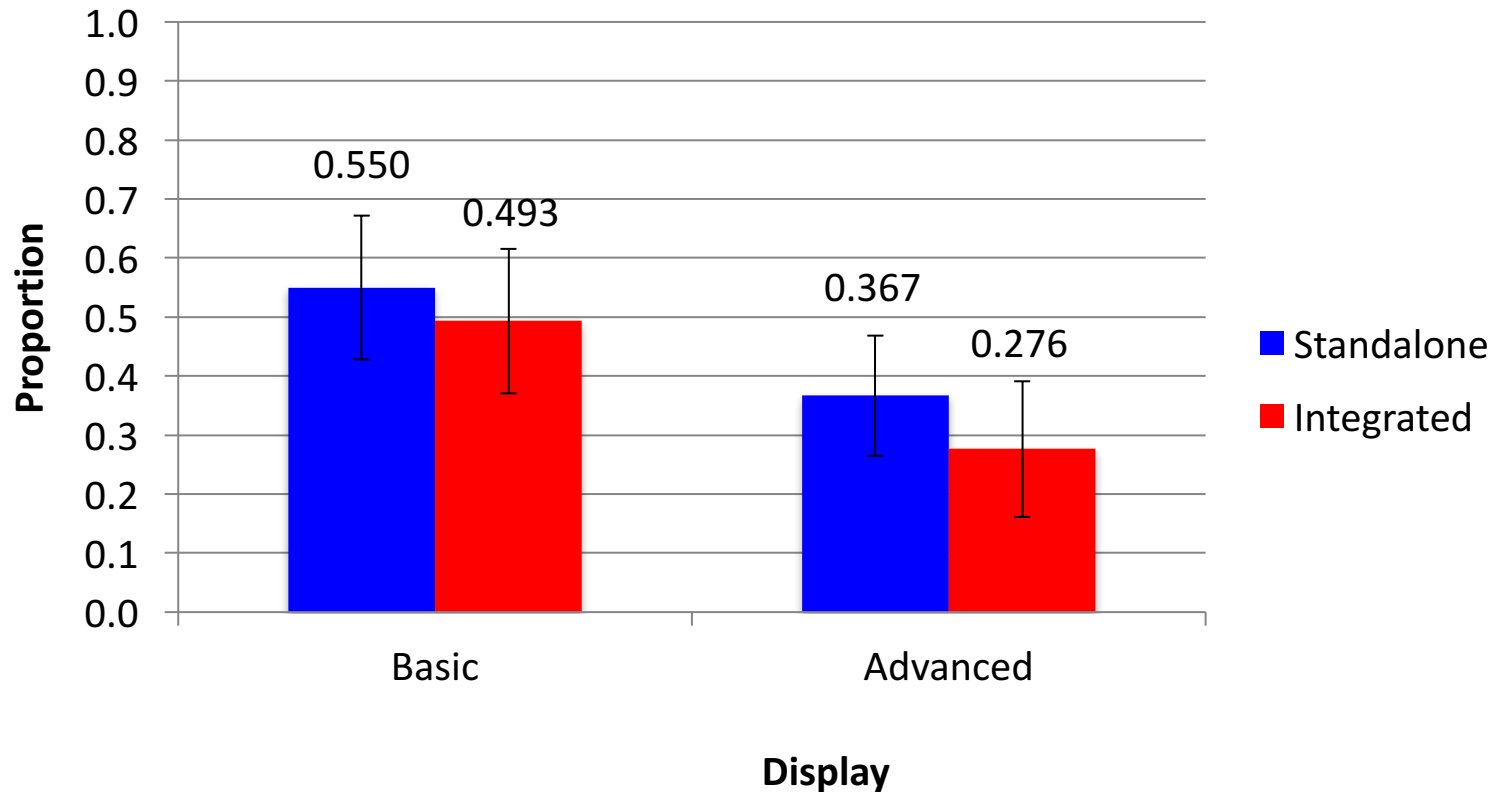


- There was a significant main effect of Information on Total Response Time,  $p < .05$ 
  - Advanced was significantly faster (by 7.79 seconds on average) compared to Basic
- Pilots took an average of **37.87 seconds** to complete their final edit in response to DAA/CA alerts (from first alert appearance)

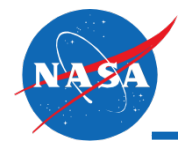
- There was no significant main effect of Display on Total Response Time,  $p > .05$
- Pilots took an average of **37.87 seconds** to complete their final edit in response to DAA/CA alerts (from first alert appearance)



# Experiment 1 – Losses of DAA Well Clear



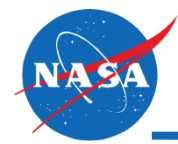
- There was not a significant main effect of Information on Proportion of Losses of DAA Well Clear,  $p > .05$
- On average pilots failed to avoid a loss of well clear 44% of the time



# Experiment 1 – Results Summary

---

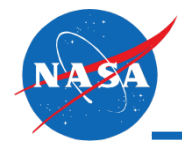
- Consistent advantage seen for Advanced over Basic displays in pilot response times
- No significant differences in proportion of losses of DAA well clear, however, advanced trended toward lower proportion of LoDWC than basic
- There were no significant differences between the Standalone and Integrated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



## Experiment 2 – Experimental Design

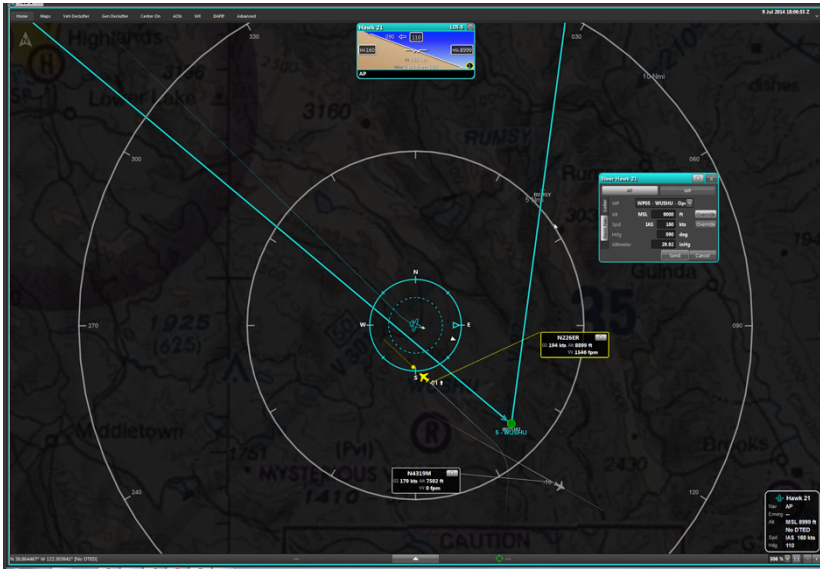
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- Goal: Determine the individual contributions of the various PT4 advanced display features to pilots' response times and ability to maintain well clear
- One-Way Repeated Measures Factorial: Display Information Level (4 Level; Within Subjects)
  - 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 Exp 1

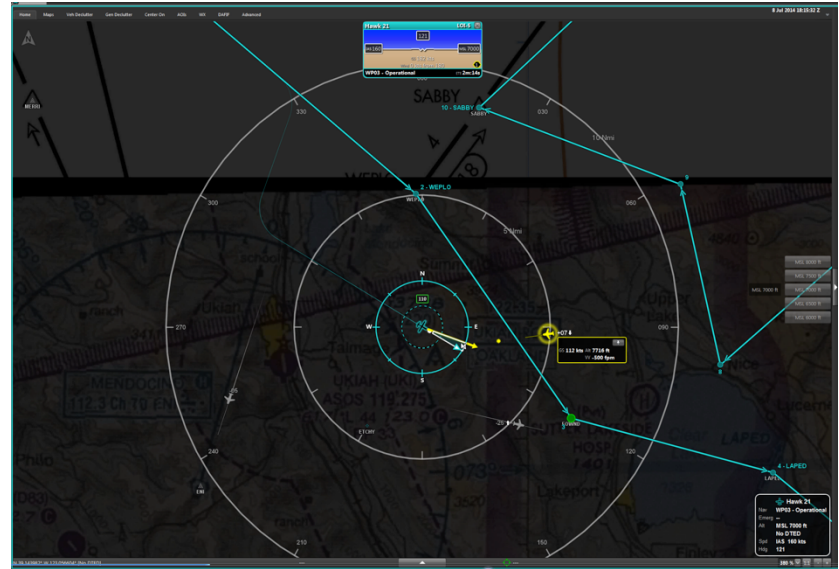


# Experiment 2 – Display Conditions

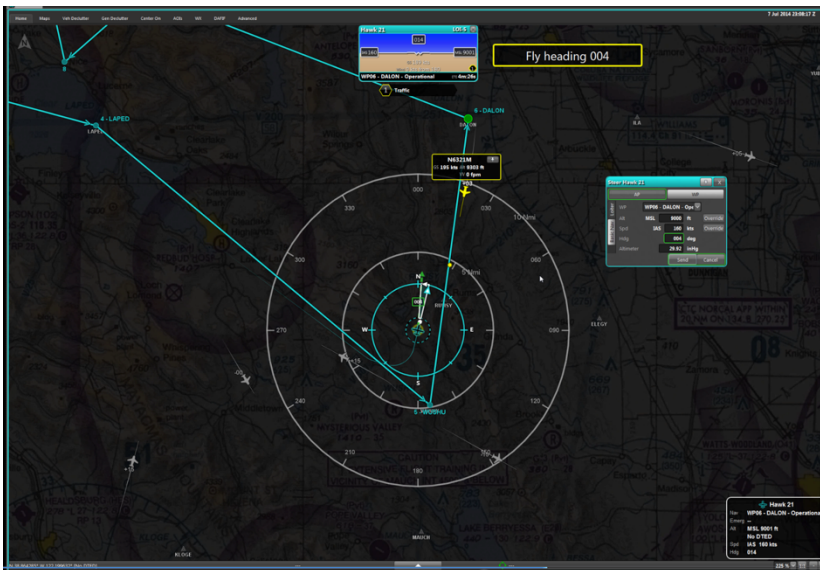
D1



D2



D3

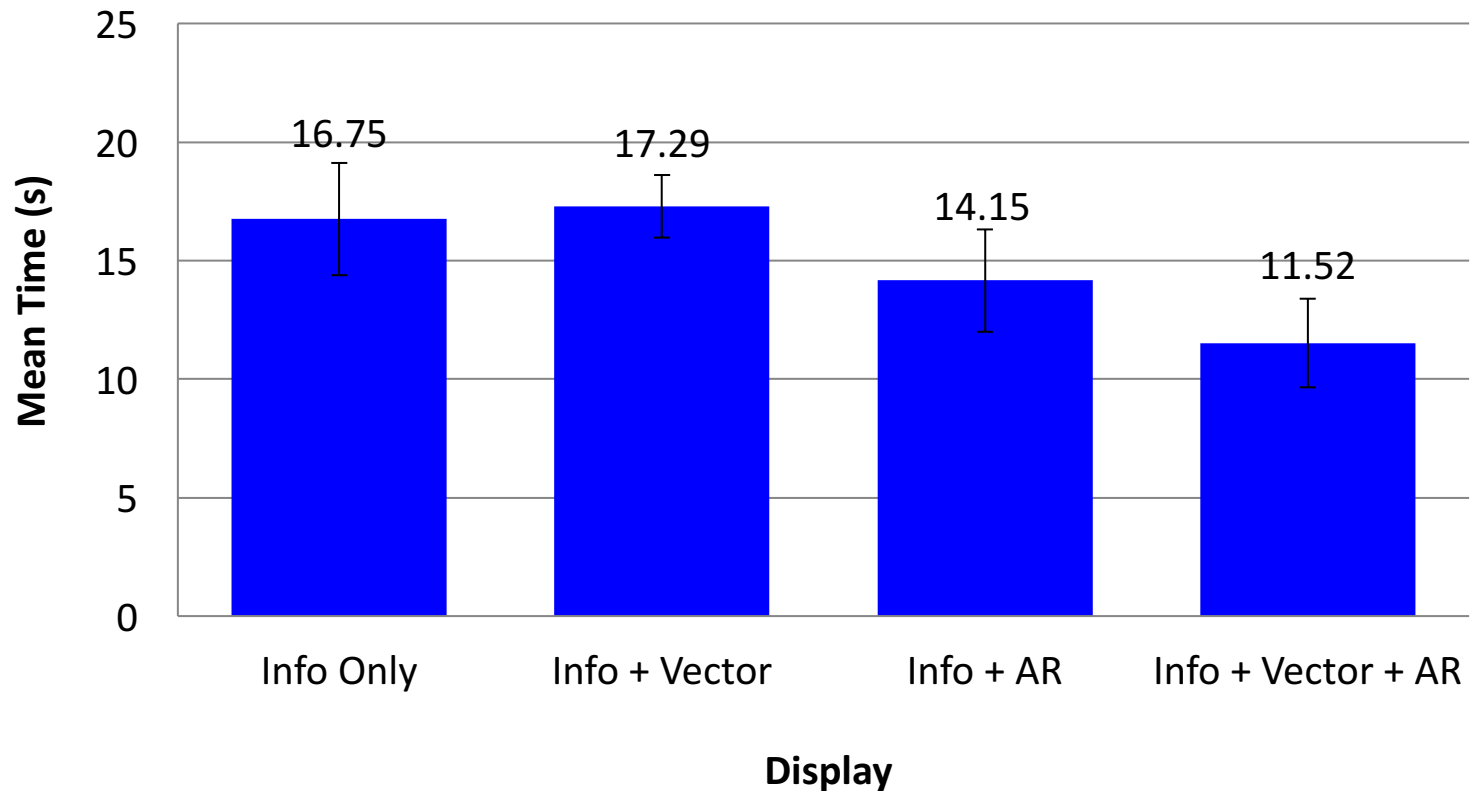


D4





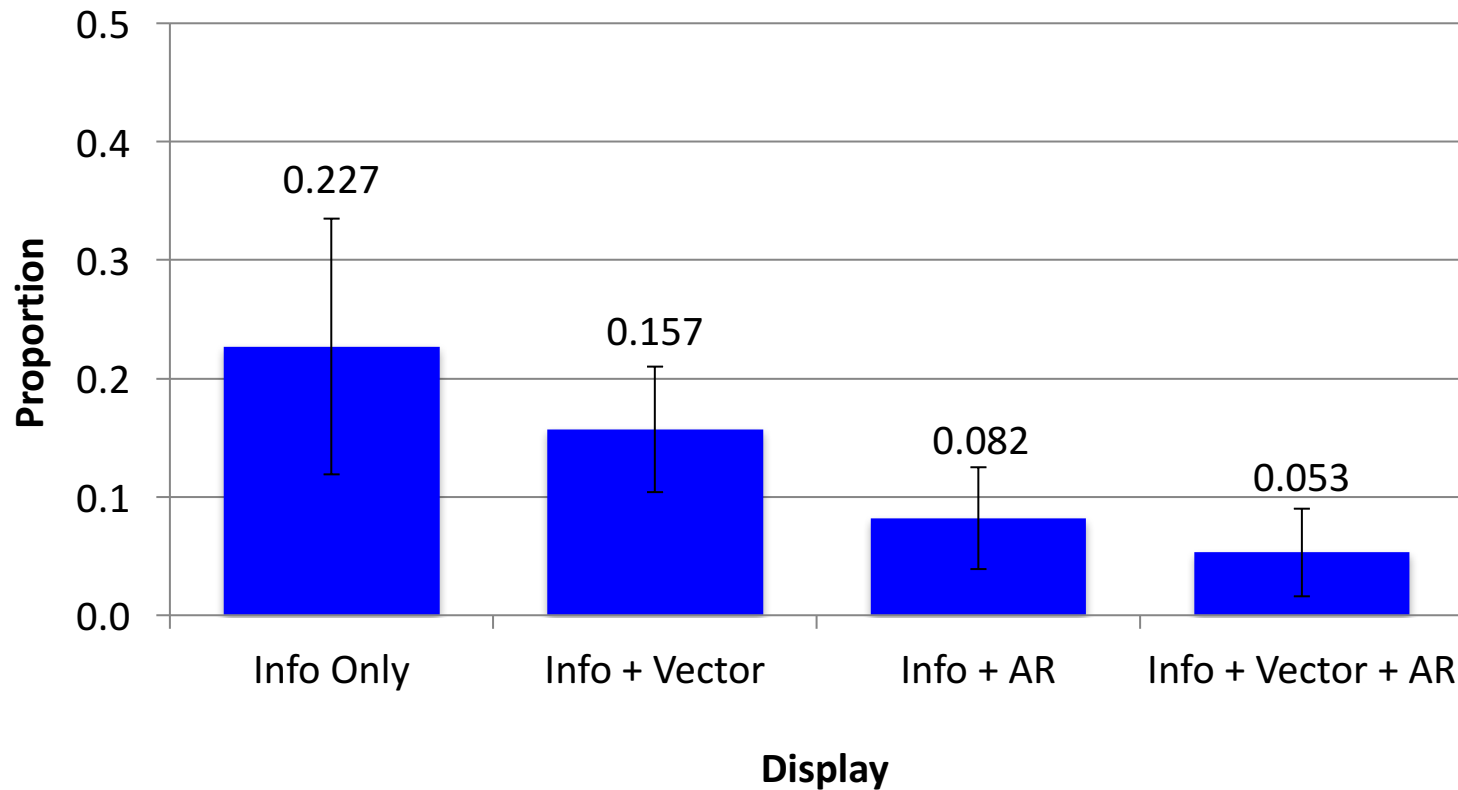
## Experiment 2 – Total Response Time Results



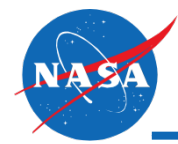
- There was not a significant main effect of Information on Total Response Time,  $p > .05$
- Pilots took an average of 14.92 seconds to complete their final edit in response to DAA/CA alerts (from first alert appearance)



## Experiment 2 – Losses of DAA Well Clear



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



# Experiment 2 – 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 navigation interface



## Experiment 3 – Overview

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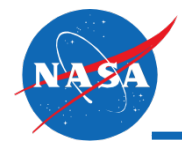
- Goal: Continue evaluation of candidate Detect and Avoid (DAA) displays and algorithms with respect to traffic avoidance and collision avoidance to inform SC-228 DAA Minimum Operational Performance Standards
- Method:
  - Build upon results of previous hitl simulations results and lessons learned to 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



# Experiment 3 – Experimental Design

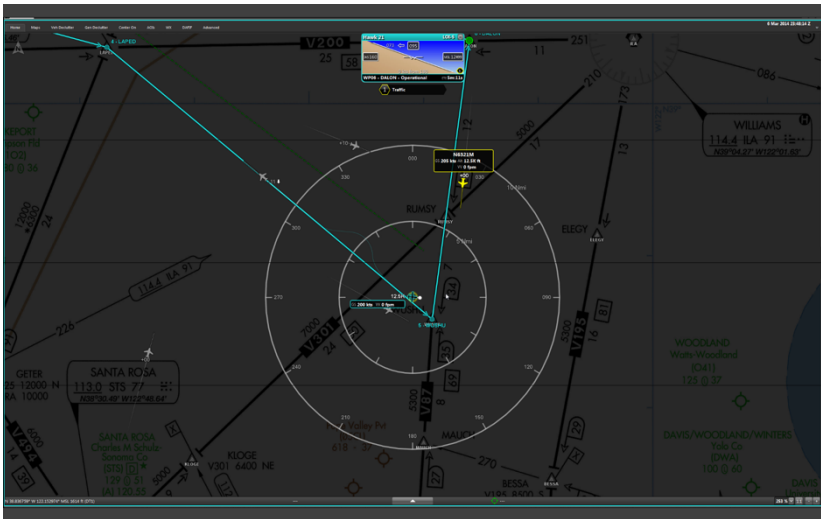
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- Mixed Factorial Design
  - Display Configuration (Within-Subjects Independent Variable):
    - Configuration 1: Minimum Information Set (No Guidance)
    - Configuration 2: Stratway+ No Fly Bands
    - Configuration 3: JADEM Omni Bands
    - Configuration 4: JADEM Vector Planning Tools



# Experiment 3 – Display Conditions

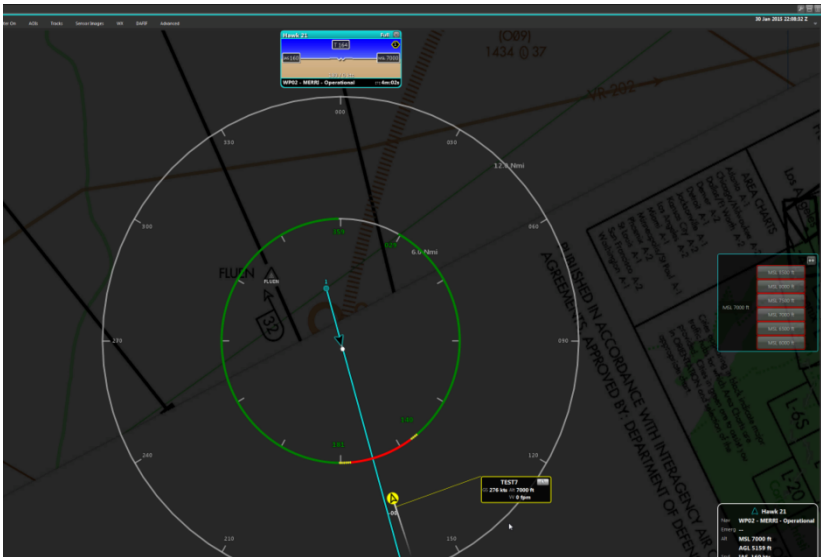
D1



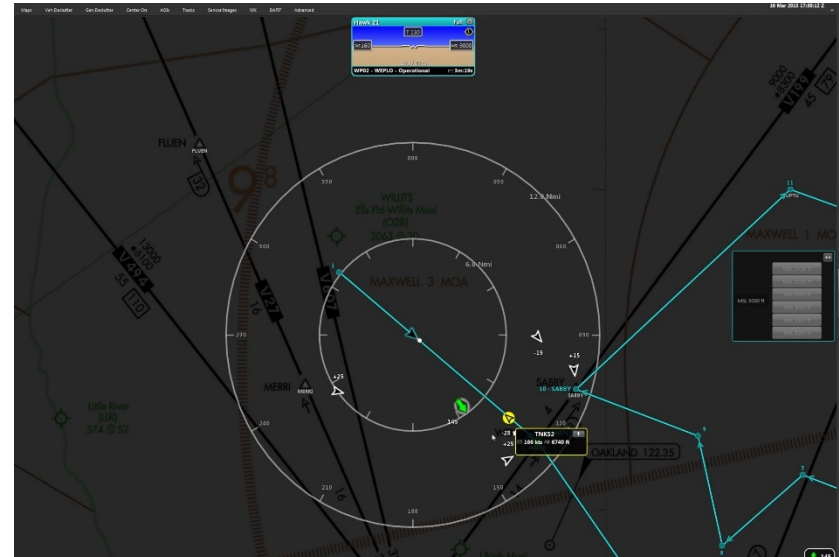
D2

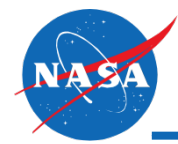


D3

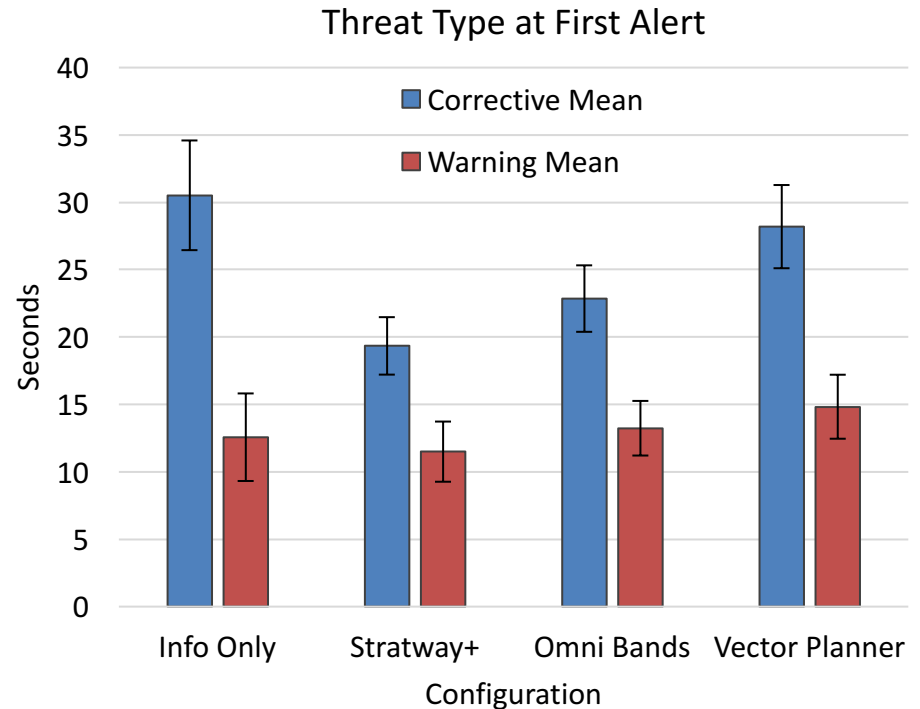
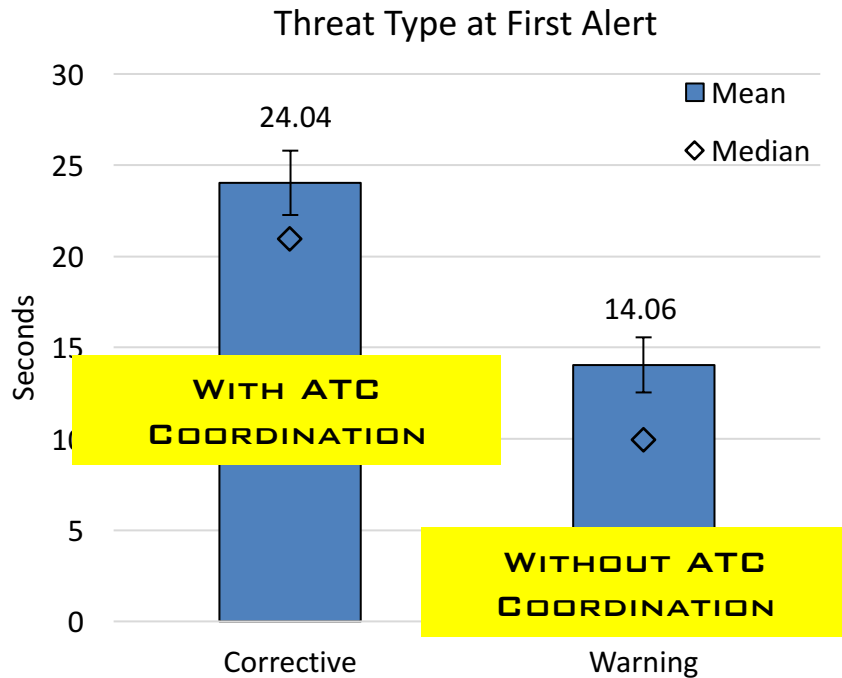


D4

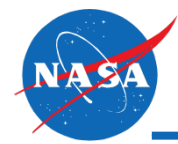




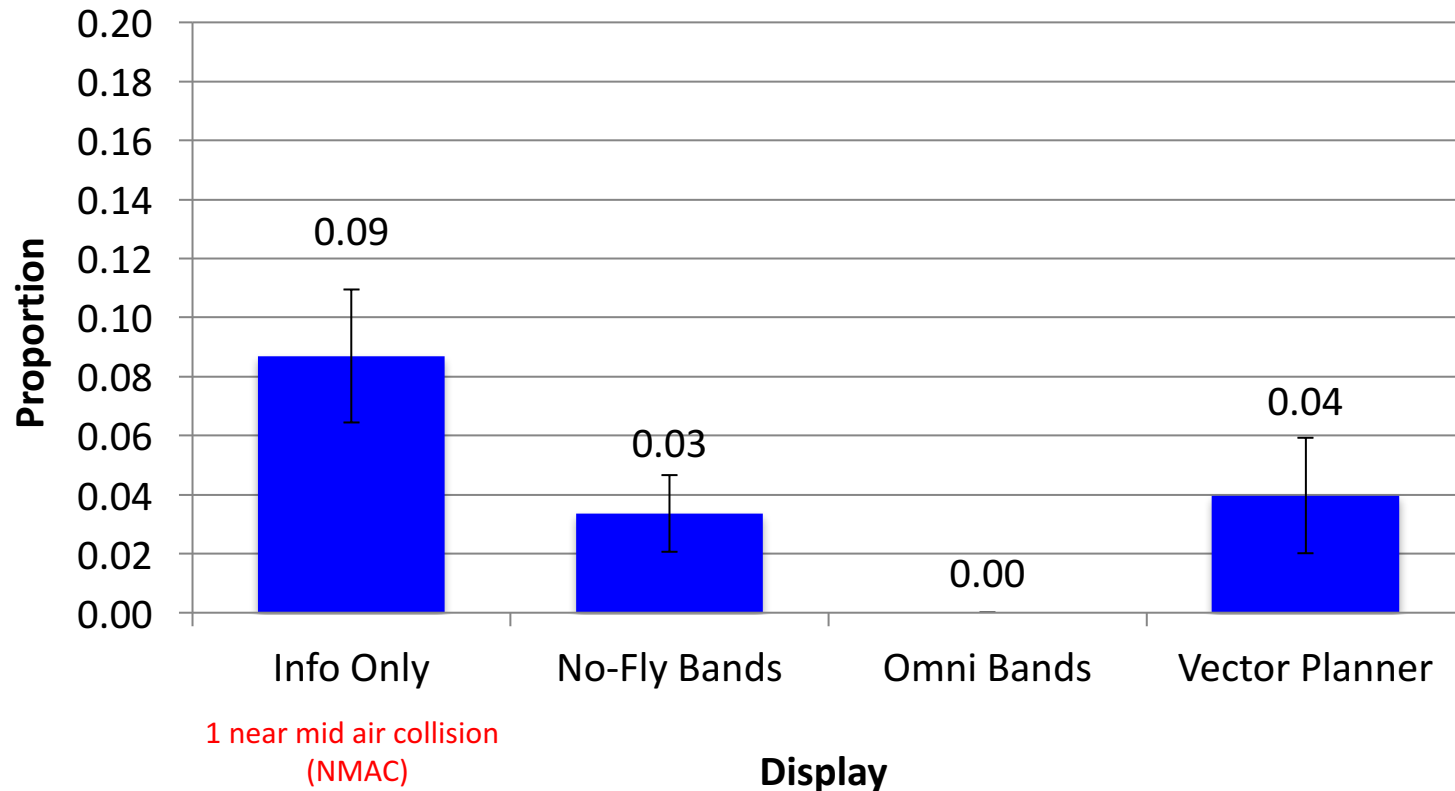
# Experiment 3 – Total Response Time Results



- There was a significant main effect of Information on Total Response Time,  $p < .05$ 
  - Stratway+ No Fly Bands resulted in significantly faster response times compared to Info Only
- Pilots responded, on average, 10s faster to Warning Alerts than they did to Corrective Alerts
  - Pilots exhibited less variability between displays when responding to DAA Warning Alerts than to Corrective DAA Alerts
  - Variability due to coordination with ATC – adds ~ 10 secs to total response time



## Experiment 3 – 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



# Experiment 3 – Results Summary

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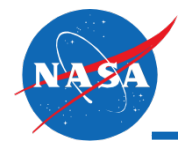
- Suggestive guidance in the form of banding resulted in safer and more timely maneuvers away from conflicts
  - Lower overall proportion of LoWC for both banding displays (none for omni bands)
  - Only NMAC observed in Info Only condition
  - Shorter Total RTs for both banding displays
  - Pilots self-report 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)



## Experiment 3 – Results Summary

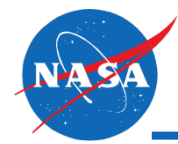
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- Experiment 3 results also inform the DAA alerting structure and thresholds:
  - Pilots responded consistently to a DAA Warning alert (no ATC coordination required) in ~ 15 seconds
  - Responded to a DAA Corrective alert (ATC coordination is required) in ~ 25 seconds, though more variability
  - Therefore, ATC coordination adds approximately 10 seconds to DAA timeline



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# Implications of first three HITLs on Draft DAA MOPS



# Overview Summary of HITLs

## Experiment 1

Integrated Basic  
(Minimum Information)

Integrated Advanced

Standalone Basic  
(Minimum Information)

Standalone Advanced

## Experiment 2

Information Only

Information +  
Vector Planner

Information + Auto  
Resolutions

Information + Trial  
Planner + Auto  
Resolutions

## Experiment 3

Info Only

Stratway+  
No Fly Bands

JADEM  
Fly/No Fly Bands

Vector Planner

Display Types:

Informative

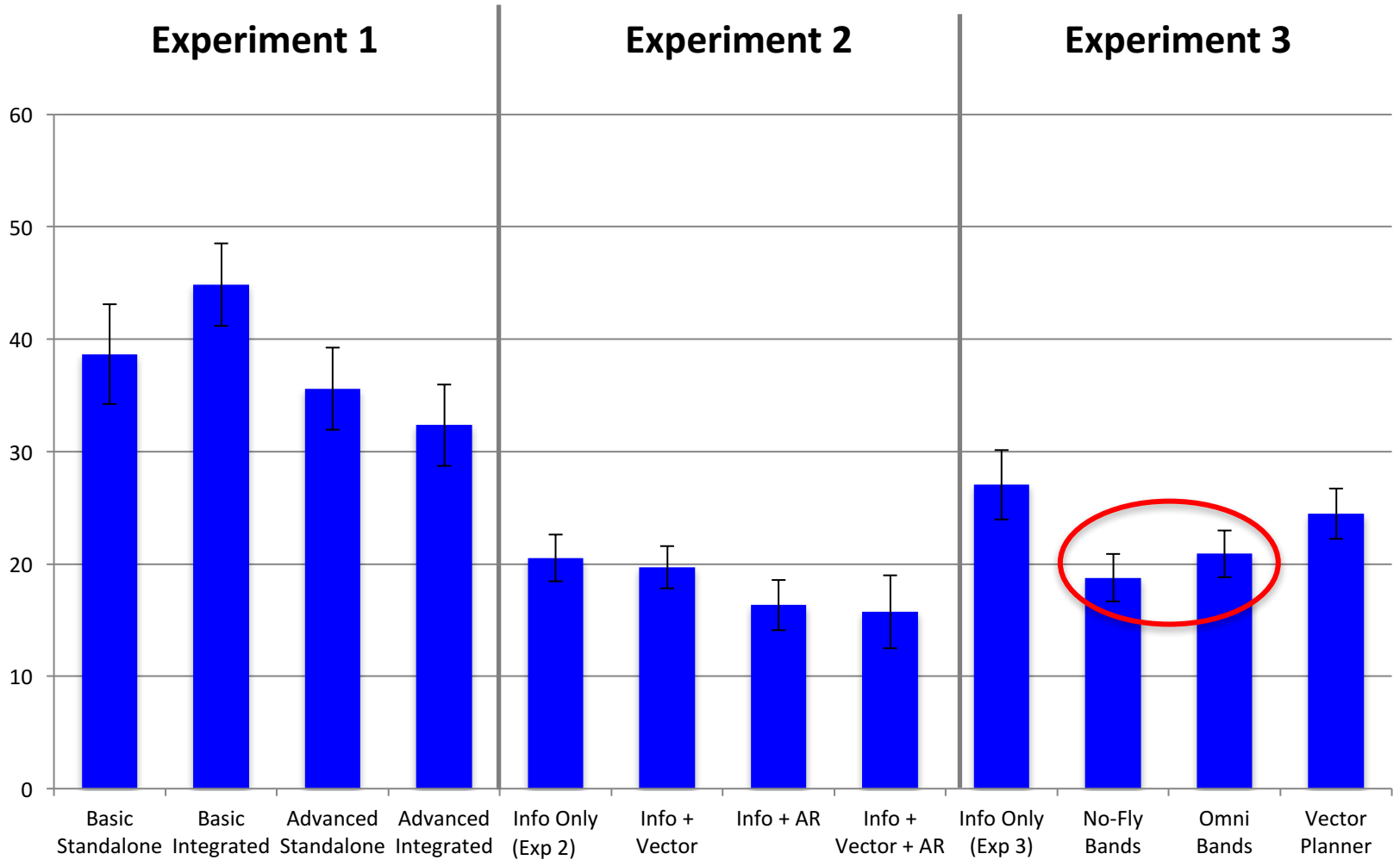
Suggestive

Directive



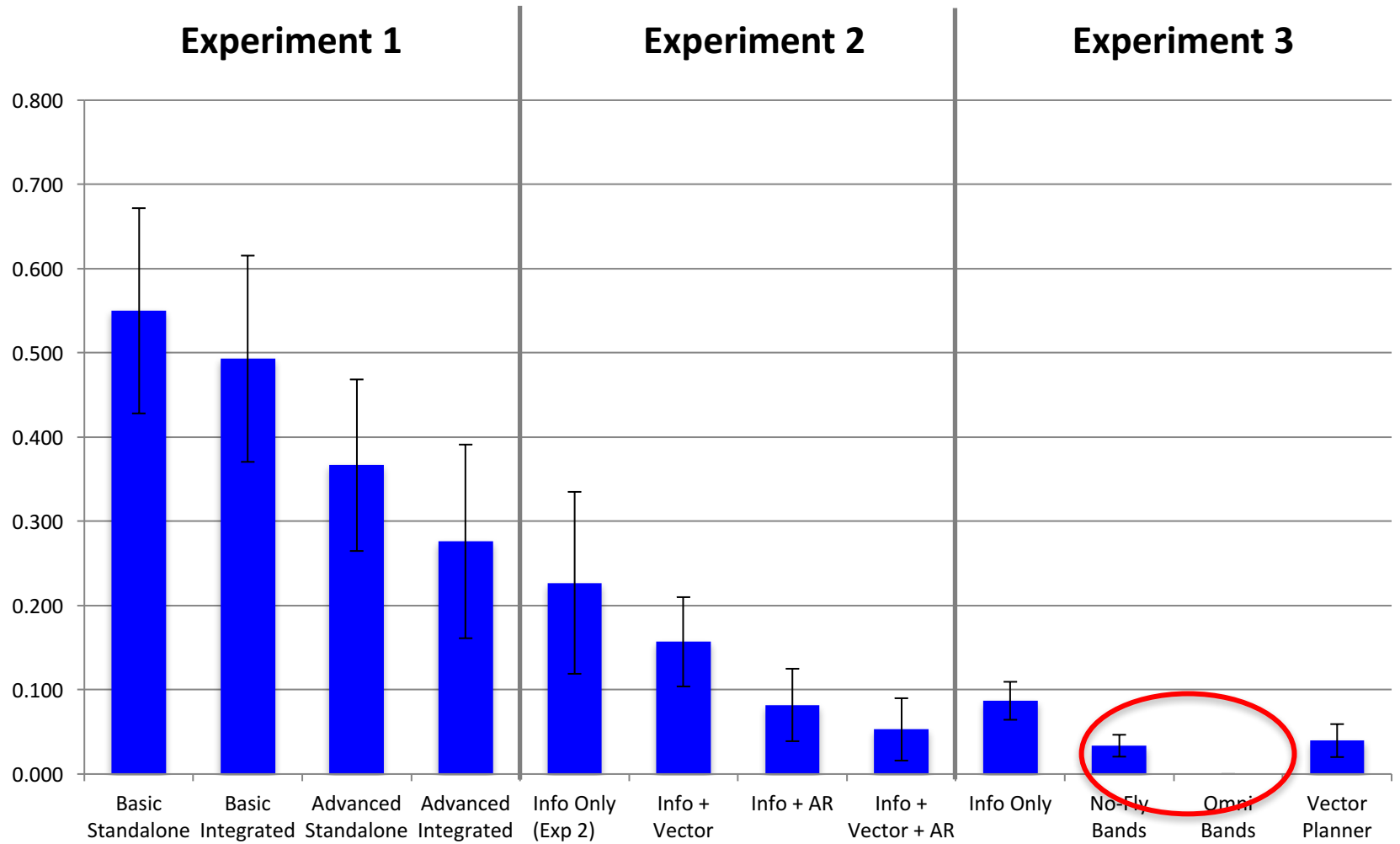


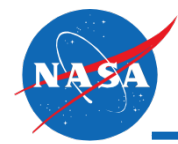
# Total Response Times Across Simulations





# Losses of DAA Well Clear Proportions Across Simulations

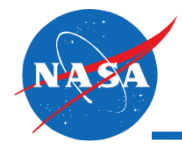




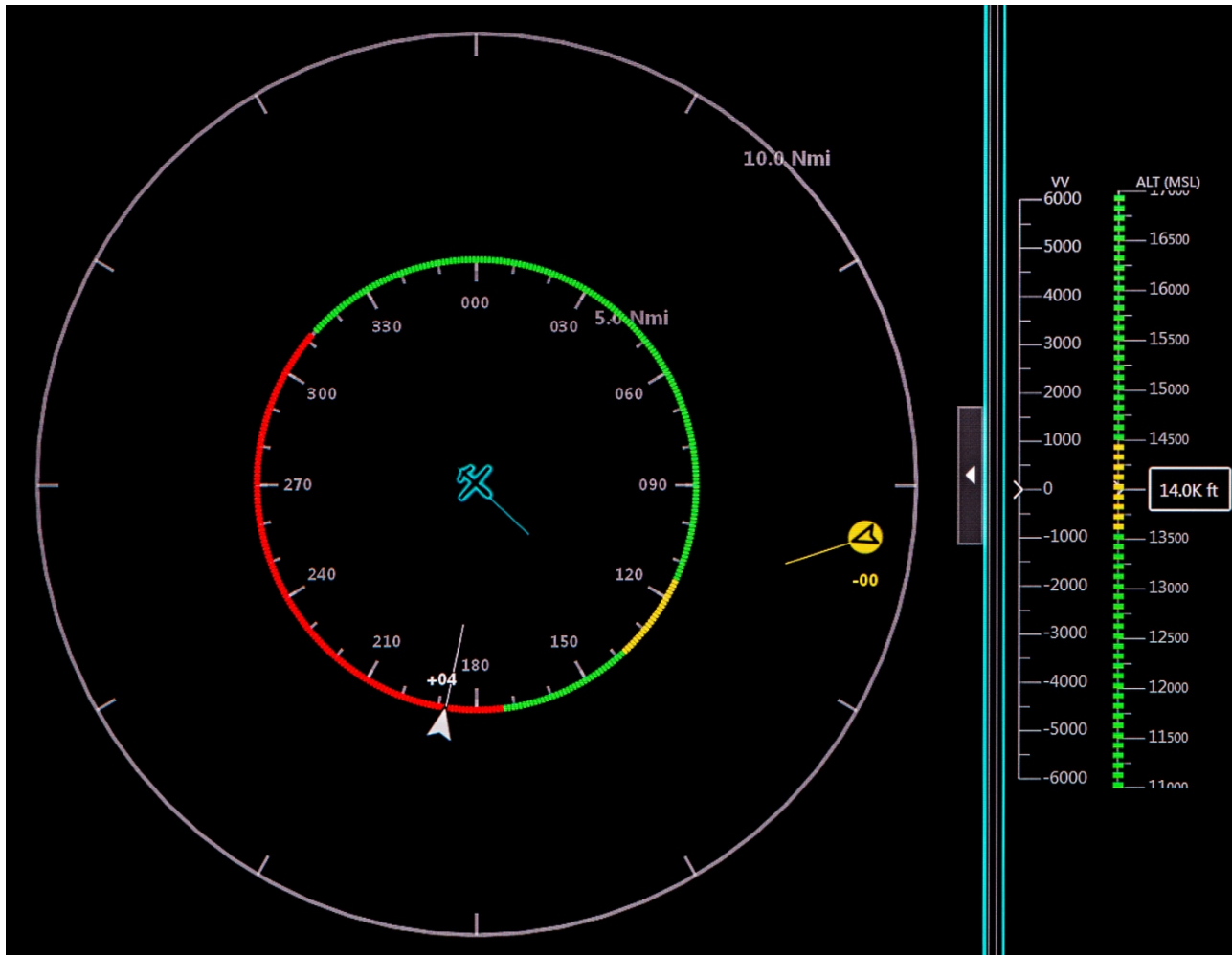
# Draft MOPS Informed by HITLs

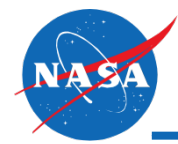
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- Maneuver guidance in the form of bands
- Alerting structure with DAA Warning and Corrective alerts and their corresponding pilot actions
- Minimum thresholds for alerting levels
- Minimum surveillance range for onboard radar

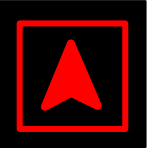






# Draft MOPS Informed by HITLs: Suggestive Maneuver Guidance



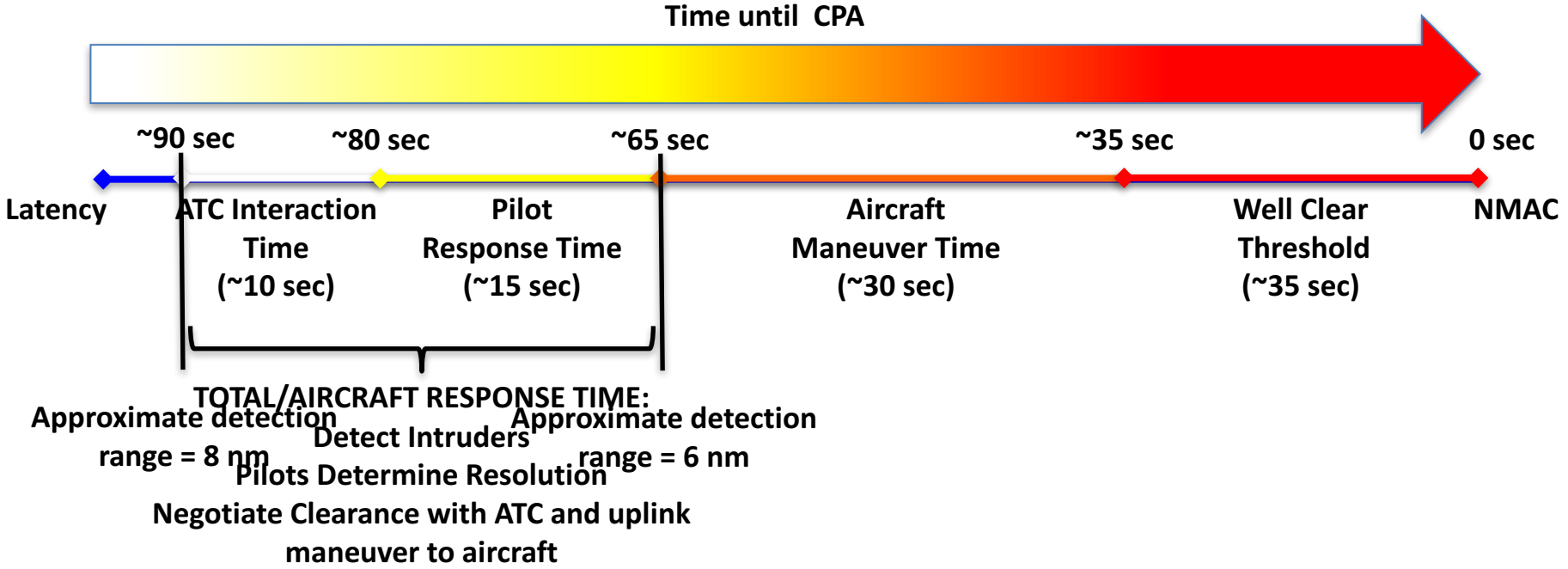


# Draft MOPS Informed by HITLs: Alerting Levels and Thresholds

Symbol	Name	Pilot Action	Average Alerting Time	Aural Alert Verbiage
	DAA Warning Alert	<ul style="list-style-type: none"><li>• <b>Immediate action required</b></li><li>• Notify ATC as soon as practicable after taking action</li></ul>	25 sec (TCPA approximate: 60 sec)	“Traffic, Maneuver Now”
	DAA Corrective Alert	<ul style="list-style-type: none"><li>• On current course, <b>corrective action required</b></li><li>• Coordinate with ATC to determine an appropriate maneuver</li></ul>	55 sec (TCPA approximate: 90 sec)	“Traffic, Avoid”
	DAA Preventive Alert	<ul style="list-style-type: none"><li>• On current course, corrective action <b>should not be required</b></li><li>• Monitor for intruder course changes</li><li>• Talk with ATC if desired</li></ul>	55 sec (TCPA approximate: 90 sec)	“Traffic, Monitor”
	Guidance Traffic	<ul style="list-style-type: none"><li>• <b>No action required</b></li><li>• Traffic generating guidance bands outside of current course</li></ul>	X	N/A
	Remaining Traffic	<ul style="list-style-type: none"><li>• No action expected</li></ul>	X	N/A

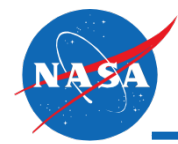


# Draft MOPS Informed by HITLs: Surveillance Range





# Experiment 4 (Validation)



# Experiment 4 – Overview

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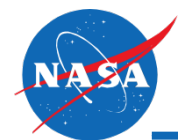
- Purpose:
  - Conduct final V&V activity in support of SC-228 DAA HMI requirements for displays, alerting and guidance
  - Determine if pilot performance w/ minimum requirements (as currently defined in the draft MOPS) comparable to previous simulations, such as Experiment 3?
- Goals:
  - Implement the minimum display, alerting and guidance requirements as close as possible in simulation
  - Test in representative simulated flight environment
  - 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









# Experiment 4 – Experimental Design

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- 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



# Experiment 4 – Experimental Design

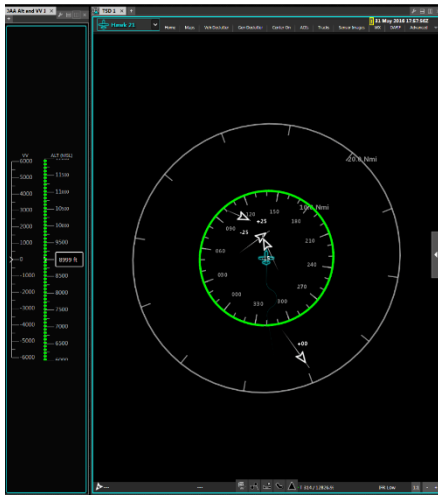
Symbol	Name	Pilot Action	Buffered Well Clear Criteria	Time to Loss of Well Clear	Aural Alert Verbiage
	TCAS RA	<ul style="list-style-type: none"> <li><b>Immediate action required</b></li> <li>Comply with RA sense and vertical rate</li> <li>Notify ATC as soon as practicable after taking action</li> </ul>	<ul style="list-style-type: none"> <li>*DMOD = 0.55 nmi</li> <li>*ZTHR = 600 ft</li> <li>*modTau = 25 sec</li> </ul>	0 sec (+/- 5 sec) (TCPA approximate: 25 sec)	“Climb/Descend”
	DAA Warning Alert	<ul style="list-style-type: none"> <li><b>Immediate action required</b></li> <li>Notify ATC as soon as practicable after taking action</li> </ul>	<ul style="list-style-type: none"> <li>DMOD = 0.75 nmi</li> <li>HMD = 0.75 nmi</li> <li>ZTHR = 450 ft</li> <li>modTau = 35 sec</li> </ul>	25 sec (TCPA approximate: 60 sec)	“Traffic, Maneuver Now” x2
	Corrective DAA Alert	<ul style="list-style-type: none"> <li>On current course, <b>corrective action required</b></li> <li>Coordinate with ATC to determine an appropriate maneuver</li> </ul>	<ul style="list-style-type: none"> <li>DMOD = 0.75 nmi</li> <li>HMD = 0.75 nmi</li> <li>ZTHR = 450 ft</li> <li>modTau = 35 sec</li> </ul>	55 sec (TCPA approximate: 90 sec)	“Traffic, Avoid”
	Preventive DAA Alert	<ul style="list-style-type: none"> <li>On current course, corrective action <b>should not be required</b></li> <li>Monitor for intruder course changes</li> <li>Talk with ATC if desired</li> </ul>	<ul style="list-style-type: none"> <li>DMOD = 0.75 nmi</li> <li>HMD = 1.0 nmi</li> <li>ZTHR = 700 ft</li> <li>modTau = 35 sec</li> </ul>	55 sec (TCPA approximate: 90 sec)	“Traffic, Monitor”
	Guidance Traffic	<ul style="list-style-type: none"> <li><b>No action required</b></li> <li>Traffic generating guidance bands outside of current course</li> </ul>	Associated w/ bands outside current course	X	N/A
	Remaining Traffic	<ul style="list-style-type: none"> <li><b>No action required</b></li> <li>No coordination required</li> </ul>	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)

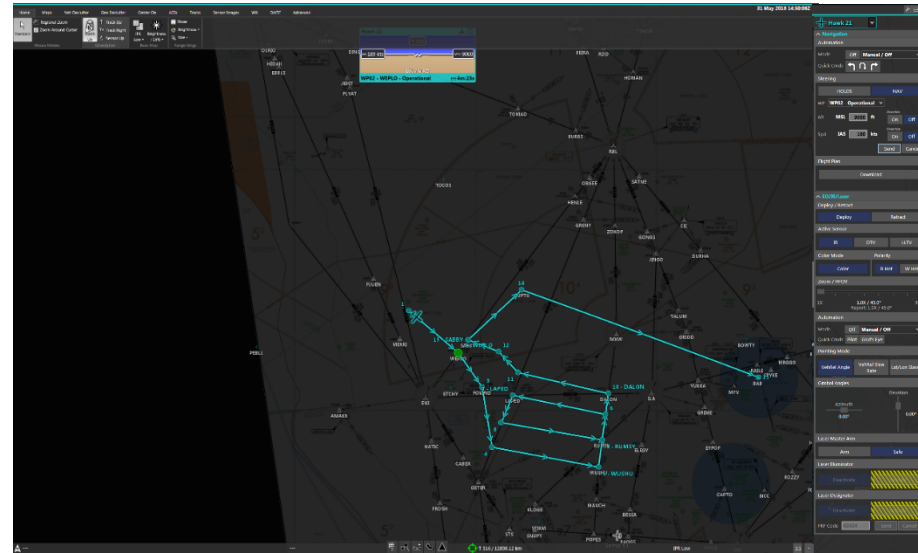


# Experiment 4 – Display Conditions

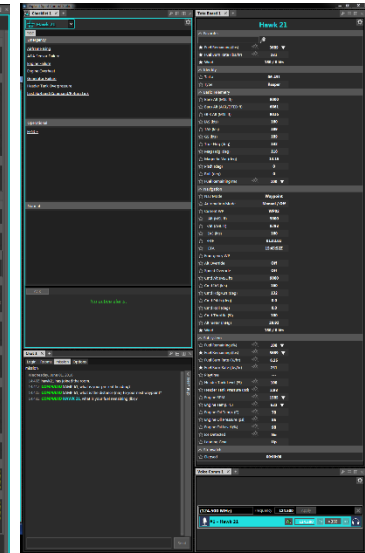
## Standalone Configuration



DAA Display



TSD (Moving Map)



Side Panel

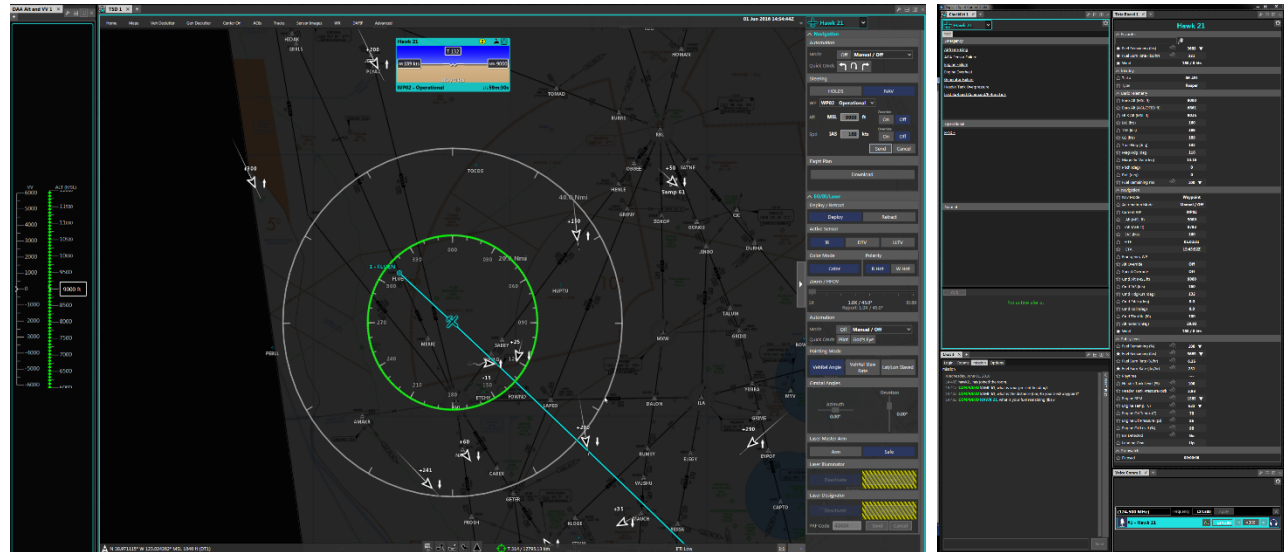
### Notes:

- 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



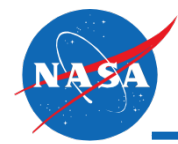
# Experiment 4 – Display Conditions

## Integrated Configuration



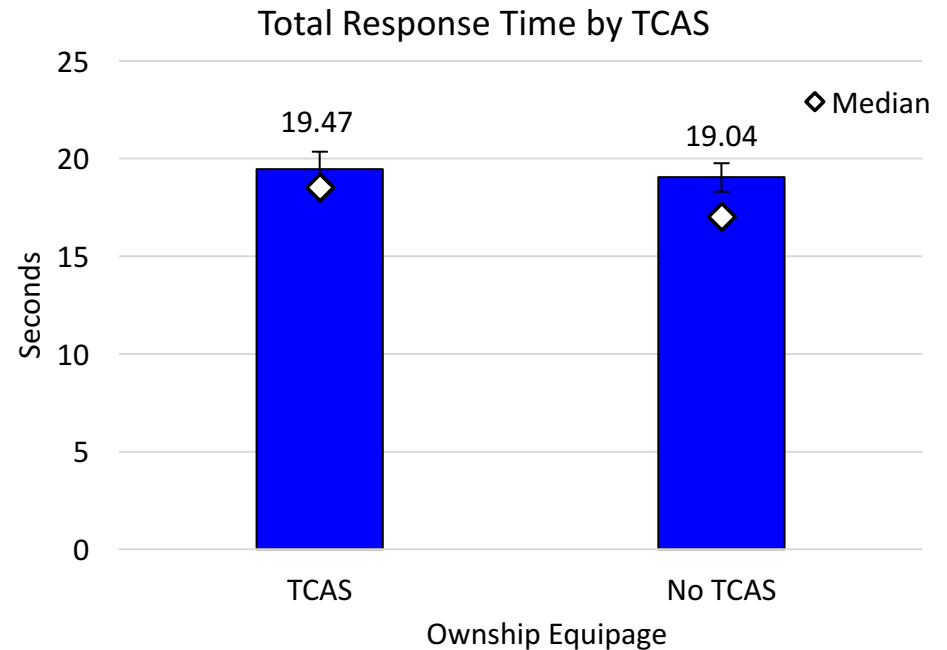
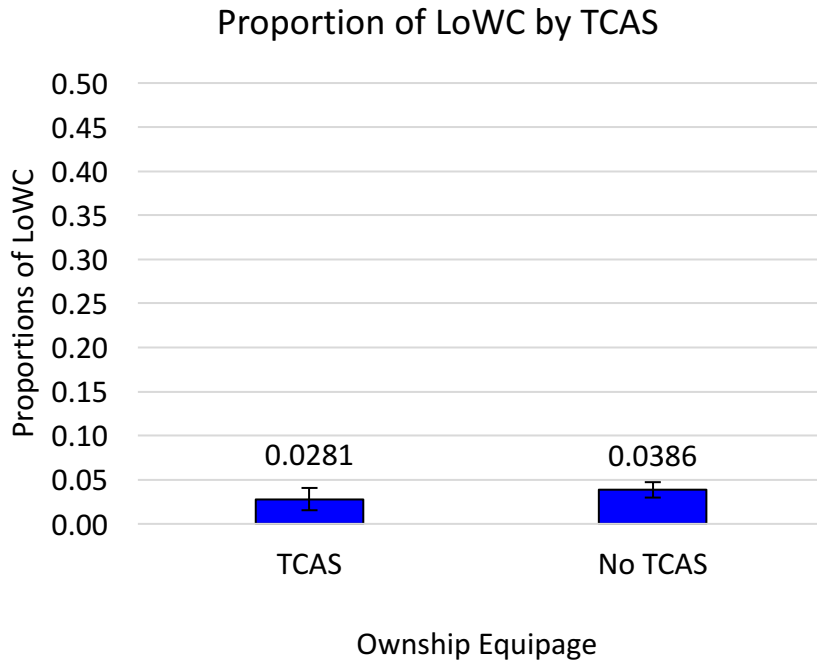
TSD w/ DAA Display

Side Panel



# Experiment 4 – TCAS II Effects

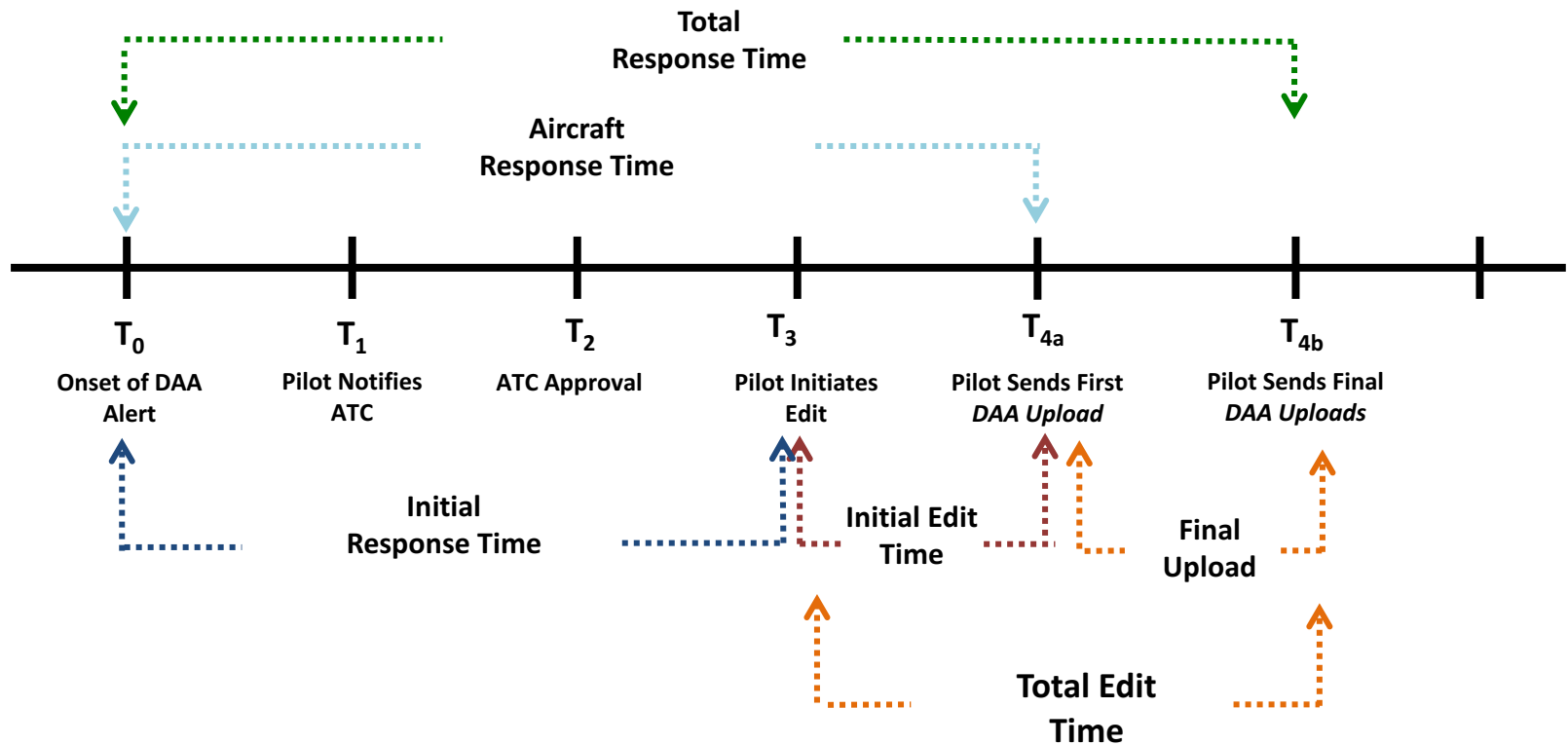
- TCAS II equipage was split between first half and second half of data collection
  - No significant main effect on proportion of LoWC
  - No significant main effect on total response time
- *Remaining results are collapsed across the TCAS variable*

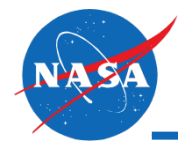




# Experiment 4 – Response Time Results

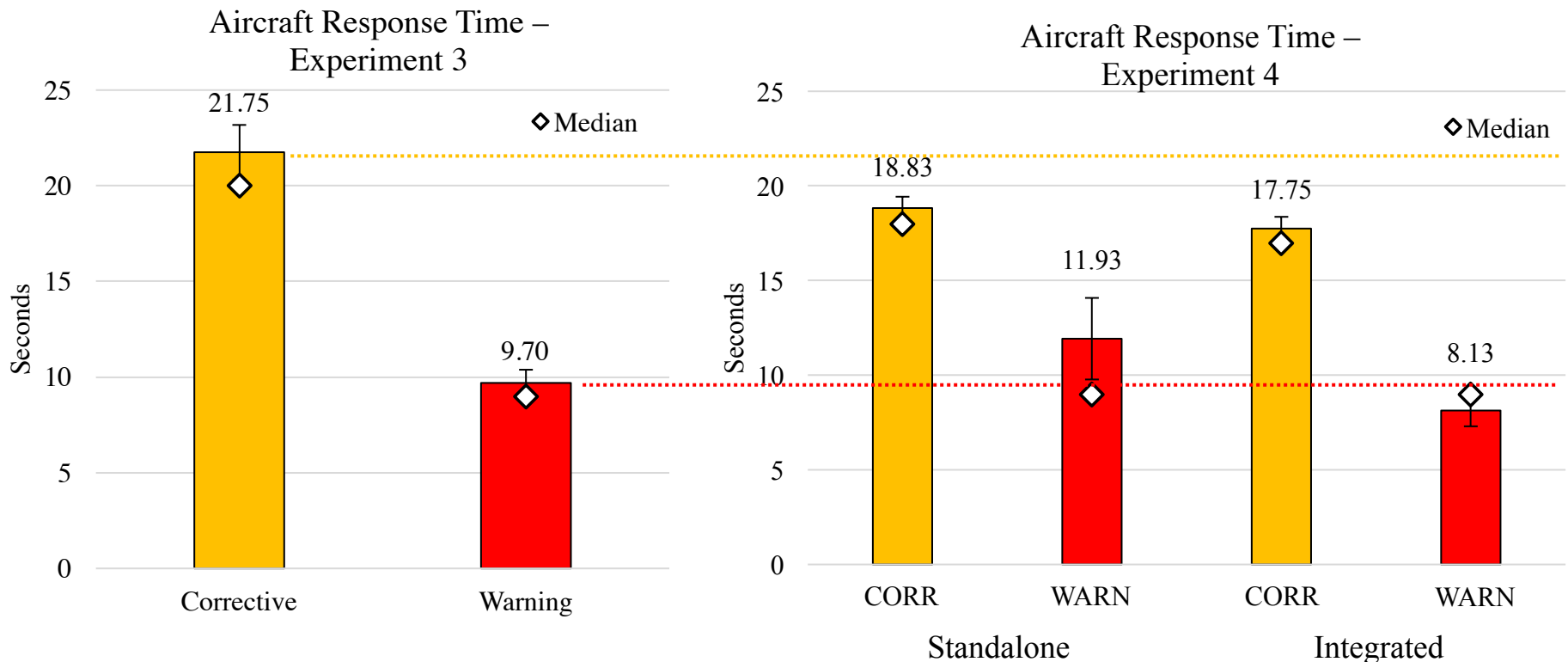
- Exp 4 to Exp 3 comparison uses aircraft response time instead of total response time
  - Difference is whether we are measuring at the first vs final upload





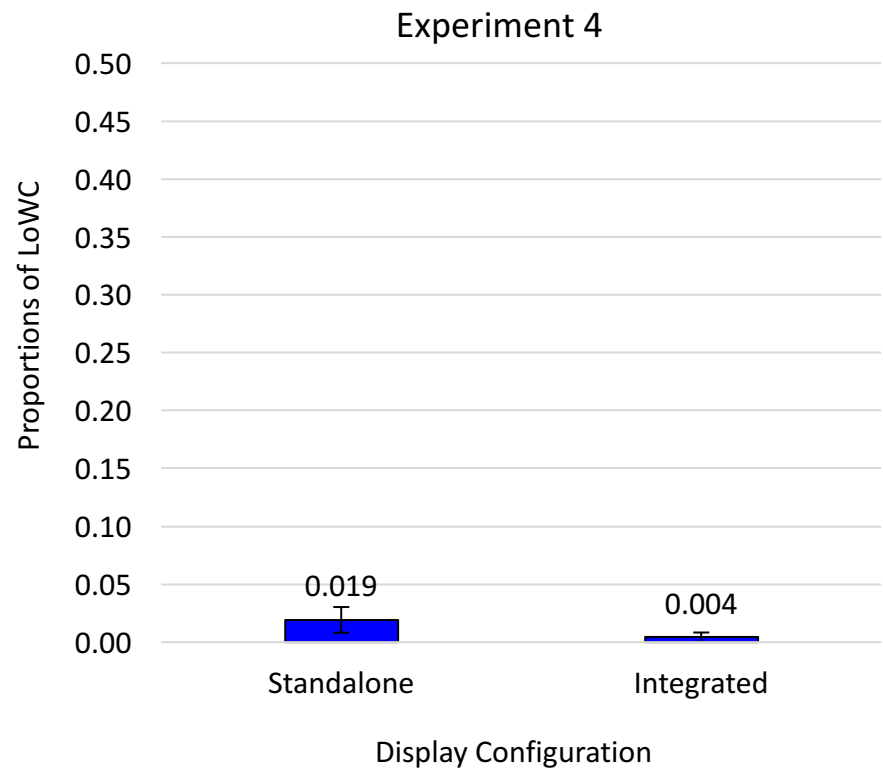
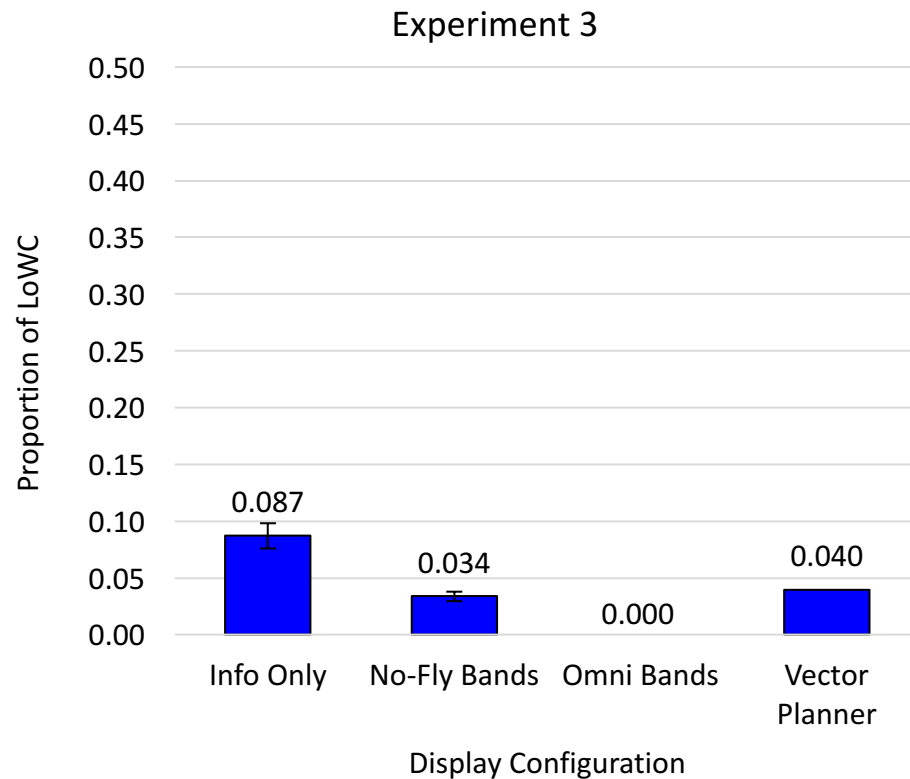
# Experiment 4 – Aircraft Response Time

- Pilots sent their *first* upload to their aircraft **1.3 sec faster** in the Integrated display configuration (statistically significant;  $p < .05$ )
  - More pronounced difference between displays when separated by alert level
- Comparable to Exp 3 results, although response to Warning in Standalone configuration is slower in Exp 4





# Experiment 4 – Losses of DAA Well Clear



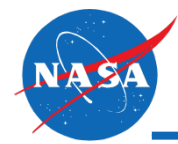
- There was not a significant main effect of Display Configuration on Proportion of DAA Losses of Well Clear,  $p < .05$
- Proportion of LoWC where pilot was at fault (i.e., had enough time to respond) lower in Experiment 4 than all conditions in Experiment 3 *except for Omni Band*



## Experiment 4 – Results Summary

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- 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 LoDWC 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**



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# Summary of Contributions to Phase 1 MOPS



# Summary of NASA HITL Contributions to SC-228

- Suggestive DAA guidance requirements
- Alerting logic and thresholds
- Display integration
- Pilot response timeline
  - Derived RADAR Requirements
- V&V of alerting, guidance and display draft MOPS

- TCAS/DAA interoperability concept
  - Requirements for DAA guidance and alerting
- Regain well clear guidance logic/display

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

Experiments 1 – 4

DAA-TCAS  
Interoperability HITL

Special Cases  
Mini HITL



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Questions?