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

ACAS-Xu Run 5 Human-in-the-Loop Sim

SC-147 Results Outbrief

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Experiment Objective

- Goal: assess **ACAS Xu Run 5** in a human-in-the-loop (HITL) simulation in order to measure pilot and system performance in real-time
  - An emphasis on pilots' ability to comply with:
    - Remain Well Clear (RWC) alerting and guidance
    - Resolution Advisory (RA) alerting and guidance
      - Vertical, Horizontal and 'Blended' (vertical + horizontal) RAs

- Where appropriate, we will compare ACAS Xu Run 5 results to previous SC-228 Phase 1 DAA work
  - The Phase 1 V&V HITL was conducted in 2016 using NASA's DAIDALUS algorithm to provide DAA alerting and guidance
  - The design of the present scenarios were kept as similar as possible to the Phase 1 sim to allow for comparisons, *however*:
    - Sensor noise was **not** modeled in the Phase 1 study & the simulated RADAR detection range was **8nm**

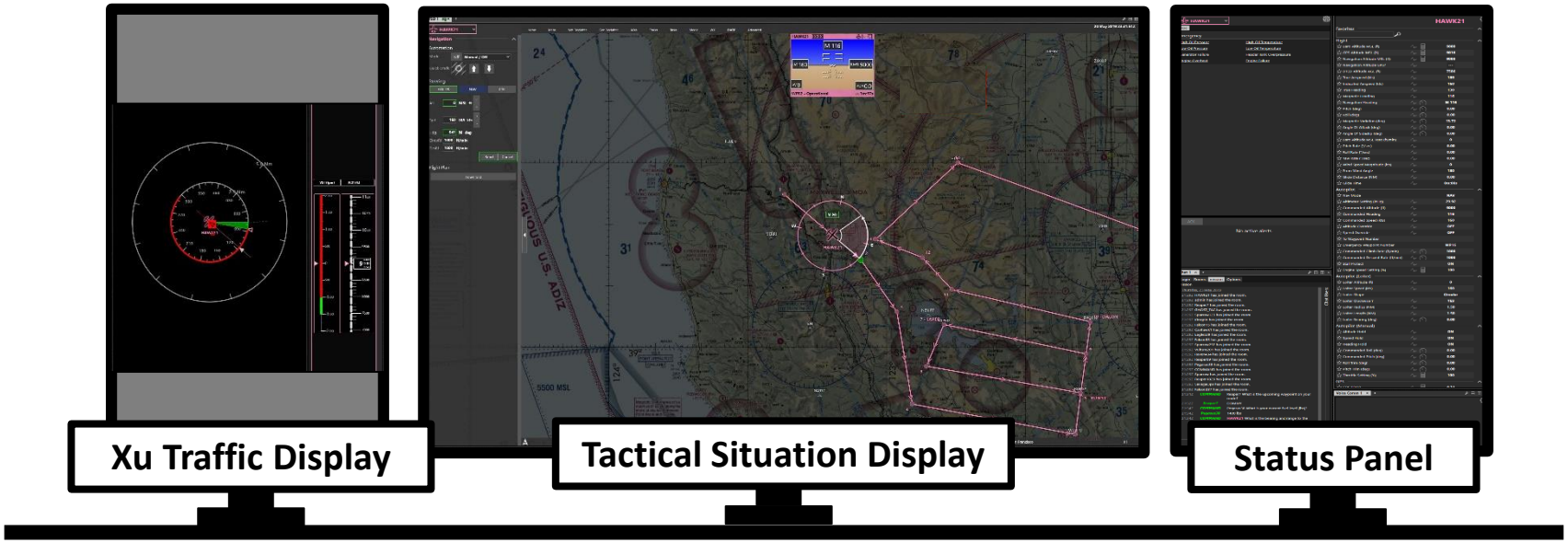
- Note – results have been shared with the Xu team and have been incorporated into the pre-FRAC version of Xu

Experiment Design

- Independent Variables:
  - Display Configuration (2 levels, **within-subjects**)
    - Integrated – DAA information presented within TSD
    - Standalone – DAA information shown in separate, dedicated display
  - Threat Type at First Alert (2 levels, **within-trial**)
    - Corrective DAA Alert: encounter scripted to provide the *maximum allowable* Corrective DAA (RWC) alerting time
    - Resolution Advisory: encounter scripted to "**force"** RAs without a preceding DAA alert (i.e., pop-up or blundering intruders)
  - Intruder Equipage (2 levels, **within-trial**)
    - Cooperative (ADS-B)
      - Detection Range: 20 nm, 360° field of regard
      - Vertical Range: +/- 10000 ft MSL
    - Non-Cooperative (RADAR-only)
      - Detection Range: **6.7 nm**
      - Field of regard: 110° azimuth & 15° elevation

Experiment Design

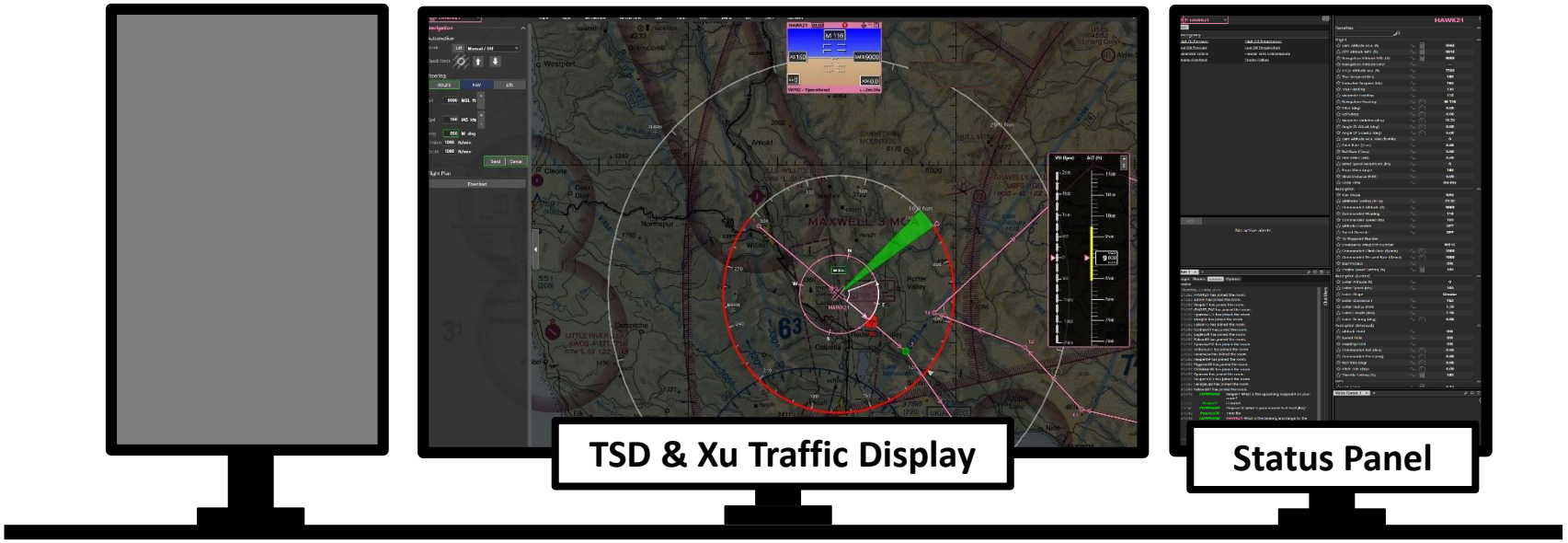
STANDALONE CONFIGURATION



- DAA & CA information **presented separately** from navigation and vehicle control interfaces

Experiment Design

INTEGRATED CONFIGURATION



- DAA & CA information **collocated** with navigation and vehicle control interfaces

Test Setup

- Simulation Elements
  - UAS pilots situated at AFRL's Vigilant Spirit Control Station (VSCS)
    - Simulated Oakland Center, Class E airspace
    - Pilot booth isolated from rest of simulation environment
    - Honeywell Sensor Model provided representative ADS-B and RADAR sensor noise

- ATC confederates and 'pseudo' pilots managed airspace
  - Provided realistic comms & background traffic
  - Used retired Oakland Center controllers and general aviation pilots as confederates

Test Setup

- 16 total participants
  - All active UAS pilots
  - 4 experimental trials per pilot (~45min per trial)
    - 2 mission routes x 2 display configurations

- Pilot task
  - Maintain safety of aircraft along pre-filed flight path
    - Manually respond to DAA and RA guidance from Xu
  - Coordinate with center controller as appropriate
  - Respond to scripted chat messages and system failure events

- Ownship configuration
  - Generic MQ-9 model
  - Cruise speed: 160 KIAS
  - Climb/descent rate: 1,000 fpm
  - Turn rate: 3° per second

HITL Display Modifications

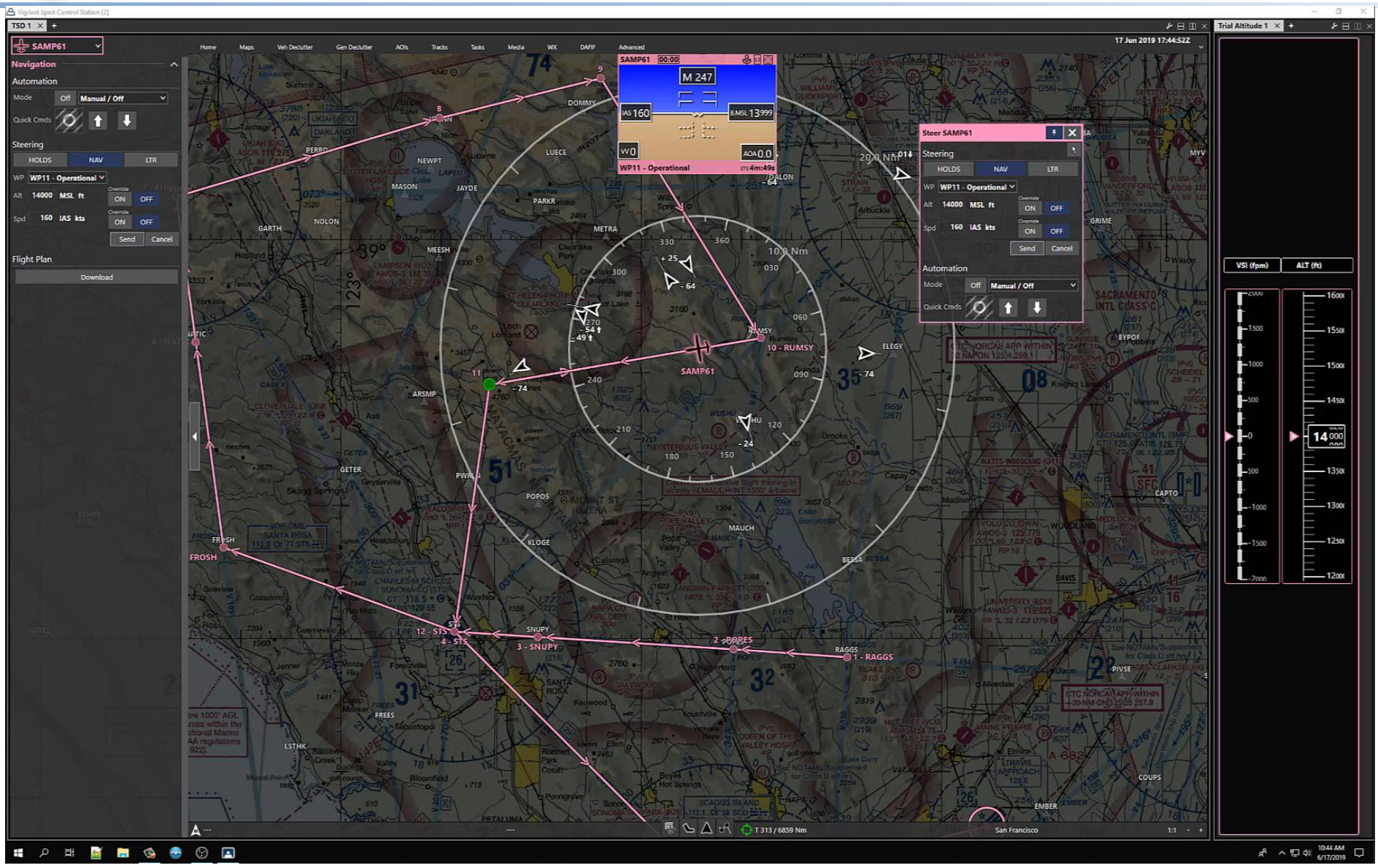
- Several display modifications were made based on results from a prior engineering analysis and early testing with Run 5
  - An RA 'auto-fill' feature was added to the GCS control interfaces to help reduce RA response times
    - Eliminated need to manually input RA target heading or vertical speed
    - Pilot only had to approve & click "Send" button
  - Horizontal RA target headings were capped at a 5 second update rate
    - Testing showed that target headings could update up to once-a-second
    - The pre-FRAC version of Xu implemented similar behavior
    - Note: target heading updates were not annunciated
  - GCS converted Xu's native DAA vertical speed guidance to discrete altitudes within DAA altitude bands
    - SC-228 requires RWC/DAA vertical guidance to be shown in altitudes if the GCS cannot upload vertical rates

ACAS Xu Alerting Logic

Symbol	Name	Pilot Action	Aural Alert Verbiage
	Resolution Advisory (RA)	• ***Immediate action required to comply with RA*** • Must upload maneuver within 5 seconds • Notify ATC after maneuver	"Climb/Descend" x2 "Turn Left/Right" x2 or a combination of above
	Corrective DAA Alert	• **Action required to remain 'DAA well clear'** • Coordinate with ATC prior to maneuvering	"Traffic, Avoid"
	Preventive DAA Alert	• **No action required** • Generating peripheral guidance bands • Monitor for potential increase in severity	"Traffic, Monitor"
	Guidance Traffic	• **No action required** • Ownship maneuvers against traffic might generate increase in threat level	N/A
	"Other"	• **No action required** • No coordination required	N/A

Phase 1 Enroute DWC Criteria: *DMOD = 4000ft, VertSep = 450ft, modTau = 35sec*

Non-Coop Encounter Example



Scenario Design

- 6 scripted encounters per scenario:

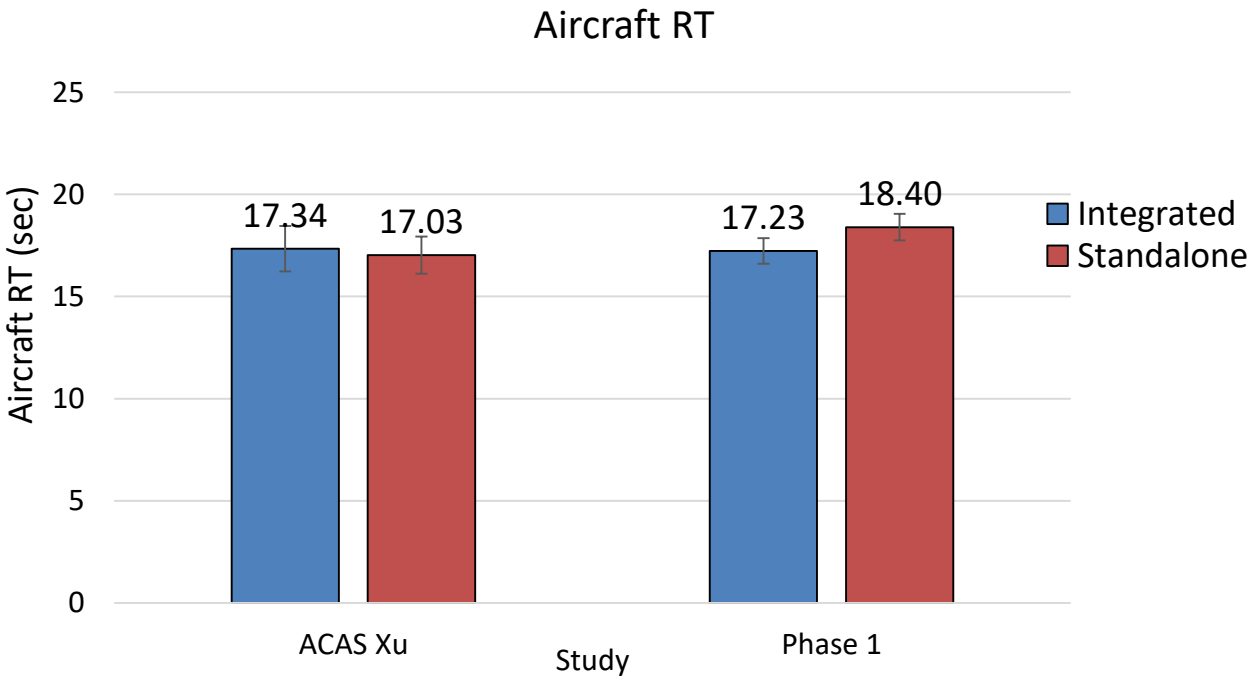
Scripted Threat Type	Non-Cooperative (RADAR Only)	Cooperative (ADS-B & RADAR)
Corrective DAA Alert	1	3
Resolution Advisory (RA)	1	1

- "Forced" RAs were executed differently depending on intruder equipage:
  - Cooperative forced RAs were triggered by a late intruder climb/descent into ownship (i.e., a 'blunder')
  - Non-cooperative forced RAs were triggered by the intruder popping-up on the scope
    - Could not consistently force immediate non-coop RAs through blunders due to sensor noise

REMAIN WELL CLEAR (RWC) RESULTS

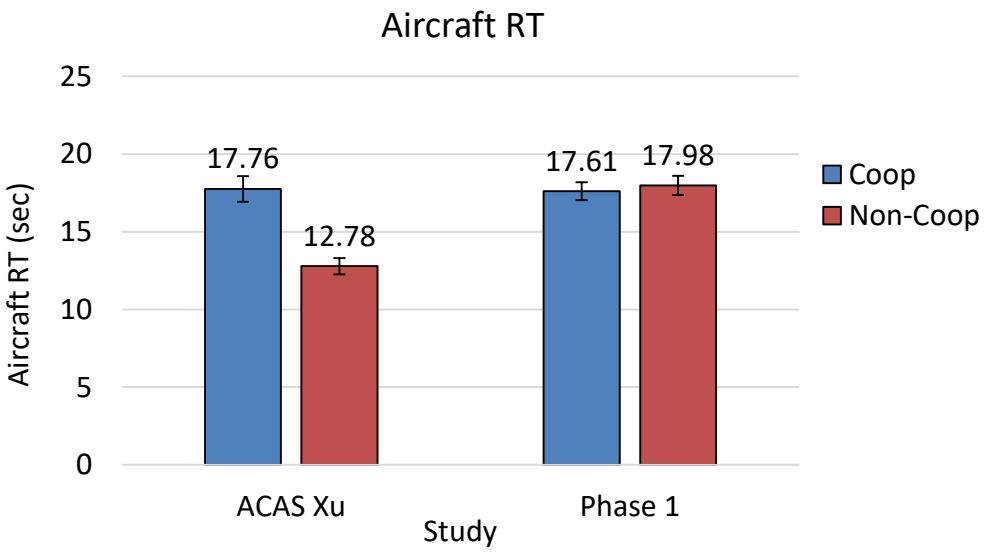
RWC / Corrective Alert Response Times

- Display Configuration Variable
  - No difference in aircraft response times between Standalone and Integrated display conditions
    - **Aircraft response time** = time from appearance of a **Corrective DAA** alert to the first upload sent to aircraft
  - Overall aircraft response times nearly identical to the **Phase 1** V&V HITL

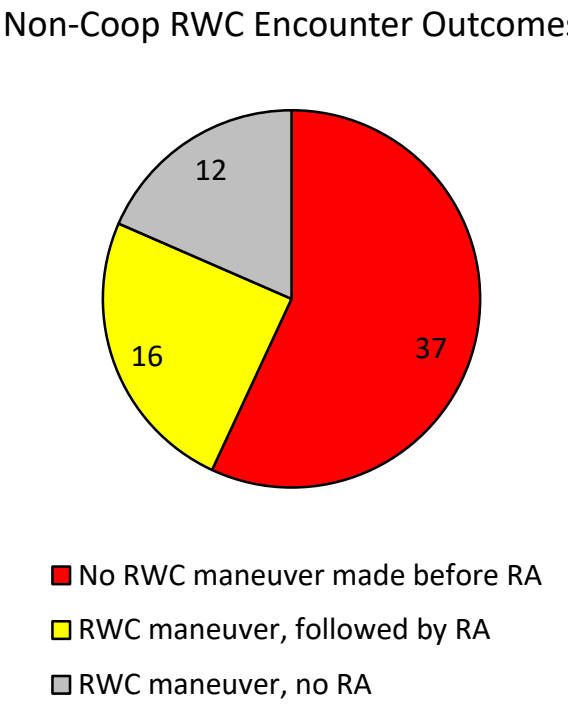


RWC / Corrective Alert Response Times

- Intruder Equipage Variable
  - Aircraft response times to non-cooperative intruders in this study were ~5 seconds faster than:
    - Cooperatives intruders in this study
    - Both coop & non-coop intruders in the Phase 1 sim
  - Limited RADAR detection range (6.7nm) resulted in shortened DAA Corrective alert durations (~**15 seconds)** for non-cooperatives
    - 37 of 65 (57%) non-coops progressed to RA before they could maneuver



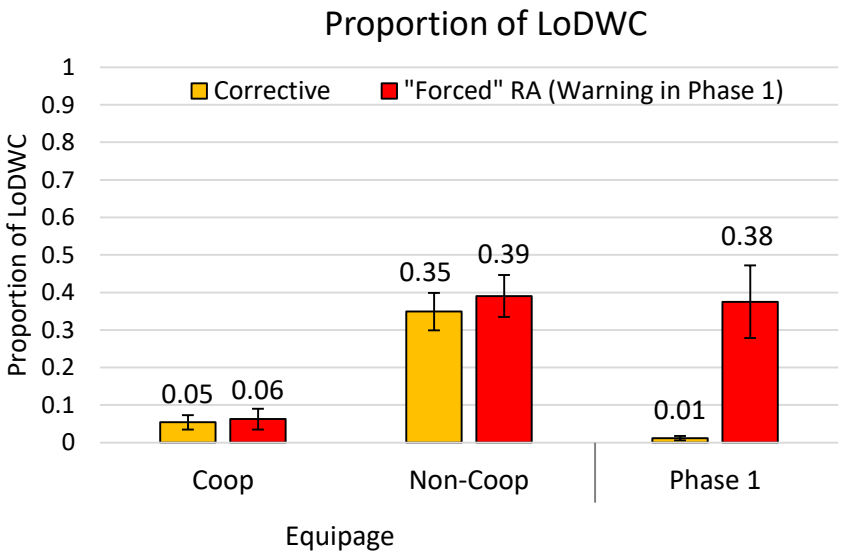
**Non-coop aircraft RTs only include instances where pilots maneuvered against a CORR alert*

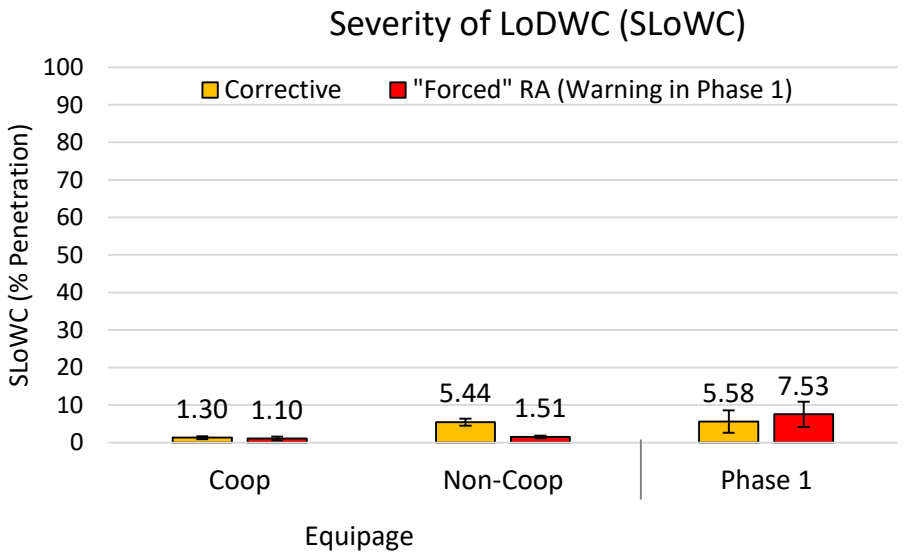


DAA WELL CLEAR PERFORMANCE

Loss of DAA Well Clear (LoDWC) Results

- Proportions of LoDWC were low for cooperative traffic but high for non-cooperatives
  - Similar to proportion of LoDWC in Phase 1's blunder/Warning alerts
- High proportion of non-cooperative LoDWC against scripted Corrective alerts was due to short-duration Corrective alerts (~15 sec duration)
  - Pilots were typically unable to begin their RWC/DAA maneuver before the RA was issued
  - On average, non-cooperative RAs were issued closer to CPA compared to cooperatives
- LoDWC severity (SLoWC) was extremely low against both equipages
  - Lower than SLoWC values observed in Phase 1
  - Aided by auto-filled directive guidance before LoDWC





DWC Criteria: *HorzSep = 4000ft, VertSep = 450ft, modTau = 35sec*

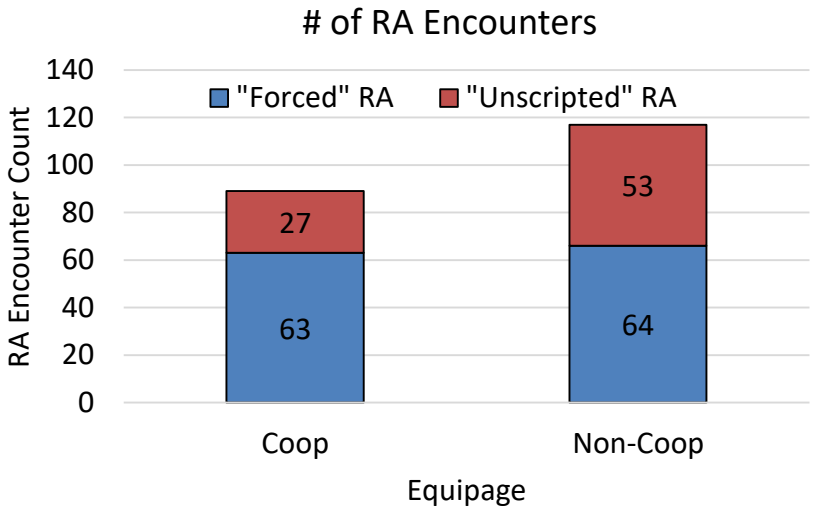
Causes of Cooperative LoDWC

- 9 total LoDWC against cooperative Corrective DAA threats
  - 6/9 were due to conversion from vertical rate RWC guidance to altitude guidance
    - Altitude guidance showed a climb/descent was safe when that was not the case
    - A result of the conversion to altitude bands assuming a variable vertical rate from the UA
  - 1/9 - return to course too soon
  - 1/9 - ineffective pilot maneuver
  - 1/9 - long ATC coordination time (frequency congestion)

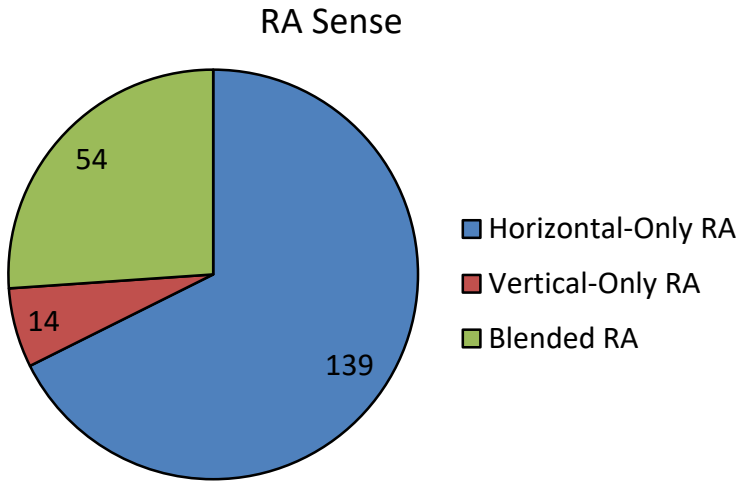
RA RESULTS

RA Results Summary

- 207 Total RA Encounters
  - 61% were the scripted, “Forced” RAs
    - 1 coop & 1 non-coop per trial
  - Remaining 39% were “Unscripted” RAs
    - I.e., intruder first appeared as Corrective DAA alert and progressed to an RA
    - 2/3 of ”Unscripted” RAs were against non-cooperative intruders

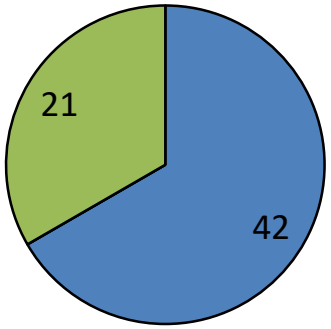


- 67% of RA encounters were exclusively horizontal
  - 26% included both a horizontal and vertical sense
  - Remaining 7% were exclusively vertical
    - All “Unscripted” RAs against cooperatives
      - Typically following a DAA maneuver

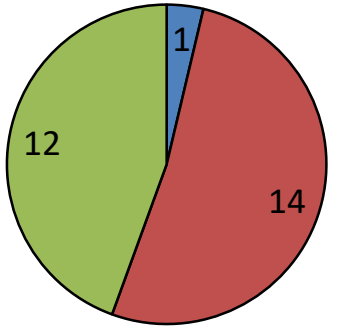


RA Sense

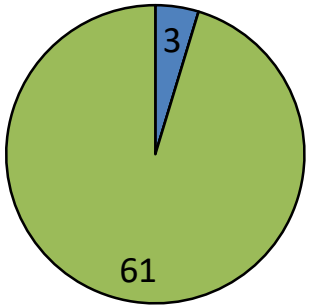
COOP: "Forced" RAs



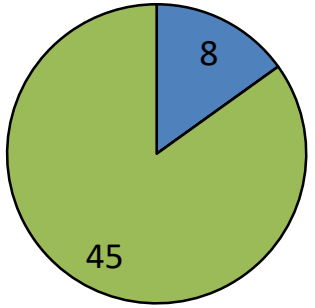
COOP: "Unscripted" RAs



NON-COOP: "Forced" RAs

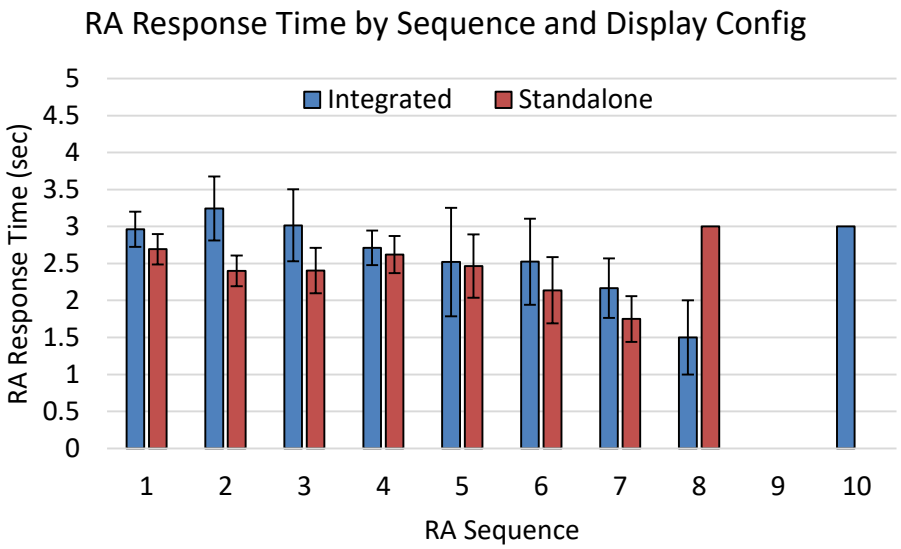


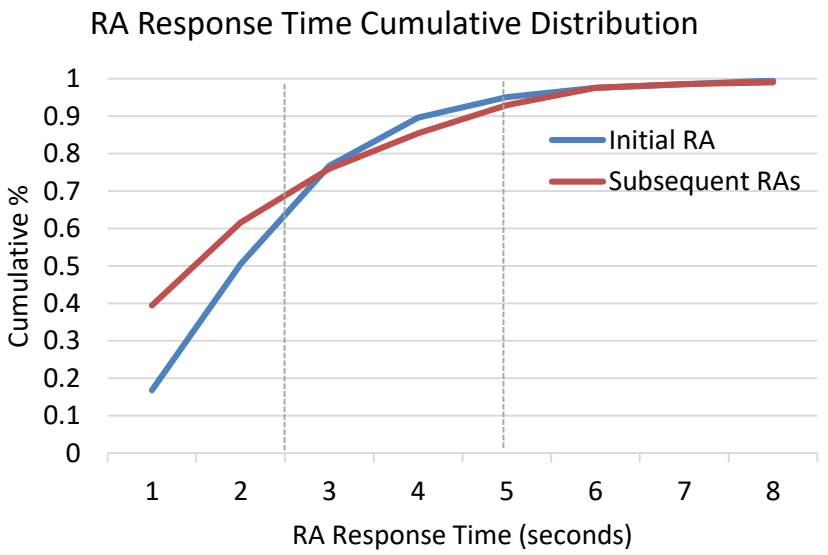
NON-COOP: "Unscripted" RAs



RA Response Times (All RA Types)

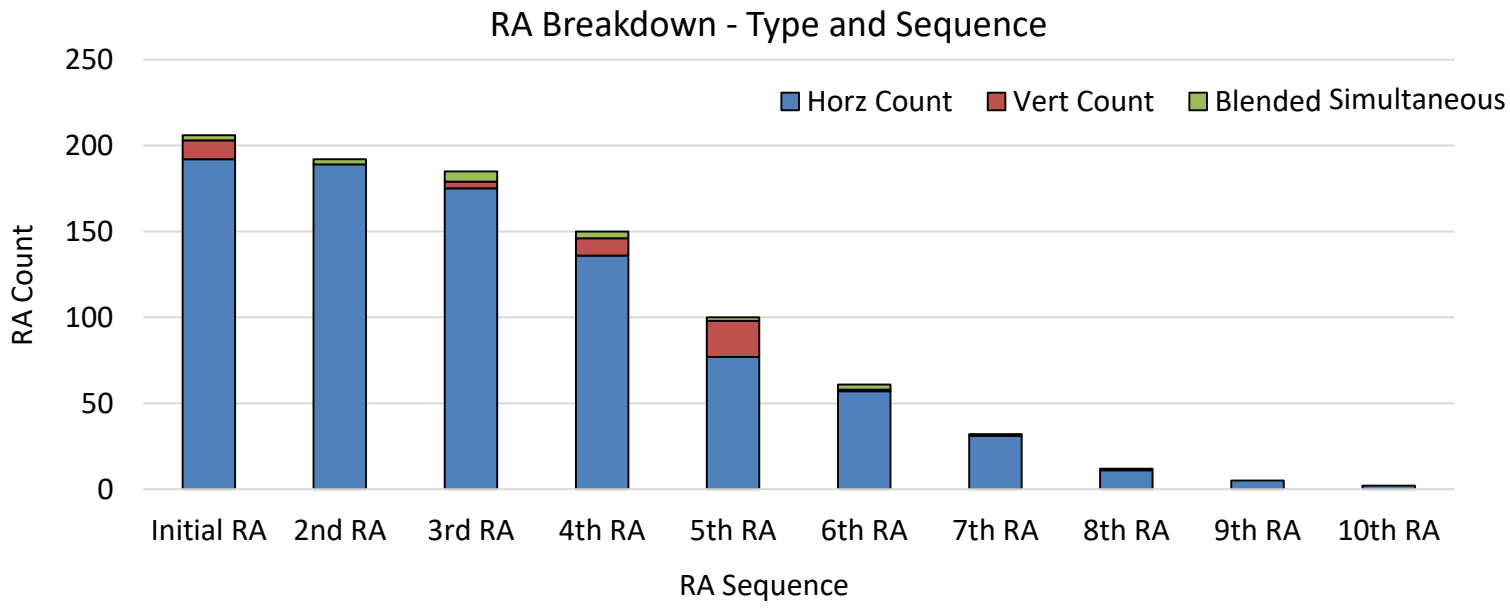
- Initial RA
  - Avg. RT = **2.89sec**
  - 97% of times under the 5 second response time requirement
- Subsequent RAs
  - Avg. RT = **2.68sec**
  - 70% of times under the 2.5 second response time requirement





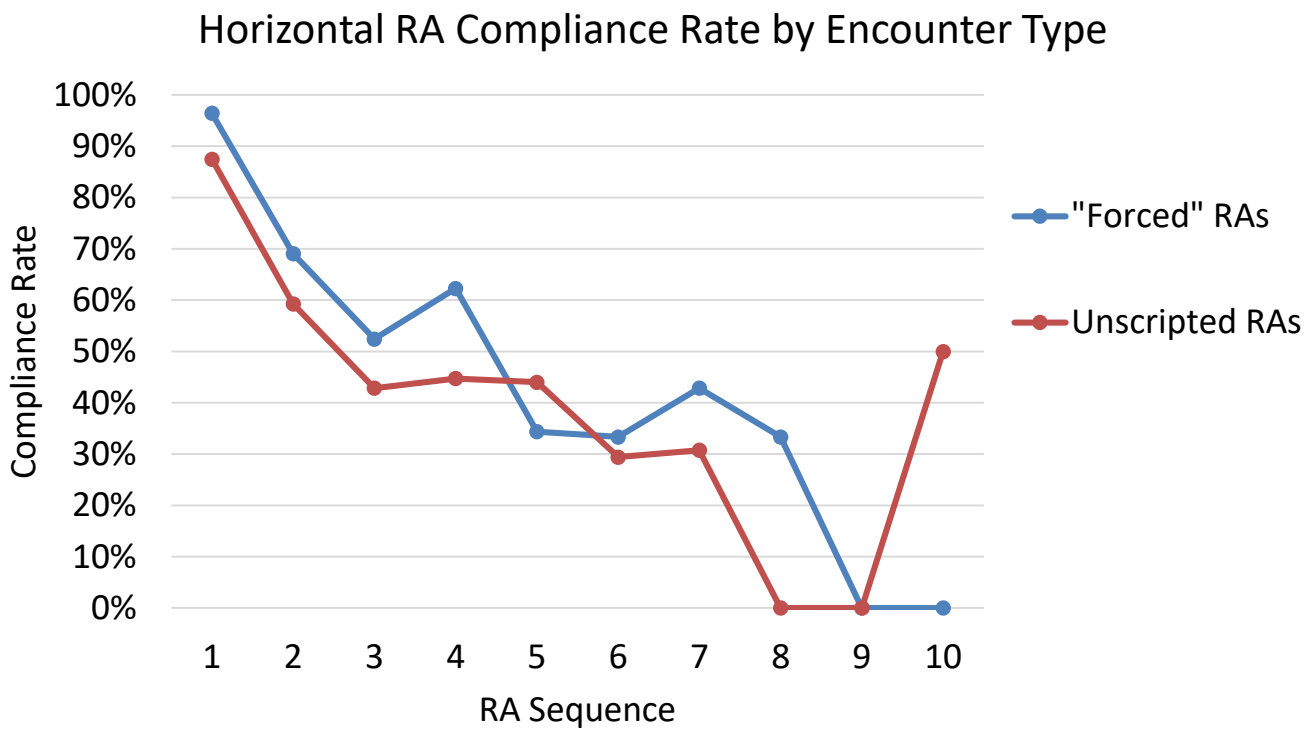
RA Target Updates

- Multiple RA target heading updates were common for each given RA encounter
  - Avg. of 4.5 target heading updates per RA
  - Simultaneous horizontal and vertical updates were rare
  - Vertical RAs were often appended to the end of a horizontal RA sequence (e.g., the 4th or 5th update), creating a blended RA



Horizontal RA Compliance Rate

- Pilots complied less often with target heading updates
  - Initial RA compliance = **88-98%**
  - Subsequent RA compliance = **51%**
- Similar compliance trends between “Forced” & “Unscripted” RAs
- Pilot feedback regarding non-compliance:
  - “Already headed that direction”



Vertical RA Compliance Rate

- Pilots complied with vertical RAs at a consistently high rate
  - **94%** (64/68) overall compliance
    - 85% compliance rate when it was *vertical-only*
      - Occasionally recommended climb/descent that was already in progress
    - 96% compliance with vertical RAs added to an existing horizontal RA
      - i.e., creating a blended RA
    - 95% compliance when vertical and horizontal were issued simultaneously

SUBJECTIVE FEEDBACK

Recurring Themes from Debrief

- **Integrated configuration was heavily preferred**
  - Standalone was manageable but not ideal
- **Horizontal RA updates were considered excessive**
  - #1 reason for non-compliance
    - Multiple updates to commanded heading before reaching initial target
  - Rated as manageable, but undesirable
  - Felt the size of the heading changes were larger than necessary
    - 90+ deg turns off-course were common for RAs w/ 5 or more updates
- **Alerting and guidance rated as intuitive**
  - Positive feedback on visual and aural RA presentation
  - Pilots did not desire an aural for every new target heading
- **Auto-fill functionality was deemed necessary**
  - 44% of pilots would be open to automatic execution of the RA response
    - Only if automation could be toggled on/off
- **Desired more ATC coordination time for non-coop DAA alerts**
  - Corrective alerting was limited by shortened RADAR range

CONCLUSION

Xu Alerting & Guidance Display Implications

- No effect of Display Configuration on pilot performance
  - Strong subjective preference for Integrated display
- Remain Well Clear
  - Comparable response times to the Phase 1 DAA study
  - Pilots maintained DWC at a high rate against cooperative intruders
  - Reducing minimum RADAR range from 8nm to 6.7nm substantially cuts RWC alerting against the Phase 1 DWC
    - LoDWC rates went up considerably against non-cooperatives
  - Conversion of RWC vertical speed guidance to altitude guidance should assume ownship's default vertical speed performance
- Resolution Advisories
  - Effective at limiting severity of DWC violations
  - Auto-fill function may enable compliance with TCAS II RA response time requirements while remaining in the loop
    - Avg. RA responses were close to the 5 sec and 2.5 sec requirements
  - High compliance rates to vertical RAs and initial horizontal RAs (~95%)
    - Compliance rate dropped substantially as target heading updates increased
      - Pre-FRAC applied refinements to rounding & hysteresis logic for horizontal RAs

QUESTIONS?

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