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

ACAS-Xu Run 5 HITL (June 2019)

SC-228 WG 1.3 Results Outbrief

Human Systems Integration
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UAS INTEGRATION IN THE NAS

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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: Run 5.1 (FRAC) was released shortly after this HITL; at the end of this brief we will show a few charts on tests we performed with the updated logic

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

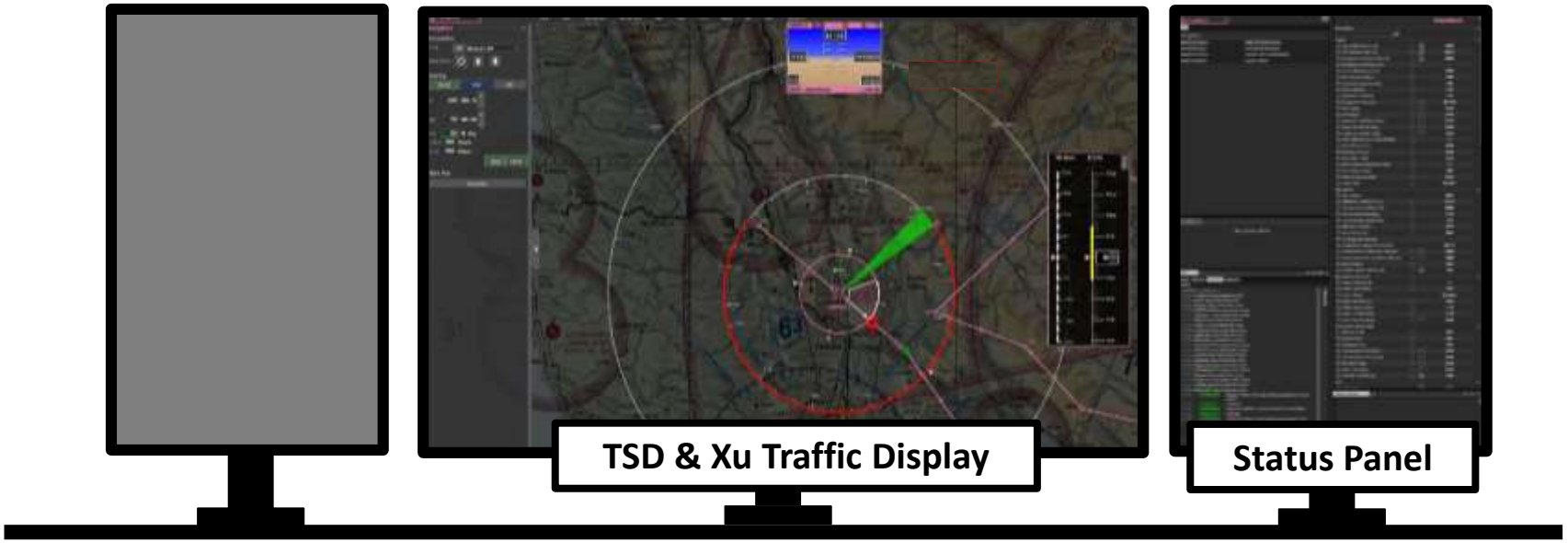
Experiment Design

STANDALONE CONFIGURATION

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

Experiment Design

INTEGRATED CONFIGURATION



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

Test Setup

- 16 active-duty 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 (*not present in PT6*)

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

Test Setup

- 4 experimental trials per pilot (~45min per trial)
  - 2 mission routes x 2 display configurations

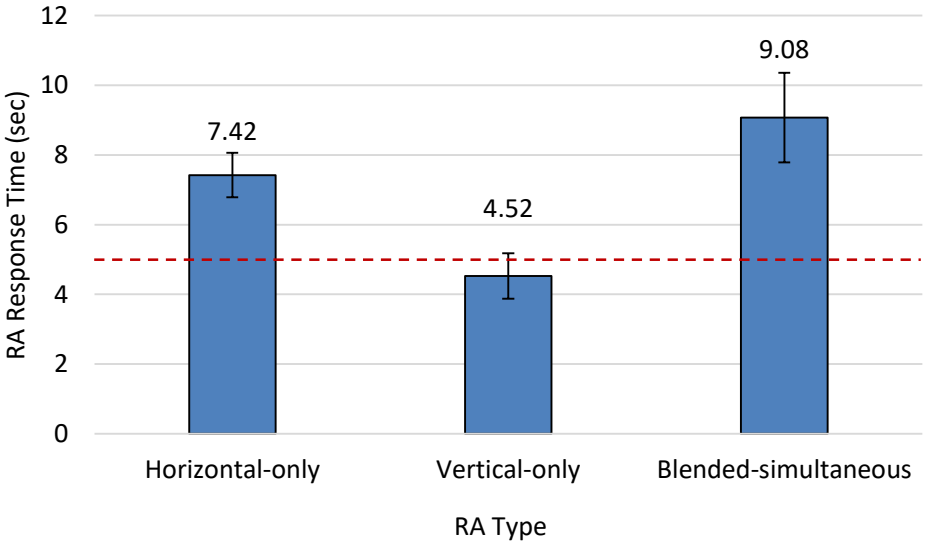
- Pilot task
  - Maintain safety of aircraft along pre-filed flight path
    - Manually respond to DAA and RA guidance from Xu
  - Coordinate with center controller as appropriate
  - Respond to scripted chat messages and system failure events

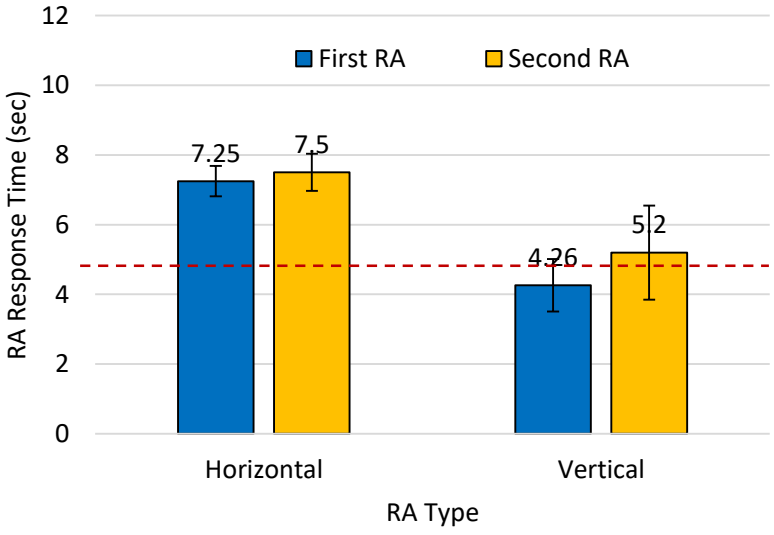
- Ownship configuration
  - Generic MQ-9 model
  - Cruise speed: 160 KIAS
  - Climb/descent rate: 1,000 fpm
  - Turn rate: 3° per second

Xu Display Implementation

- Data from an engineering analysis showed pilots (with the GCS under test) could not meet the desired response times for initial (5 sec) and subsequent RAs (2.5 sec)
  - Particularly slow to respond to horizontal & blended RAs
  - Pilots were no quicker in responding to subsequent RAs
- As a result, for this study an RA 'auto-fill' feature was used to reduce RA response times
  - RA target heading/default vert. speed was automatically entered into the GCS; pilot had to click "Send" button to confirm and upload the maneuver

Engineering Analysis RA Response Times





Xu Display Implementation

- Subjective feedback from the engineering analysis indicated pilots had a particular preference for the order in which blended RAs should be issued aurally:
  - Ex. with initial horizontal RA followed X seconds later by a vertical RA:
    - **First** aural alert: "Turn Right" x2
    - **Second** aural alert:
      - If target heading *not* yet achieved: "Turn Right and Climb" x2
      - If target heading already achieved: "Climb and Maintain Heading" x2
  - Ex. with initial vertical RA followed X seconds later by a horizontal RA:
    - **First** aural alert: "Descend" x2
    - **Second** aural alert:
      - If vertical speed *not* yet achieved: "Descend and Turn Left" x2
      - If vertical speed already achieved: "Turn Left and Maintain Vertical Speed" x2

- Subjective feedback also indicated that pilots did not find a text box containing RA information necessary
  - Did not include a text box in this study – also made redundant by the auto-fill behavior

Xu Display Implementation

- In the process of integrating Run 5 for this study, we determined it was necessary to make a few display-side modifications:

- Early testing showed that the target headings during horizontal RAs could change as frequently as 1 Hz
  - For pilot acceptability purposes, we capped the target heading update rate to 5 sec
  - Due to frequency of updates even with this display mod, we **did not** aurally annunciate new target headings
    - FAA has made clear, however, that these updates **will need to be annunciated aurally**

- The GCS converted Xu's native DAA vertical speed guidance to discrete DAA altitude bands using a very simple formula
  - SC-228 requires RWC/DAA vertical guidance to be shown in altitudes if the GCS cannot upload vertical rates
  - The conversion **did not** take ownship's vertical rate performance into account

ACAS Xu Alerting Logic

Symbol	Name	Pilot Action	Aural Alert Verbiage
	Resolution Advisory (RA)	• ***Immediate action required to comply*** • Must upload maneuver within 5 seconds • Notify ATC after maneuver	"Climb/Descend" x2 "Turn Left/Right" x2 *or as shown on earlier slide*
	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

Pilot coordinates during Corrective DAA Alert for 16 sec, then complies with 6 horizontal RAs.

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

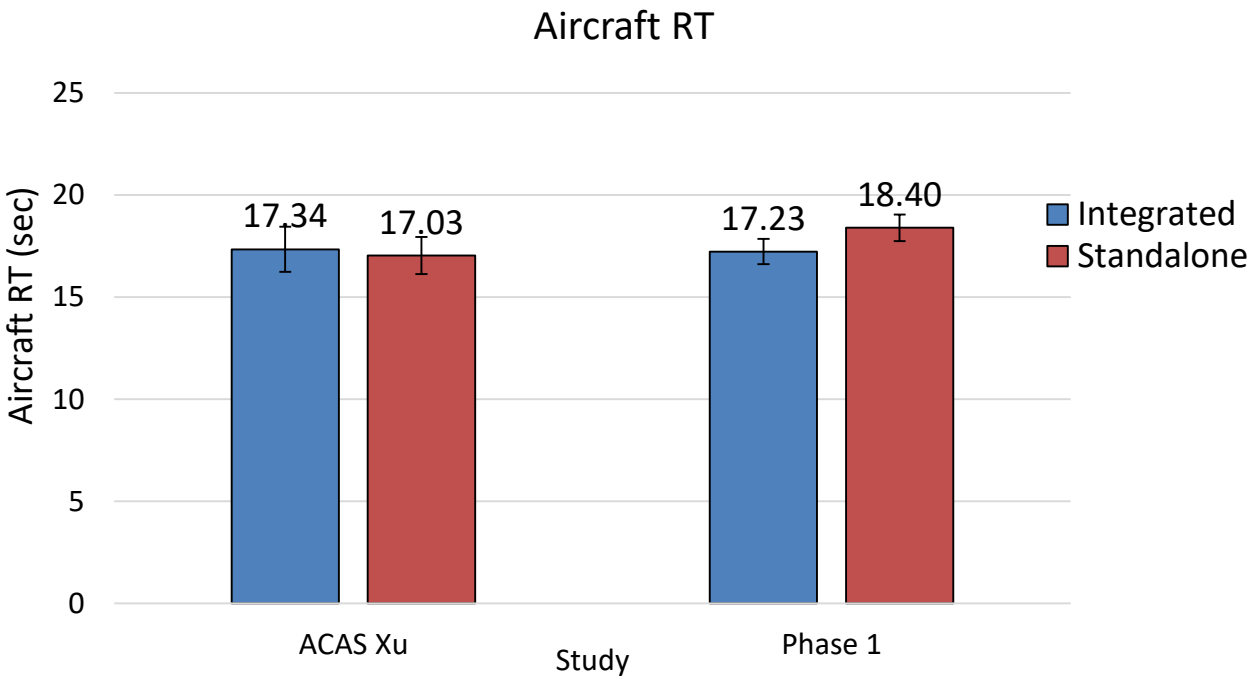
- "Forced" RAs were executed differently depending on intruder equipage:
  - Cooperative forced RAs were triggered by a late intruder climb/descent into ownship (i.e., a 'blunder')
  - Non-cooperative forced RAs were triggered by the intruder popping-up on the scope
    - Could not consistently force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

- NOTE: non-cooperative Corrective DAA encounter was head-on intruder at 140kts; resulted in high closure rate

REMAIN WELL CLEAR (RWC) RESULTS

RWC / Corrective DAA Alert Response Times

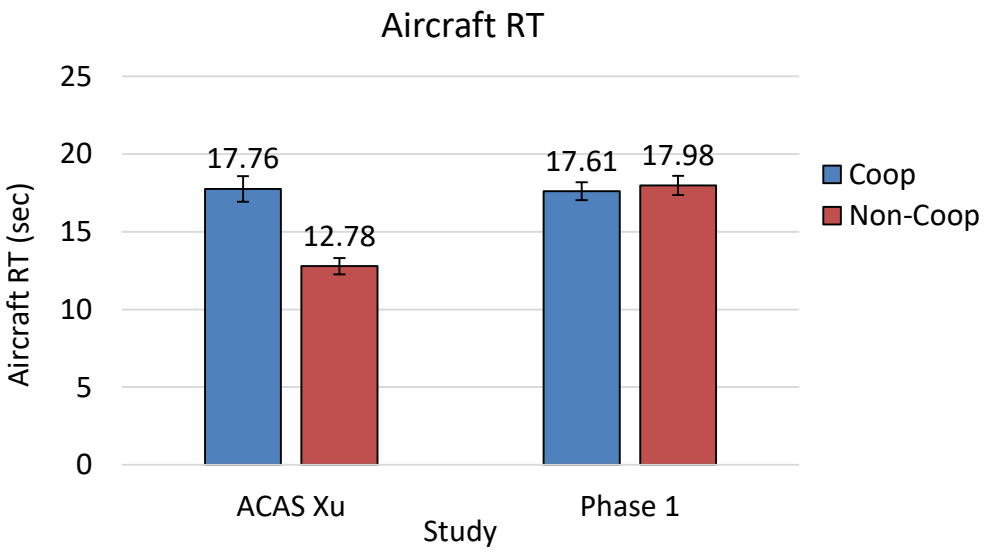
- Display Configuration Variable
  - No difference in aircraft response times between Standalone and Integrated display conditions
  - Overall aircraft response times nearly identical to the **Phase 1** V&V HITL



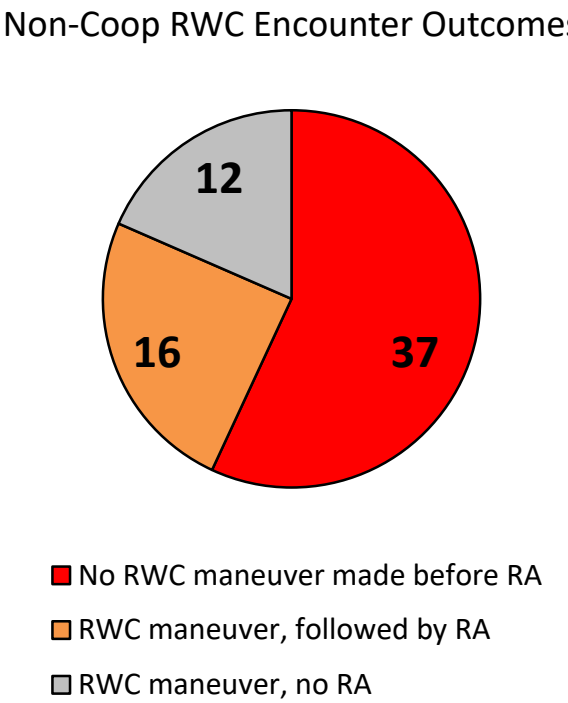
Aircraft response time **– elapsed time from alert to first maneuver upload**

RWC / Corrective DAA 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 range (6.7nm) resulted in shortened Corrective alert durations **(avg. 16 seconds)** for non-cooperatives
    - 37 of 65 (57%) non-coops progressed to RA before pilot could maneuver



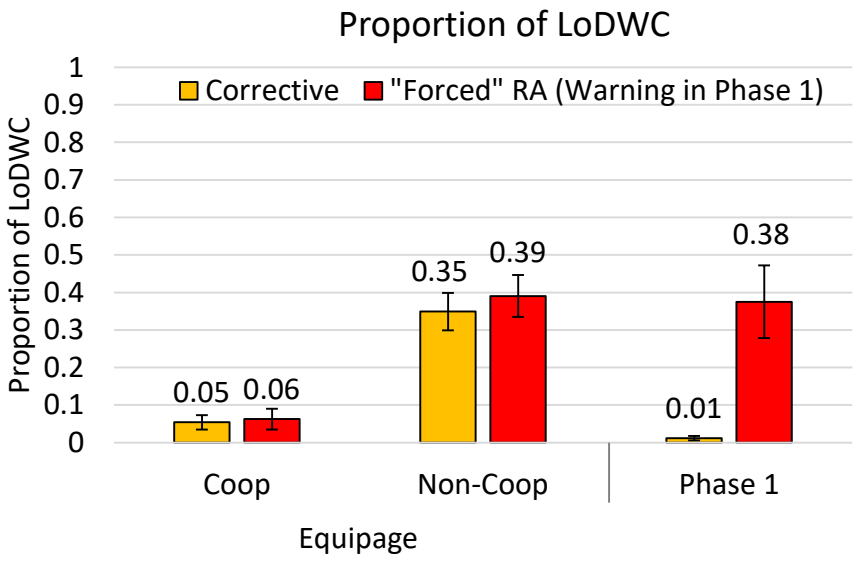
**Non-coop aircraft RTs only include instances where pilots maneuvered against a CORR alert*

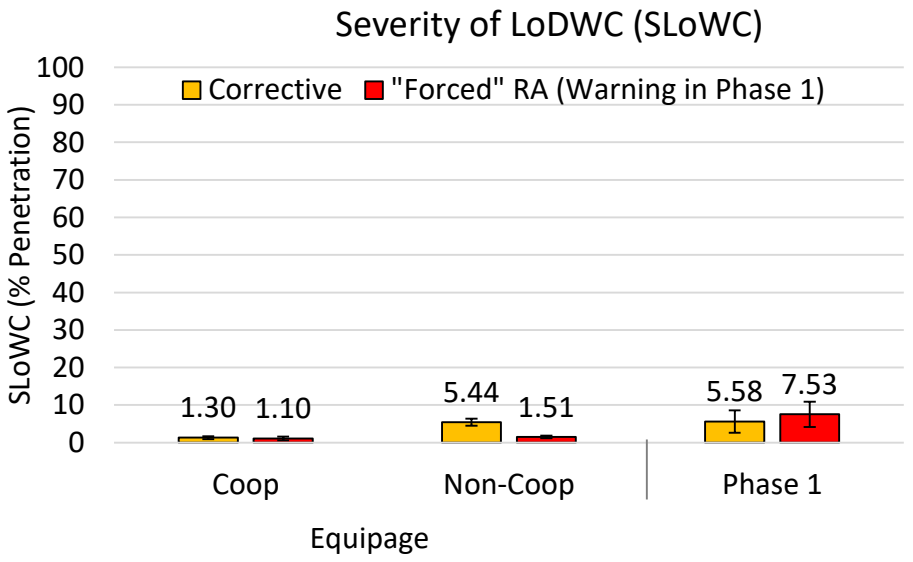


DAA WELL CLEAR PERFORMANCE

Loss of DAA Well Clear (LoDWC) Results

- Higher proportions of LoDWC for non-cooperatives
  - Similar to separation performance against Phase 1's blunder encounters
  - Pilots were typically unable to begin their RWC/DAA maneuver before RA was issued
    - Short-duration Corrective alerts (~16 sec duration)
  - 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*

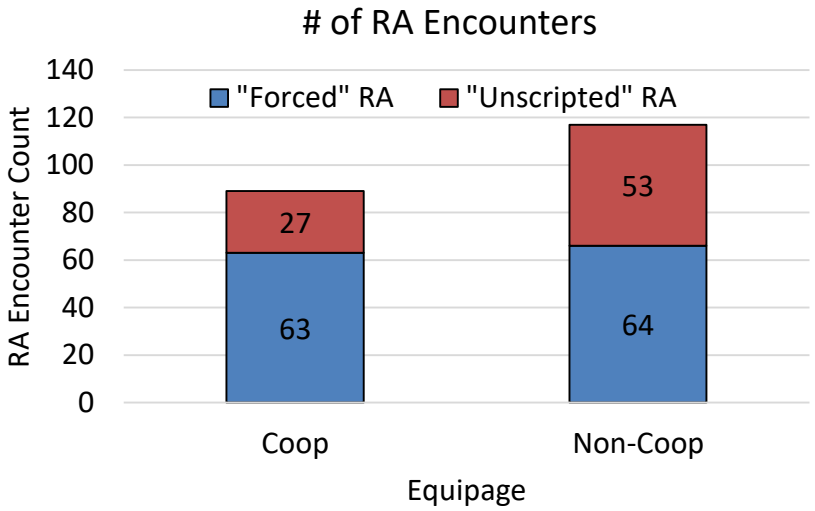
Causes of Cooperative LoDWC

- 9 total LoDWC against cooperative Corrective DAA threats
  - 6/9 were cases where the altitude guidance showed a climb/descent was safe when that was not the case
    - Issue: simply converting vertical speeds to altitude bands made it appear that larger altitude displacements were safe, when the guidance was really saying a higher climb/descent rate was safe
      - The display *should have* saturated the altitude bands with Corrective guidance as soon as the vertical rate guidance exceeded ±1000fpm (the simulated default vertical rate)
  - 1/9 - return to course too soon
  - 1/9 - ineffective pilot maneuver
  - 1/9 - long ATC coordination time (frequency congestion)

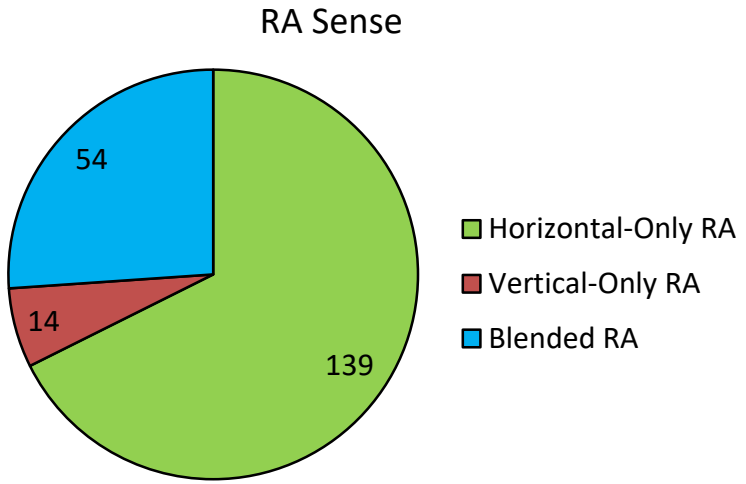
RA RESULTS

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
    - Twice as many Unscripted RAs observed for non-cooperative encounters

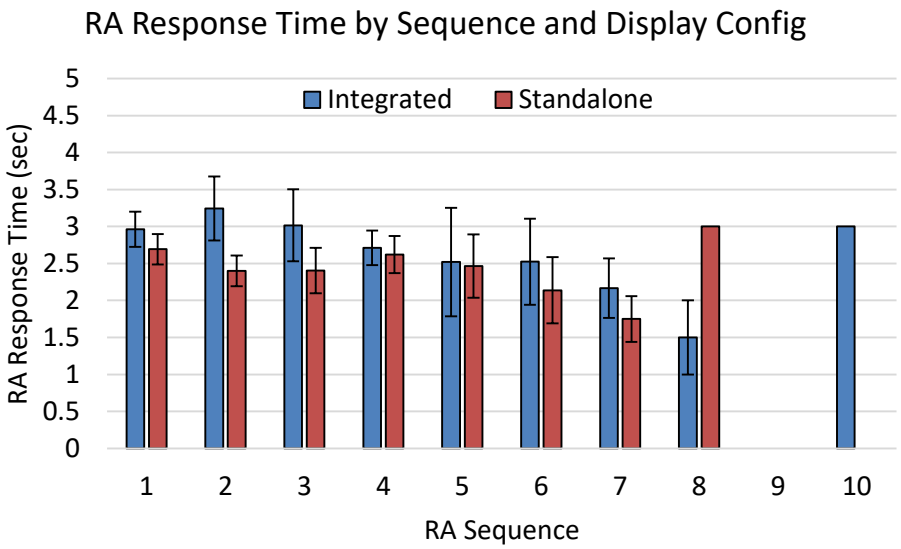


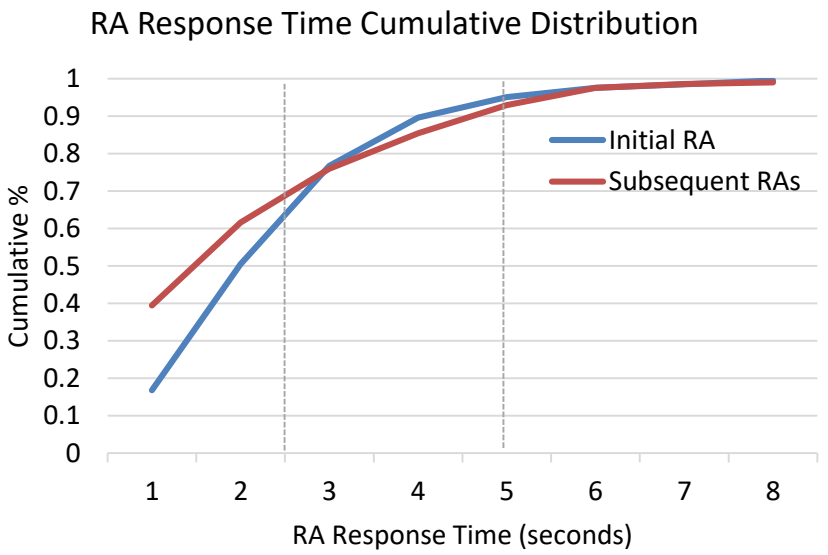
- 67% of RA encounters were exclusively horizontal
  - 26% included both a horizontal and vertical sense
  - Remaining 7% were exclusively vertical
    - All “Unscripted” RAs against cooperatives
      - Typically following a DAA maneuver



RA Response Times (All RA Types)

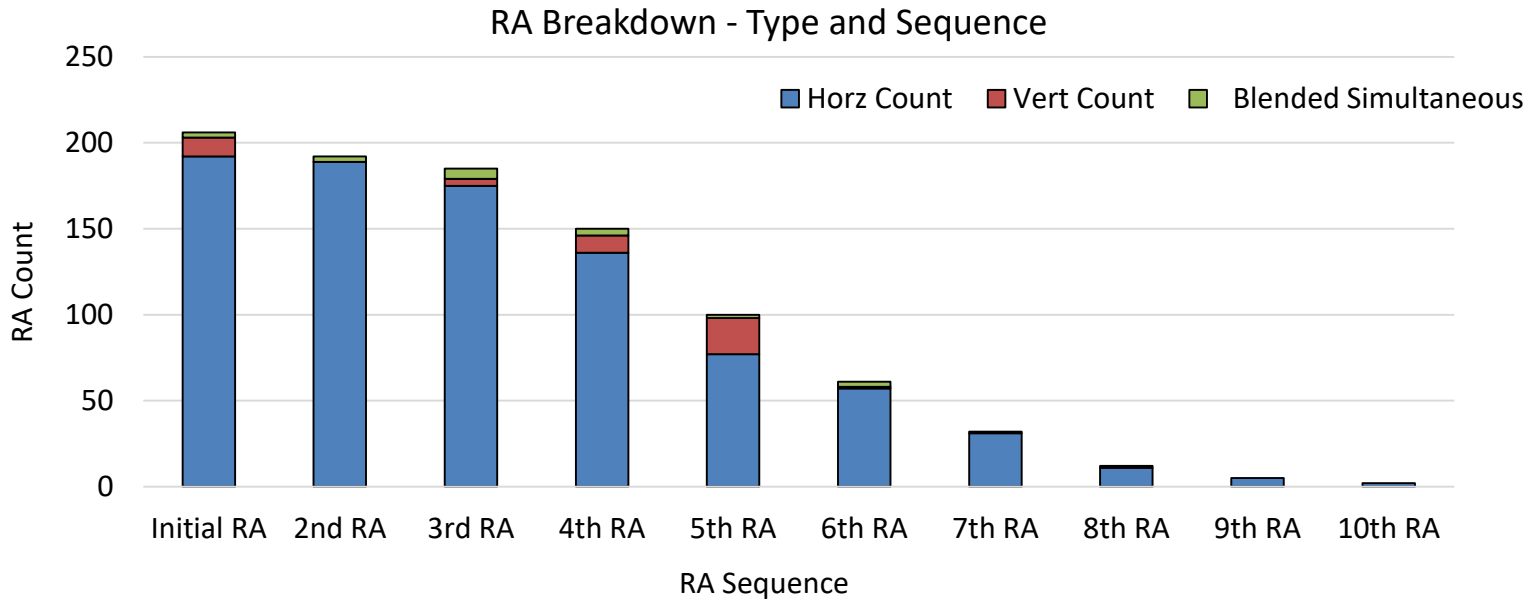
- Initial RA
  - Avg. RT = **2.89sec**
  - 97% of times under the 5 second response time requirement
- Subsequent RAs
  - Avg. RT = **2.68sec**
  - 70% of times under the 2.5 second response time requirement





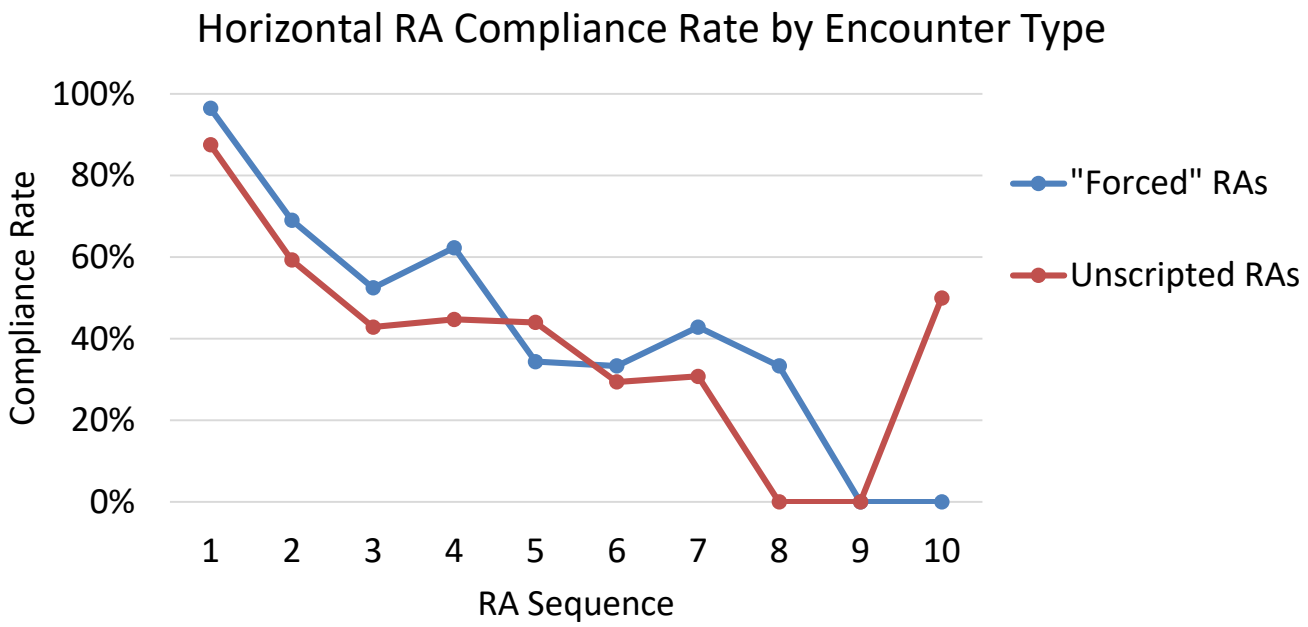
RA Target Updates

- Multiple RA target heading updates were common for each given RA encounter
  - Avg. of 4-5 target headings per horizontal RA
    - This is with the target heading update rate capped at 5 sec
  - 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%**
  - NOTE: pilots were still in their turn when receiving the updated target heading, so they were still complying with the general directive to turn right/left
- Reminder: we did not issue aural alert for each target heading update
  - Feedback regarding 'non-compliance': "Already headed that direction"
- Similar compliance trends between "Forced" & "Unscripted" RAs



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 initial climb/descent that was already in progress
    - 96% compliance with vertical RAs added to an existing horizontal RA
      - i.e., creating a blended offset RA
    - 95% compliance when vertical and horizontal were issued simultaneously

SUBJECTIVE FEEDBACK

Recurring Themes from Questionnaires & Debrief

- **Integrated configuration was heavily preferred**
  - Standalone was manageable but not ideal
- **Horizontal RA updates were considered excessive**
  - #1 reason for non-compliance
    - Rated as manageable, but undesirable
- **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 – this would be mitigated if the logic were updated to included fewer updates
- **Did not think the addition of a text box would have been helpful**
  - Likely influence by the auto-fill behavior, which provided the target RA value
- **Auto-fill functionality was deemed necessary**

Notes on ATC

- **Did not** have a structured interview/questionnaire with our 2 confederate ATC in this study
  - Controllers had participated in prior UAS HITL research and were very familiar with these types of operations
  - Informally, the confederate controllers indicated that the UAS operations were acceptable
  - This is consistent with past confederate ATC feedback on UAS DAA maneuvering
    - DAA warnings – like RAs – require UAS pilots to maneuver horizontally and/or vertically *without coordinating* with ATC prior to their maneuver
    - Controllers have indicated that this is acceptable, especially against non-cooperative intruders, since the priority is the safety of the aircraft at these distances

Results Summary

- No effect of Integrated vs Standalone on pilot performance
  - Strong subjective preference for Integrated display
  - Consistent with Phase 1 findings

- Remain Well Clear / DAA
  - Comparable response times to the Phase 1 DAA study
  - Pilots maintained DWC at a high rate against cooperative intruders
    - Would have been better with appropriate conversion of RWC vertical speed guidance to altitude guidance - i.e., saturate altitude bands if vertical rate bands exceed default vertical rate
  - LoDWC rates went up considerably against non-cooperatives
    - Result of shorter RDR relative to Phase 1 (6.7nm vs 8nm) and only including high closure rate non-coop encounter type in this study

- Resolution Advisories
  - Effective at limiting severity of DWC violations (lower SLoWC than Phase 1)
  - Auto-fill function enabled pilots to largely meet the desired RA response times while remaining in the loop
  - High compliance rates to vertical RAs and initial horizontal RAs (~95%)
    - Pilots failed to keep up with target heading updates (often intentionally) because they were in their turn while the heading target fluctuated

Follow-On Analysis with Run 5.1 (FRAC Version)

- In late 2019 we integrated Run 5.1 into our lab and ran each of the two Xu HITL traffic scenarios twice with a researcher in-the-loop
  = 8 total “scripted” RAs (4 coop & 4 non-coop)
  = 4 total “unscripted” RAs (all non-coop)

- Researcher waited ~15sec to respond to Corrective alerts & ~3 sec to respond to RAs
  - No background traffic/ATC in the loop

- Provided a quick-and-dirty look at differences between Run 5.1 vs Run 5 logic
  - Also allowed us to dig into new data that we did not prioritize for the full HITL

Follow-On Analysis with Run 5.1

- Focused on the 2 primary, display-related effects of the Xu logic:

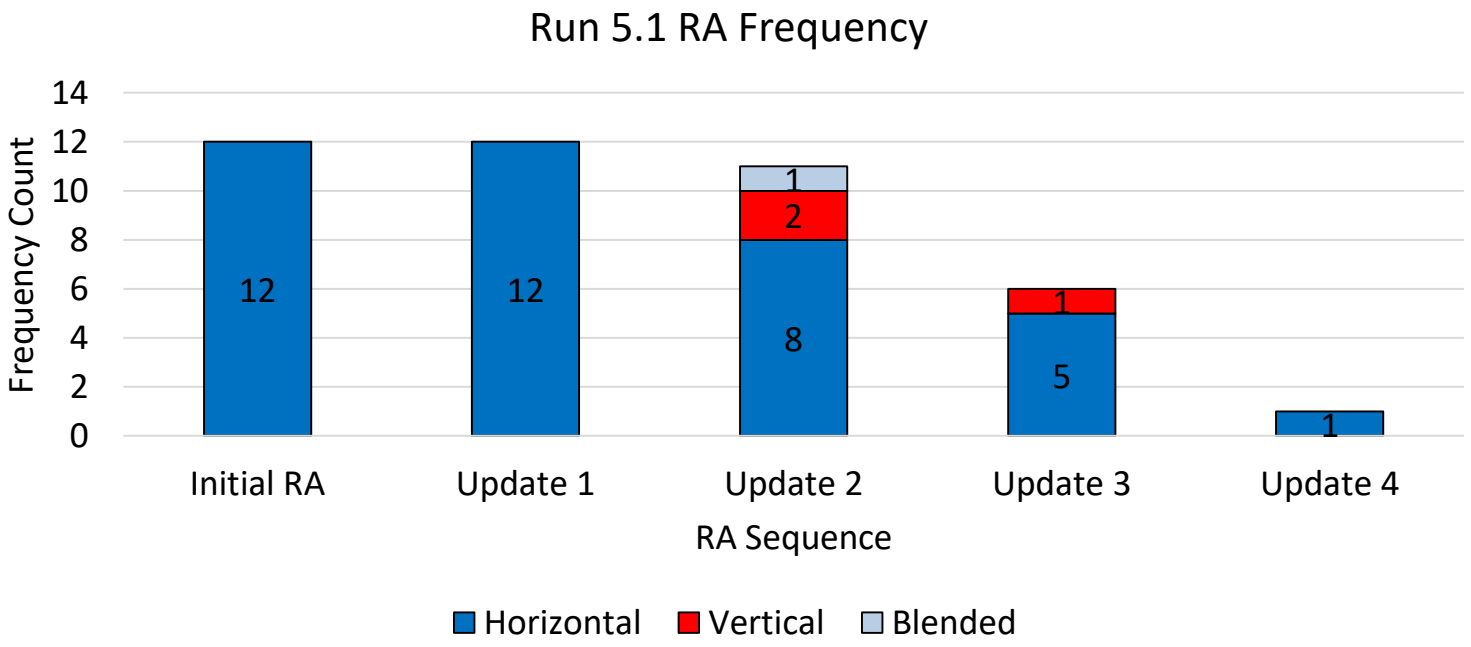
1. Frequency of RA target heading updates – pilots in the HITL found the rate of updates frustrating/unnecessary
   - Run 5.1 implemented logic similar to the display-side logic that was implemented in the HITL:
     - New logic restricts updates to no more than every 5 sec and requires the current heading to be within 23deg of target heading

2. Horizontal-vertical DAA band alignment - observed during HITL that Corrective vertical bands would intercept ownship altitude earlier and remain longer than horizontal bands
   - Were not able to extract that data from the HITL but did collect it here for reference
   - NOTE: we **did not** see evidence that this impacted pilot performance in the HITL, and subjectively, pilots did not indicate that it was a problem
     - Regardless there should be some DAG input on this behavior

Frequency of RA Target Updates

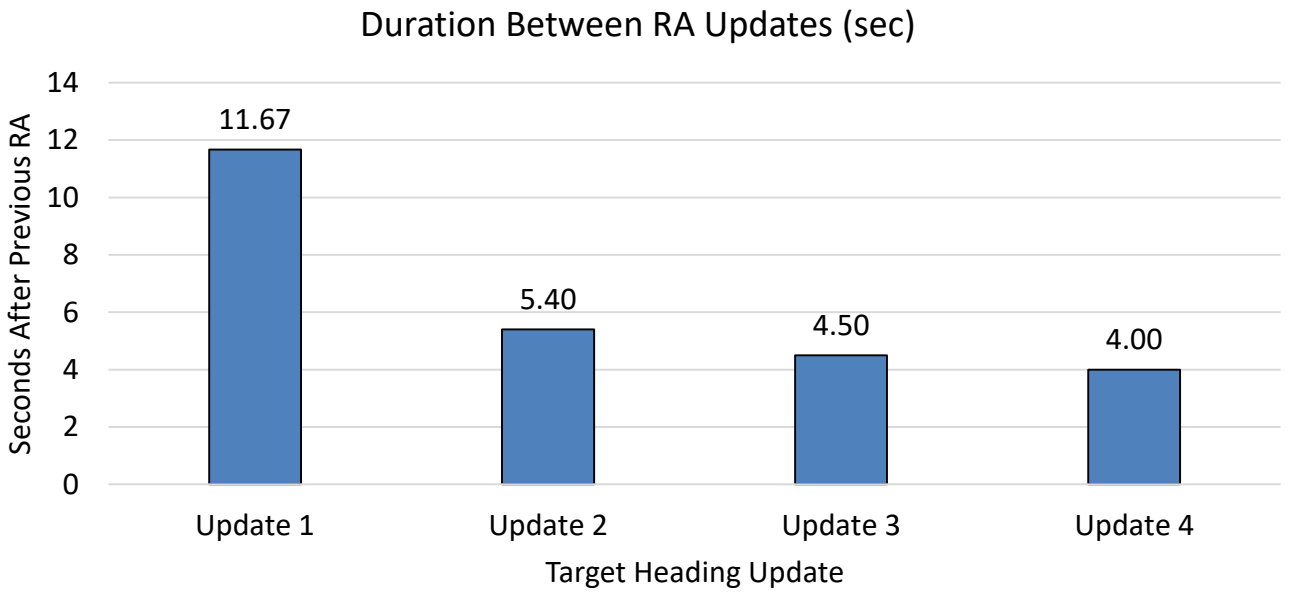
- Fewer target heading updates in Run 5.1 compared to Run 5
  - 3-4 headings per RA vs. 4-5
  - More time spent in initial RA stage (next slide)

- Vertical/blended RAs were still relatively rare overall and happened later in the RA sequence



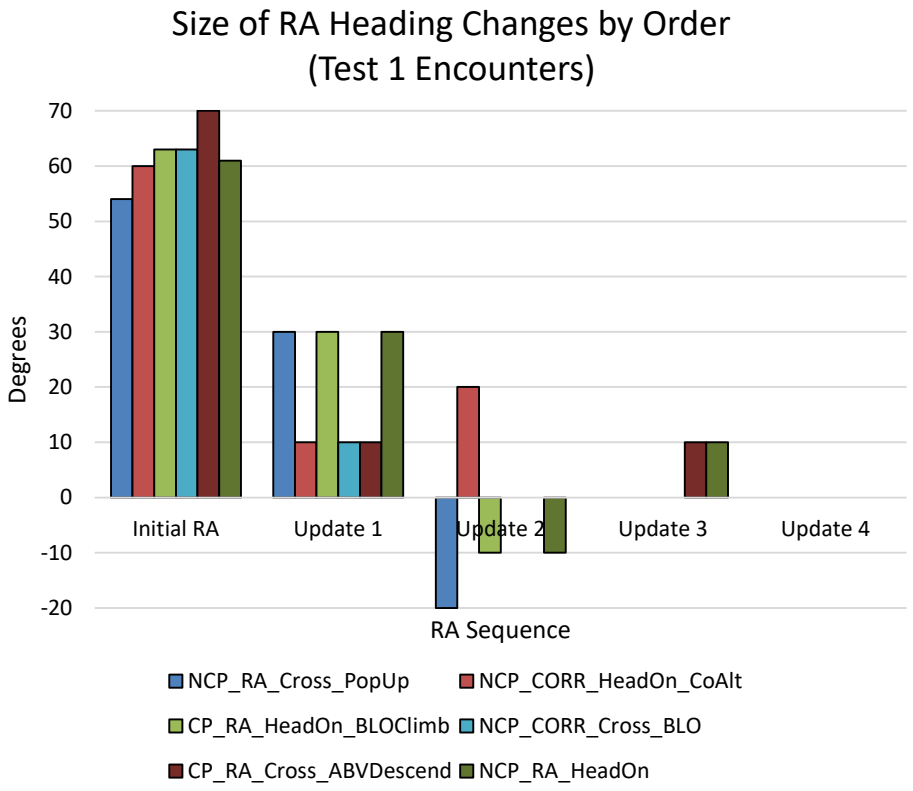
Time Between Each Target Update

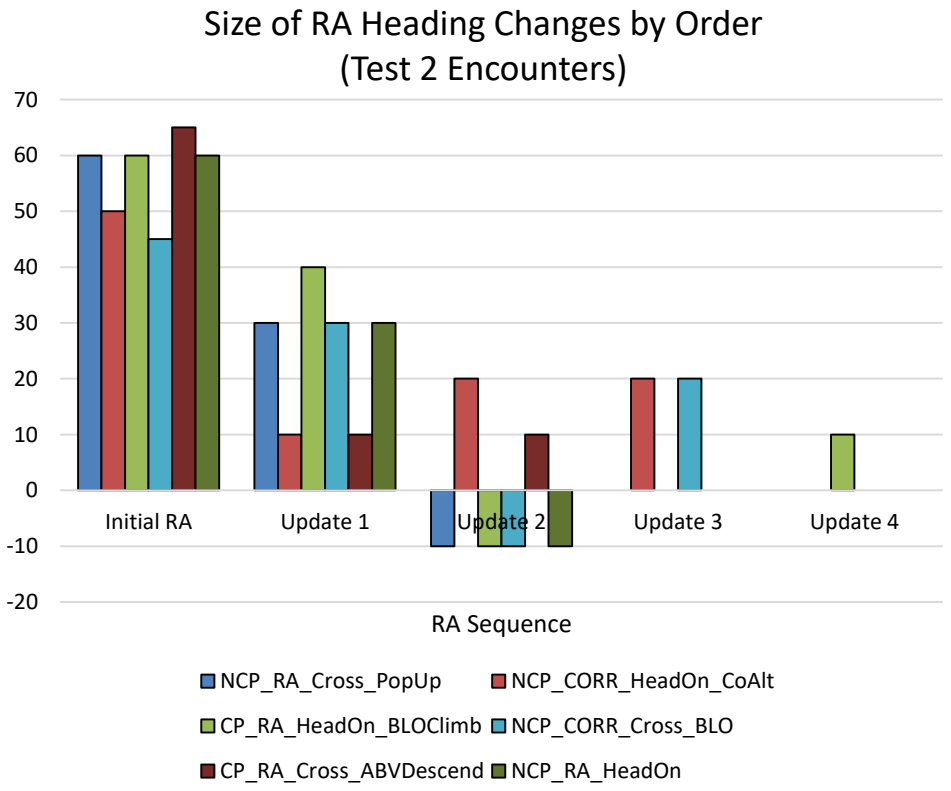
- ~11 seconds elapsed between the initial RA and first target heading update
  - Substantial improvement over Run 5 which typically updated every 5 sec
- ~4-5 seconds elapsed between subsequent RAs
  - Similar to Run 5
  - Note: 5-second update rate applied to weakening horizontal RAs only



Size of Resolution Advisories by Order

- Logic appears to use the first target heading update to increase the heading magnitude and then reduces the size with the second update

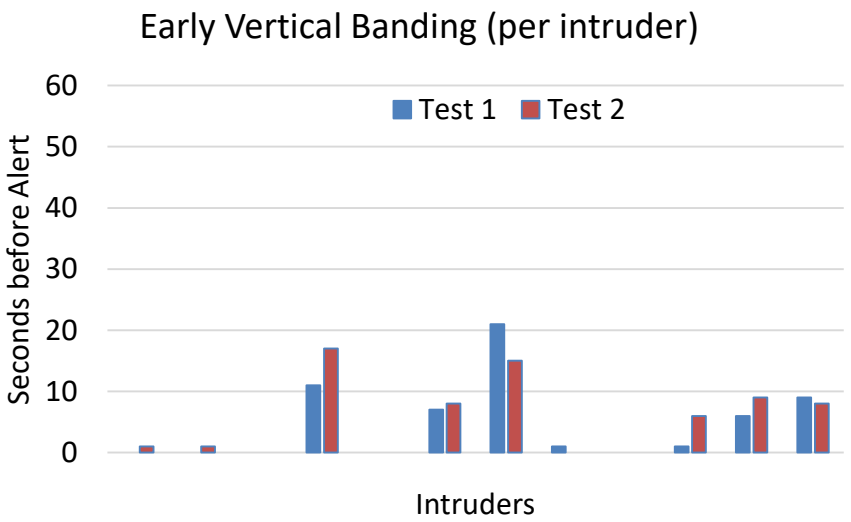


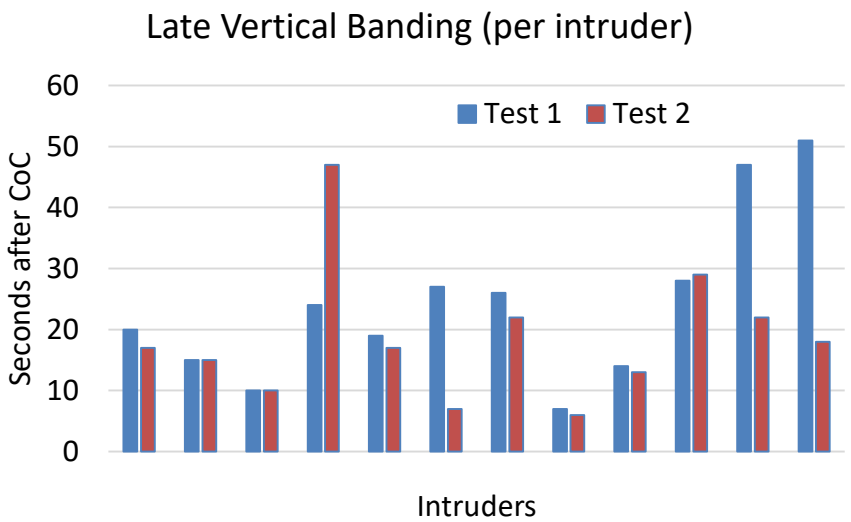


Horizontal-Vertical DAA Band Alignment

- Early vertical DAA banding = how long did vertical DAA corrective banding intersect ownship's altitude prior to the horizontal banding doing the same (thus generating an alert)
  - Most prevalent during cooperative encounters
  - Exceeded 5 sec in 11/24 cases
  - Avg. duration of **5 sec**

- Late vertical DAA banding = how long did vertical DAA corrective banding persist after the horizontal banding had disappeared (i.e., Clear of Conflict)
  - Longest duration during cooperative encounters
    - Exceeded 5 sec in all cases; considerable variability
  - Avg. duration of **20 sec**





Overall Conclusions

- Pilots performed very well with ACAS Xu Run 5
  - High favorability ratings regarding how the DAA & RA alerting and guidance was presented
  - Responses to DAA guidance & rates of LoDWC consistent with Phase 1 work
  - Pilots' quick responses to RAs led to very low severities of LoDWC
- Potential quality of life improvements remain mainly around the issue of target heading updates and horizontal-vertical DAA band alignment:
- A larger initial target heading for horizontal RAs could reduce the need to issue updates and would add stability from the pilots' perspective
  - Even with Run 5.1, the 2nd & 3rd updates came in quick succession (~5 sec)
- Run 5.1 still had an issue with holding on to vertical DAA bands long after a DAA corrective alert had been removed

HITL QUESTIONS?

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