A Human-in-the-Loop Evaluation of ACAS Xu

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***Abstract*—Detect and avoid (DAA) systems provide unmanned aircraft systems (UAS) with an alternative means of compliance with the see-and-avoid requirements associated with operations in the National Airspace System (NAS). Previous studies have examined the efficacy of different DAA alerting and guidance structures and formats. Prior research has also investigated the integration of DAA information with the alerting and guidance generated by the Traffic Alert and Collision Avoidance System (TCAS II). The next-generation replacement for TCAS II – the Airborne Collision Avoidance System X (ACAS X) – includes a variant to be used by UAS (ACAS Xu) that will provide both DAA and Collision Avoidance (CA) guidance. The alerting and guidance issued by ACAS Xu differs from previous DAA and CA systems, a result of new capabilities that were not available to earlier systems. Differences include the removal of warning-level DAA alerting and guidance, as well as the issuance of new types of CA guidance, referred to as Resolution Advisories (RAs). Whereas TCAS II only issues vertical RAs, ACAS Xu adds horizontal and blended (i.e., simultaneous vertical and horizontal) RAs. The current study assessed pilots' ability to respond to and comply with the DAA and RA alerting and guidance generated by ACAS Xu in a human-in-the-loop simulation. Sixteen active UAS pilots participated in the study and were tasked with responding to scripted DAA and RA traffic conflicts. Results showed that pilots were effective at making timely maneuvers against DAA threats. The proportion of losses of DAA well clear against non-cooperative intruders was found to be significantly higher than the proportion of losses against cooperative intruders, a result of the limited declaration range of the simulated onboard RADAR. Results also demonstrated that pilots could consistently meet the five second response time requirement for initial RAs. Rapid responses to RAs had the corresponding effect of minimizing the severity of losses of DAA well clear. While pilots complied with initial RAs at a high rate, compliance dropped substantially when the target heading was updated during a horizontal RA. Pilot performance with ACAS Xu will be presented alongside results from prior DAA research.**

Keywords—unmanned aircraft systems, detect and avoid, collision avoidance

I. Introduction

The beginning of the 21st century has experienced an expansion of unmanned aircraft system (UAS) activity. Understanding their potential, UAS manufacturers and regulators have invested in identifying and overcoming the technical barriers to routine access to the National Airspace System (NAS). One such barrier is the development of an alternative means of compliance with the general operating and flight rules outlined in Part 91 of Title 14 of the US Code of Federal Regulations, which requires pilots to mitigate collision risk by visually acquiring traffic from on board the aircraft and maneuvering as necessary to maintain "well clear" [1]. Currently, detect and avoid (DAA) system requirements are under development that would allow UAS operators to maintain "DAA well clear" from surrounding traffic using onboard sensors and ground control station (GCS) interfaces.

Radio Technical Commission for Aeronautics (RTCA) Special Committee 228 (SC-228) has assembled representatives from government, academia, and industry to publish an initial set of UAS DAA Minimum Operational Performance Standards (MOPS) and is presently working on revisions to the document (Revisions A and B) that will enable a wider range of operations and platforms [2-4]. The first version of the DAA MOPS, referred to as DO-365, defines the requirements for Class 1 and Class 2 DAA systems and limits the scope of UAS operations to transitioning through Class D, E, and G airspace to and/or from Class A or special use airspace. Class 1 DAA systems refer to UAS platforms that only provide alerting and guidance to maintain DAA well clear. By contrast, Class 2 DAA systems provide alerting and guidance generated by the Traffic Alert and Collision Avoidance System II (TCAS II) in addition to DAA alerting and guidance. Unlike DAA systems, which attempt to alert pilots to potential conflicts well before they become collision hazards, TCAS II and other Collision Avoidance (CA) systems are a method of final recourse for preventing midair collisions. The different functions that DAA and CA systems

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serve, and their relative urgency, has led to the use of different types of alerting and guidance. DAA systems provide "suggestive" guidance, presenting pilots with a range of maneuver options and leaving maneuver selection to the pilot's discretion. This is enabled by the greater time horizon on which DAA operates. CA systems, conversely, utilize "directive" guidance, which provides pilots with a single maneuver option and with which the pilot is expected to immediately comply.

Substantial research efforts helped to develop the necessary display, alerting, and guidance requirements for Class 1 and Class 2 systems as documented in DO-365. A portion of this work consisted of human-in-the-loop (HITL) simulations that investigated different DAA display concepts as pilots were presented with scripted traffic conflicts in representative airspace [5-12]. The research into Class 1 DAA systems resulted in a DAA alerting and guidance structure that was designed to ensure pilots not only maneuvered effectively against predicted traffic conflicts, but also knew when to coordinate their maneuver with air traffic control (ATC). A multi-level alerting and guidance structure communicated this information to pilots. Caution-level DAA information was associated with conflicts where pilots had sufficient time to coordinate with ATC prior to maneuvering, while warning-level DAA information was issued once pilots needed to maneuver immediately in order to maintain DAA well clear. DAA maneuver guidance was also developed to indicate which ranges of horizontal and/or vertical trajectories were predicted to result in a loss of DAA well clear. An additional type of guidance, referred to as "regain" DAA well clear guidance, was issued once DAA well clear could no longer be maintained. This ensured that pilots had guidance throughout an encounter to assist in maximizing separation at closest point of approach.

The research into Class 2 systems focused on identifying ways in which the DAA alerting and guidance could be modified to best accommodate the specific requirements of TCAS II [12]. A number of interoperability requirements were prescribed which replaced TCAS II Traffic Advisories (TAs) with DAA alerting and guidance. Additionally, Resolution Advisories (RAs) were incorporated into the multi-level DAA alerting and guidance structure. TCAS II RAs consist of warning-level alerting and guidance and command the pilot to maintain a target vertical speed. While the Class 2 interoperability requirements were found to be effective, a foundational limitation of TCAS II is its inability to detect non-cooperative (i.e., non-transponder-equipped) traffic. TCAS II requires altitude reports from a Mode C or Mode S transponder in order to generate RAs. The DAA system does not share this limitation, relying on an onboard, or ground-based, RADAR to detect and alert to non-cooperative traffic. This discrepancy between the systems necessitated different alerting structures for cooperative and non-cooperative traffic, with RA alerting and guidance only issued against cooperative intruders. Class 2 systems also required changes to the regain DAA well clear guidance requirements to mitigate potential inconsistencies with RA guidance. These changes resulted in a more complex alerting and guidance schema for Class 2 systems than was required for Class 1.

An update to DO-365 (Revision B) adds a new class of DAA equipment – Class 3 – that may resolve the limitations associated with Class 2 systems while also providing CA protection. Class 3 systems will use the Airborne Collision Avoidance System (ACAS) Xu to generate both DAA and RA alerting and guidance for UAS [4, 13-14]. Developed by the Federal Aviation Administration's (FAA) TCAS II Program Office, ACAS Xu is the unmanned variant of the next-generation replacement for TCAS II, referred to generally as ACAS X. Unlike the other versions of ACAS X, ACAS Xu issues DAA alerting and guidance in accordance with DO-365 (with some important deviations to be detailed below). Also unique to the Xu variant of ACAS is the ability to alert against non-cooperative traffic and issue new types of RAs. While the other types of ACAS X (and TCAS II) issue vertical RAs, ACAS Xu also issues horizontal RAs that provide pilots with a target heading, and blended RAs that provide pilots with a target heading and a target vertical speed simultaneously.

While ACAS Xu meets the caution-level DAA alerting and guidance requirements in DO-365, it is not designed to meet the warning-level alerting and guidance requirements. Instead, ACAS Xu replaces all warning-level DAA information with RA alerting and guidance, which is applied to all intruders, regardless of equipage. This approach simplifies the alerting and guidance structure, but delays the onset of warning-level information in an encounter by approximately 15 seconds relative to Class 1 and Class 2 systems. Phase 1 research determined that the DAA Warning alert was associated with lower rates of, and less severe, losses of DAA well clear, and led to more appropriate ATC coordination [11]. By delaying the issuance of warning-level guidance, ACAS Xu may increase the likelihood of a loss of DAA well clear. Such a tradeoff may be acceptable, however, since the directive guidance associated with ACAS Xu RAs is expected to incur faster pilot response times than are achievable with DAA warning alerts, which are accompanied by suggestive guidance. Further details regarding the design of ACAS Xu can be found in DO-386 (MOPS for ACAS Xu), under development within RTCA SC-147 [14].

The purpose of the current study was to investigate the effectiveness of ACAS Xu in the context of a HITL simulation. Specifically, researchers wanted to understand how well ACAS Xu supported pilots' ability to maintain DAA well clear and how well they were able to interpret and comply with ACAS Xu RAs. Pilots' ability to manage the DAA function with ACAS Xu will be shown relative to pilot DAA performance in [9], which served as a validation of DO-365's Class 1 DAA system requirements.

This study incorporates findings from an engineering analysis by the authors that investigated different ways of providing the visual and aural alerts for each type of ACAS Xu RA [15]. Most consequentially, the engineering analysis led to a change in how the UAS pilots complied with ACAS Xu RAs within the research GCS used for the current study. This modification removed the need for pilots to manually input the RA command and was incorporated so that pilots had a better chance of meeting the response time requirements associated with ACAS Xu. Pilots are required to successfully command a maneuver to the vehicle within 5 seconds of the initial RA and within 2.5 seconds of any subsequent RAs. These requirements are derived from the TCAS II RA response time requirements, but are expected to remain in place for ACAS Xu.

II. METHOD

A. Participants

Sixteen instrument flight rules (IFR) rated UAS pilots (*M* = 34 years of age) were recruited for this study. On average, participants had 955 (629 military-related) hours of manned flight experience and 1,013 hours of unmanned flight experience (all of which were military related) with a Group 5 UAS. All but two of the sixteen participants self-rated as at least “Somewhat Familiar” with TCAS II. Two retired air traffic controllers from Oakland Center served as confederate ATC and two general aviation pilots served as confederate “pseudo” pilots.

B. Simulation Environment

1) Vehicle and Airspace Simulation Software

The current study utilized the Air Force Research Laboratory’s Vigilant Spirit Control Station (VSCS) software suite as its UAS ground control station (GCS) testbed [16]. VSCS was configured to simulate an MQ-9 Reaper and provided the UAS pilot participants with the displays and controls necessary to remotely operate the vehicle and manage ACAS Xu. VSCS was operated using a computer mouse and keyboard; its control interface is discussed in further detail in the Experimental Design section. Researchers utilized a separate software component called Vigilant Spirit Simulator to inject scripted events into each scenario. For the purposes of the current study, the scripted events included chat messages designed to assess pilot situation awareness and scripted traffic conflicts designed to generate ACAS Xu alerts. The types of traffic conflicts included in the current study will be discussed in further detail in the Experimental Design section.

The Multi Aircraft Control System (MACS) was used as the airspace simulation software for the current study [17]. MACS was configured to emulate Oakland Air Route Traffic Control Center (ZOA - 40/41) airspace. The MACS constructive traffic generator provided representative background traffic. A MACS en-route controller display allowed the confederate ATC to manage traffic with standard en-route controller tools. The confederate “pseudo” pilots used MACS to manage all simulated manned aircraft and responded to confederate ATC clearances in real time to mimic typical Oakland Center operations. All participants communicated using push-to-talk headsets.

2) ACAS Xu and Sensor Model Software

The current study utilized ACAS Xu executable libraries that represented the latest ACAS Xu Sensor Tracker Module (STM) and Threat Resolution Module (TRM) algorithms available at the time of the test (i.e., June 2019). The STM ingests multiple surveillance sources and transforms them into a single estimated intruder track. The fused track is sent to the TRM, which determines whether a maneuver is required and, if so, the type of maneuver to command. Horizontal and vertical maneuvers are determined independently by the TRM [13]. The FAA TCAS Program Office made the ACAS Xu libraries available to RTCA SC-147 members to aid in the validation and verification of the ACAS Xu logic. ACAS Xu v5.0 was integrated into the existing simulation infrastructure as a Windows executable and it provided all DAA and RA alerting and guidance for this study. The algorithm description document (ADD) for the final version of ACAS Xu, which includes several updates that were not available for this study, can be found in DO-386 [14].

Simulated automatic dependent surveillance-broadcast (ADS-B) and airborne RADAR measurements were generated from models initially developed by Honeywell and later delivered to the researchers. These, as well as the ownship’s state measurements, provided input data to ACAS Xu’s STM. The ADS-B model was configured to a 20 nautical mile horizontal range and an unrestricted altitude range. Horizontal position errors were modeled as a Gaussian-Markov process with a standard deviation of 2 meters in both east and north directions. Vertical position errors were modeled as Gaussian white noises with a standard deviation of 25 feet. Velocity errors were modeled as Gaussian white noises with standard deviations of 2.0, 2.0, and 0.0 meters per second in north, east, and down directions, respectively. The airborne RADAR’s field of regard was defined by a 6.7 nautical mile horizontal range, a ±110 degrees azimuth range, and a ±15 degrees elevation range. The RADAR position errors were modeled as Gaussian noises with standard deviations of 10 meters, 0.4 degrees, and 0.4 degrees in range, azimuth, and elevation, respectively. Velocity errors were modeled as Gaussian noises with standard deviations of 4.0, 4.0, and 4.0 meters per second in range, cross range, and up directions, respectively. The ownship measurements were injected with small, representative Gaussian white noise errors.

3) ACAS Xu Alerting and Guidance Structure

ACAS Xu issues alerting and guidance in accordance with DO-365 Revision B [4]. While its alerting and guidance structure shares some similarities with Class 1 and 2 systems, ACAS Xu differs in several critical respects. As with DAA equipment Classes 1 and 2, ACAS Xu issues Preventive and Corrective DAA alerts. The alert symbology and aural alert associated with Preventive and Corrective alerts are shown in Table 1. A DAA Preventive alert informs UAS pilots that an aircraft is close in altitude but is not currently predicted to lose DAA well clear. Corrective DAA alerts inform UAS pilots that an aircraft is predicted to lose DAA well clear within

TABLE I. ACAS XU ALERTING STRUCTURE.

Symbol	Name	Pilot Action	Aural Alert
	Resolution Advisory (RA)	Immediately comply with RA	“Climb/Descend” x2 “Turn Left/Right” x2
	Corrective DAA Alert	Maneuver following ATC coordination	“Traffic, Avoid”
	Preventive DAA Alert	No action required; monitor traffic	“Traffic, Monitor”
	Guidance Traffic	No action required	N/A
	Basic Traffic	No action required	N/A

approximately 60 seconds. Upon issuance of a Corrective alert, pilots should contact ATC and coordinate a maneuver to maintain DAA well clear. Pilots are able to utilize the horizontal and vertical DAA guidance that accompanies a Corrective alert to determine an appropriate maneuver. DAA guidance is depicted as caution-level (amber) "banding" that highlights the horizontal and vertical trajectories that are predicted to lead to a loss of DAA well clear. The current study depicted horizontal DAA guidance on the inner range ring of the VSCS traffic display and vertical DAA guidance on an altitude tape (Fig. 1). ACAS Xu natively outputs vertical DAA guidance as vertical speeds. The vertical speed DAA guidance was converted to discrete altitudes by multiplying the vertical speed, issued by ACAS Xu in feet per second, by 30 seconds. This conversion allowed the pilot to decide upon a target altitude that could then be coordinated with ATC.

While there is no fixed time at which ACAS Xu issues an RA relative to a loss of DAA well clear, RAs are typically issued approximately 10 seconds prior to a loss of DAA well clear (i.e., 15 seconds after Class 1 and Class 2 systems are designed to issue a DAA Warning alert). An ACAS Xu RA informs the pilot that they must immediately comply with the provided guidance and notify ATC once the maneuver has been initiated. The alert symbology and aural alerting associated with ACAS Xu RAs are shown in Table 1. RA directive guidance includes a red "avoidance" band and a green "fly-to" band. There are three types of ACAS Xu RAs: 1) horizontal RAs, which issue a target track angle (converted in this study to a target heading), 2) vertical RAs, which issue a target vertical speed, and 3) blended RAs, which issue both RA types concurrently. Blended RAs are typically the result of a vertical RA being added to an existing horizontal RA. Horizontal RAs were displayed using a red arc on the inner range ring to depict the avoidance band and a green "wedge", 10 degrees in width, to indicate the fly-to heading region (Fig. 2). A directive aural alert of "Turn Right, Turn Right" or "Turn Left, Turn Left" accompanied all horizontal RAs. Preliminary testing with ACAS Xu v5.0 revealed frequent target heading updates. Target heading updates modify the precise heading that is commanded by ACAS Xu but do not change the direction of the turn. To reduce the frequency of these updates, a filter was implemented within VSCS that restricted heading updates to no more than once every five seconds. No

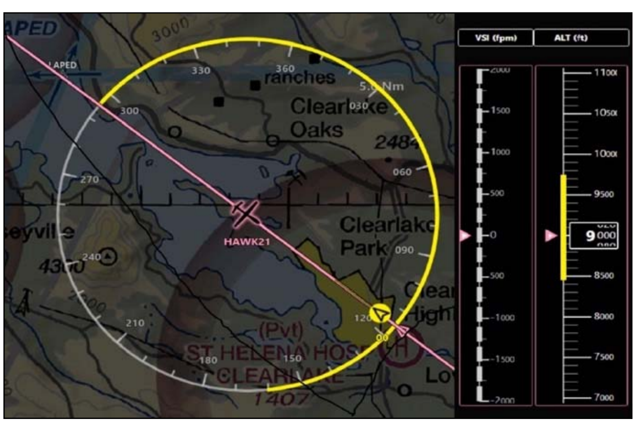

Fig. 1. ACAS Xu Corrective DAA alert intruder icon (amber, filled circle) and Corrective DAA horizontal guidance bands (amber arc on inner range ring, center) and vertical bands (amber band on altitude tape, right).

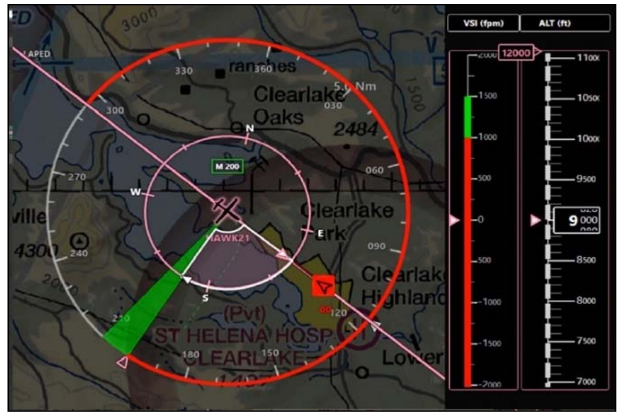

Fig. 2. ACAS Xu RA intruder icon (red, filled square) with simultaneous horizontal RA guidance (green wedge and red arc on inner range ring, center) and vertical RA guidance (green and red arcs on vertical speed tape, right).

other filters were added; any new RA types or reversals were immediately presented. Given their frequency, target heading updates were not aurally annunciated.

Vertical RA guidance was presented within a vertical speed tape, with a red arc used to depict the avoidance band and a green arc used to depict the fly-to region (Fig. 2). All vertical RAs were accompanied by a "Climb, Climb" or "Descend, Descend" aural alert. While other vertical RA types were possible, such as reversals and strengthenings, they were not observed in this study. Blended RAs displayed horizontal and vertical RA guidance simultaneously. The aural alerts for blended RAs combined the two aural alerts and inserted "and" between the two announcements. Additional logic was added to the aural alert processor to change the aural alert to "Maintain Heading" or "Maintain Vertical Speed" if the associated target heading or vertical speed had already been achieved by the time the blended RA was created.

During a single-dimension RA, DAA guidance was visible in the orthogonal dimension. During vertical RAs, the DAA guidance, depicted nominally within the altitude tape, was suppressed (indicated by grey, dashed bands) so that it did not contradict the RA guidance presented within the vertical speed tape. When there was no active RA, the vertical speed tape guidance was suppressed so that it, likewise, did not contradict the DAA guidance presented within the altitude tape.

4) Experimental Design

The current study included one within-subjects and two within-trial independent variables. The within-subjects variable, Display Configuration, compared the ACAS Xu alerting and guidance information through "Integrated" or "Standalone" displays. The Integrated condition presented the ACAS Xu information within the same display (the Tactical Situation Display, or TSD) that contained the navigational maps, vehicle controls, and routing information (Fig. 3). The Standalone condition, conversely, extracted the ACAS Xu information and displayed it on a dedicated monitor to the left of the TSD (Fig. 4). This separate display contained no maps, vehicle controls, or route information in the Standalone configuration and was turned off during the Integrated condition. Both conditions included a dedicated display to the right of the TSD that

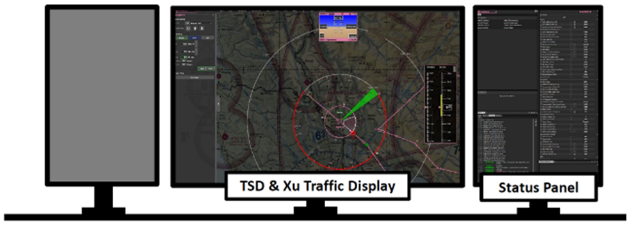

Fig. 3. Integrated display configuration layout.

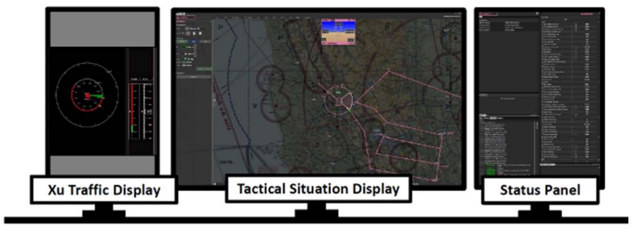

Fig. 4. Standalone display configuration layout.

contained a status panel (e.g., telemetry data) and other mission-related tools (e.g., a chat client and an electronic checklist).

The present study also manipulated two additional variables within each experimental trial. The first, Intruder Equipage, determined whether a conflict was scripted to occur against a cooperative (ADS-B-equipped) or non-cooperative (RADAR-only) intruder. Representative sensor parameters, detailed above, were applied to each type of intruder.

The second within-trial variable involved the scripted threat type of each injected traffic conflict. Conflicts were scripted to first appear as either a DAA Corrective alert or an RA. DAA Corrective threat types were designed to provide pilots with the maximum time possible in that alert state given the intruder's equipage. Since cooperative intruders were detected at a farther distance than non-cooperative intruders, their Corrective alert state was triggered earlier, providing pilots with more time to resolve cooperative conflicts. RA threat types were designed to "blunder" into the UAS when sufficiently close to the RA threshold to immediately transition to an RA upon alert. In practice, the intruder typically spent several seconds as a DAA Corrective alert before triggering the RA. RA threat types were included in the design to ensure pilots saw RAs every trial. While RA type (i.e., horizontal, vertical, or blended) cannot be fully predicted ahead of time with ACAS Xu, intruder approach angles and speeds were kept consistent between participants. Non-cooperative traffic flew at 140 knots indicated airspeed and cooperative traffic flew at 200 knots indicated airspeed. Approach angles were either head-on or crossing.

C. *Procedure*

1) Training

Participants began by reviewing and signing an informed consent form and answering a demographic questionnaire. This was followed by 90 minutes of multimodal training. During this time, pilots progressed between slide show presentations and hands-on practice sessions. The presentations briefed pilots on ACAS Xu alerting and guidance, VSCS display features and functionality, and simulated airspace procedures. Hands-on practice sessions followed the slide-show presentations and advanced through phases. Researchers followed a training checklist to ensure all relevant aspects of the systems were reviewed and understood by the participants before progressing to the next phase of the training. At the culmination of the first block of training (lasting approximately two hours), participants experienced a practice session with all simulation components in the loop (e.g., background traffic, ATC communications, and scripted traffic conflicts). This practice session lasted at least 20 minutes and continued until the pilots exhibited competence with all aspects of the test. Upon termination of the full practice session, participants moved on to experimental trials.

2) Pilot Task

Pilots were tasked with operating a simulated MQ-9 under IFR in Oakland Center Class E airspace. The same vehicle model, airspace, and background traffic used in [9] was used presently. The UAS flew at a cruise speed of 160 knots indicated airspeed, with a default climb and descent rate of 1,000 feet per minute, and a turn rate of 3 degrees per second. Pilots flew two different routes with each of the two display configurations (Integrated and Standalone), resulting in a total of four experimental trials. All trials began with the UAS already at mission altitude (9,000-14,000 feet mean sea level) and established in VSCS's waypoint-to-waypoint navigation mode. The two routes were similar in nature but were varied in order to prevent predictability with the mission. All trials lasted approximately 45 minutes. During this time, the participants' primary objective was to maintain the safety of their aircraft by complying with the alerting and guidance provided ACAS Xu.

Each trial contained six scripted conflicts in which intruder aircraft were programmed to create a midair collision with the UAS, absent pilot action. Four of the six scripted conflicts were designed to be a Corrective DAA threat type at first alert, with cooperative aircraft generating three of these scripted threats, and non-cooperative aircraft generating one. The remaining two scripted conflicts were designed to be an RA at first alert, with one cooperative and one non-cooperative intruder causing an RA per trial. While there were two scripted RAs per trial, it was possible for the Corrective DAA threat types to progress to an RA, depending on how a given conflict developed. These types of RAs are referred to as "unscripted" RAs throughout the rest of this paper since they were not a part of the original design.

For DAA threats, pilots were instructed to coordinate with ATC prior to maneuvering. Pilots had to manually input any desired heading or altitude changes in response to DAA Corrective alerts. To make a horizontal maneuver, pilots had to either manually select a desired heading with a click-and-drag heading bug on the TSD, or type in the desired heading into the auto-pilot interface. To make a vertical maneuver, pilots had to either incrementally increase or decrease their altitude by 500 feet, using "spinner" buttons, or type the target altitude into the auto-pilot interface. Once pilots entered the desired heading or altitude, they were required to click a "Send" button to upload the maneuver to the UAS. Pilots were trained to reference the horizontal and vertical DAA guidance information when maneuvering against Corrective DAA threats.

When responding to RAs, pilots were instructed to coordinate with ATC after avoidance maneuvers were performed. VSCS assisted in pilots' compliance with RA guidance by automatically entering the target heading and/or target altitude into the auto-pilot interface upon issuance of the RA. Since VSCS does not have a vertical speed hold in its auto-pilot interface, an altitude deviation of ±3000 feet was entered in place of the target vertical speed value. The maneuver was not uploaded to the UAS until pilots reviewed the maneuver and clicked "Send". Any new or updated RA guidance was automatically input into the auto-pilot interface. The auto-pilot allowed for heading and altitude commands to be uploaded simultaneously. Pilots had to monitor VSCS to ensure they were reviewing and uploading all new incoming target headings and/or altitudes over the course of an RA. Pilots were instructed that failure to upload a new or modified RA was considered non-compliance.

In addition to maintaining the safety of the aircraft, pilots were also assigned secondary tasks that were to be performed when attention was not required for the primary objective. These secondary tasks required pilots to either reply to scripted chat messages or resolve aircraft health alerts that were issued throughout the mission.

D. Metrics

ACAS Xu output logs, VSCS output logs, and screen recordings of VSCS were used to extract a variety of metrics that were intended to capture pilot performance in response to DAA and RA threat types. Different metrics were used to assess DAA and RA performance. The Display Configuration variable was analyzed using two-sided dependent samples t-tests for all three DAA metrics. The Intruder Equipage variable was also analyzed using two-sided dependent samples t-tests, but tests were only performed on the proportion and severity of losses of DAA well clear metrics. This was due to a high number of non-cooperative intruders progressing to an RA before the pilot could maneuver against the DAA threat, eliminating most DAA response times in that condition. Unlike the DAA metrics, the RA metrics were assessed using descriptive statistics only. The aim of the RA metrics were to characterize the types of RAs issued by ACAS Xu and the ability of pilots to comply with the associated guidance; statistical comparisons between experimental conditions were not of interest.

1) DAA Metrics

- DAA Response Time: a measure of the time it took pilots to upload a maneuver in response to a DAA Corrective alert, in seconds
- Proportion of Losses of DAA Well Clear: the number of losses of DAA well clear out of all intruders predicted to lose DAA well clear per trial
- Severity of Losses of DAA Well Clear (SLoWC): the percentage of the well clear volume that was penetrated by the intruder, with a SLoWC of 0% indicating no loss of DAA well clear and 100% indicating a collision

2) RA Metrics

- RA Counts: the total number of scripted and unscripted RAs issued over the course of the present study
- Initial RA Types: the total number of horizontal, vertical, and blended RAs issued as the first RA in an encounter
- Target Heading Updates: the total number of target heading updates (i.e., changes in the magnitude of the turn) issued per horizontal RA
- Horizontal and Veritcal RA Compliance Rates: the number of successful uploads conforming to horizontal or vertical RA guidance out of all horizontal or vertical RAs, including updates to the target RA value
- RA Response Times: a measure of the time it took pilots to maneuver in response to an RA, in seconds

III. Results

The present paper reports on pilot participants' objective performance while responding to DAA and RA alerting and guidance generated by ACAS Xu. The DAA metrics are presented alongside the results of [9], referred to in the rest of the paper as the "Phase 1" study. The Phase 1 study served as a HITL simulation validation of the DAA system requirements documented in DO-365. The design of the current study was kept as similar as possible to the Phase 1 study to support this comparison. The primary deviation, besides the use of ACAS Xu presently, was the use of high-fidelity sensor models in the current study. The Phase 1 study did not utilize sensor models (i.e., used "perfect" sensor data) and assumed a better-performing RADAR than was modeled here. The purpose of this comparison is to ensure that pilots utilizing ACAS Xu do not seriously underperform on the DAA task relative to what was reported in [9]. For a discussion of pilots' subjective feedback regarding the presentation and performance of ACAS Xu in the present study, refer to [18].

A. DAA Results

1) DAA Response Times

No significant main effect of Display Configuration was found in the current study, $t(15) = 0.27$, $p > .05$. As shown in Fig. 5, DAA response times in the present study were consistent with those found in the Phase 1 study. In the present study, DAA response times in the Standalone condition ($M = 17.03$ s, $SE = 0.90$ s) were slightly faster, on average, than those found in the Integrated condition ($M = 17.34$ s, $SE = 1.12$ s). Response times in both conditions were slightly faster than the overall DAA

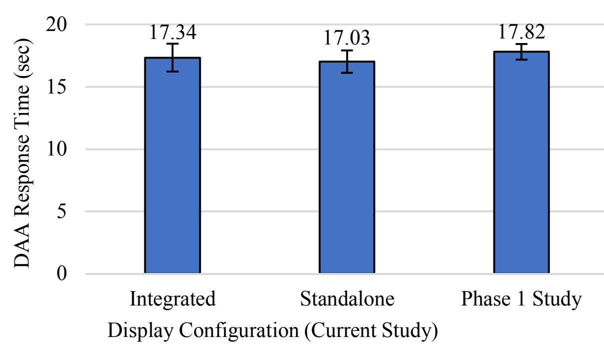

Fig. 5. Average DAA response times (in seconds) in the present study by Display Configuration (Integrated and Standalone), and the overall average response time in the Phase 1 study.

response time average reported in the Phase 1 study (M = 17.82 s, SE = 0.63 s).

2) Losses of DAA Well Clear

Display Configuration had no effect on the average proportion of DAA encounters that resulted in a loss of DAA well clear, $t(15) = -0.52$ $p > .05$. Intruder Equipage, however, was found to have a significant main effect on the proportion of losses of DAA well clear, $t(15) = -5.45$, $p < .001$. As shown in Fig. 6, non-cooperative intruders (M = 0.35, SE = 0.05) were seven times as likely to lead to a loss of DAA well clear than cooperative intruders (M = 0.05, SE = 0.02). The difference in loss of DAA well clear performance between cooperative and non-cooperative intruders is a result of the shorter non-cooperative sensor declaration range compared to the cooperative sensor. The smaller declaration range reduced the DAA alerting time by approximately 15 seconds relative to cooperative intruders. As a result, losses of DAA well clear, and consequently issuances of RAs, were much more common against non-cooperative intruders. As shown in Fig. 7, 83% (53/63) of Corrective DAA threat types with non-cooperative intruders resulted in an RA (i.e., became unscripted RAs). Of those 53 conflicts, the pilot was able to upload an avoidance maneuver prior to the RA in only 16 cases.

While the proportion of losses of DAA well clear was much lower for cooperative intruders in the present study (M = 0.06, SE = 0.01), they were more common than the overall average reported in the Phase 1 study (M = 0.01, SE = 0.01). A loss of DAA well clear against a cooperative intruder typically indicates that the pilot made a mistake, either in how they tried to avoid the intruder initially or in choosing to return back to course before it is safe to do so. A post-hoc review of each loss of DAA well clear was done to determine the cause of the nine losses of DAA well clear that occurred against cooperative DAA threats in this study. Results showed that in six of the nine cases, pilots lost DAA well clear due to the display of inaccurate vertical DAA guidance on VSCS. In those cases, the altitude guidance indicated that a climb or descent was safe when that was not the case. The cause of this misleading guidance will be discussed in further in the Discussion section. When these cases are removed from the number of losses of DAA well clear, since they were not the fault of the pilot, the number of them against cooperative intruders is reduced to three. Based upon review, one case was the result of the pilot attempting to return to the route too soon following the avoidance maneuver, a second case was caused by a poor maneuver choice by the pilot, and the final case was caused by the pilot attempting to coordinate with ATC for an excessively long time.

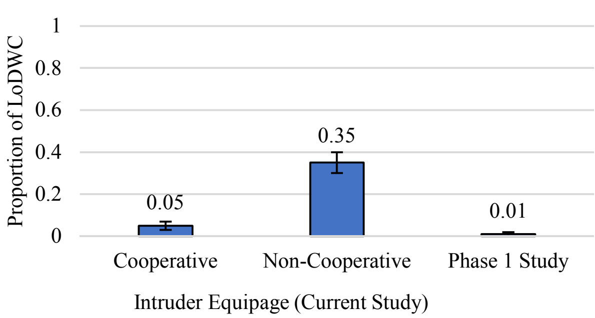

Fig. 6. Proportion of losses of DAA well clear (LoDWC) in the present study, by intruder equipage (cooperative and non-cooperative), and the overall average proportion in the Phase 1 study.

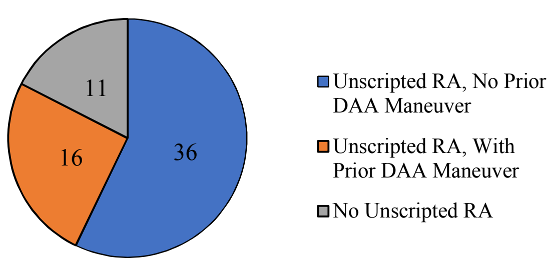

Fig. 7. Count of non-cooperative DAA conflicts that did, or did not, progress to an unscripted RA, with, or without, a maneuver prior to the issuance of the RA.

Despite the observation of a higher proportion of losses of DAA well clear in this study compared to the Phase 1 study, the average severity of those losses of DAA well clear (SLoWC) was low. The present study found no significant effect of Display Configuration on SLoWC, $t(7) = 0.18$, $p > .05$. Intruder Equipage also failed to have a significant effect, $t(4) = -0.79$, $p > .05$. On average, losses of DAA well clear against cooperative intruders (M = 1.30%, SE = 0.47%) were less severe than losses of DAA well clear against non-cooperative intruders (M = 5.44%, SE = 1.02%). As shown in Fig. 8, the average SLoWC for both cooperative and non-cooperative intruders in the current study were lower than the overall SLoWC average in the Phase 1 study (M = 7.15%, SE = 2.49%).

B. RA Results

1) RA Counts and Types

Two RAs were scripted to occur per trial, one against a cooperative intruder and one against a non-cooperative intruder. This should have resulted in a total of 64 cooperative and 64 non-cooperative scripted RAs. In one case against a cooperative intruder, a pilot maneuvered before an RA was issued and avoided the RA entirely, leading to one less RA in the cooperative condition. Further, as mentioned above, unscripted RAs were possible if the pilot did not maneuver in time when

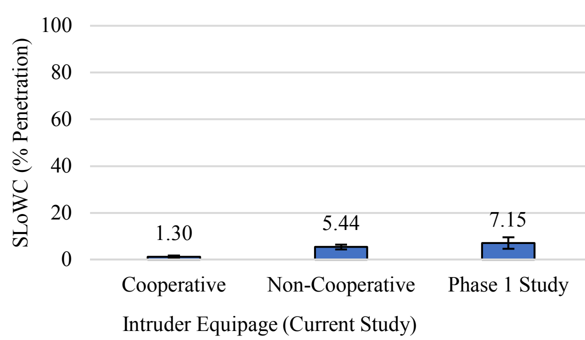

Fig. 8. Average severity of losses of DAA well clear (SLoWC, % Penetration) in the present study, by intruder equipage (cooperative and non-cooperative), and the overall average in the Phase 1 study.

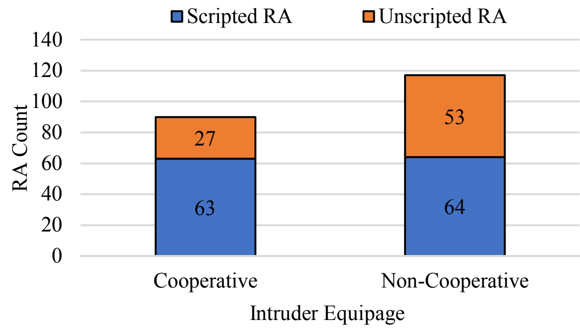

Fig. 9. Count of scripted and unscripted RAs in the present study by intruder equipage.

responding to a DAA threat type. This was particularly prevalent against non-cooperative intruders, which severely abbreviated the DAA alert duration. Results showed that 53 DAA conflicts against non-cooperative intruders, and 27 DAA conflicts against cooperative intruders, progressed to an RA (see Fig. 9). While the high number of non-cooperative unscripted RAs is expected, the number of cooperative unscripted RAs is not consistent with the finding of relatively few losses of DAA well clear against cooperative intruders (i.e., 9 total, including those that resulted from inappropriate vertical DAA guidance). This finding is likely the result of ACAS Xu's sensitivity to intruders that are in a climb or descent, which was the case in a subset of the encounter geometries with cooperative intruders, and which was compounded by the greater number of scripted cooperative Corrective DAA threats per trial. While 83% (53/64) of the non-cooperative DAA threats progressed to an RA, only 14% (27/192) of the total cooperative DAA threats resulted in an RA.

The first type of RA that was issued by ACAS Xu for each RA that occurred in this study is shown in Fig. 10. Horizontal RAs were the initial RA type in 93% (193/207) of RA encounters, while vertical and blended RAs were the initial RA type in 5% (11/207) and 2% (3/207) of RA encounters respectively. While blended RAs were extremely rare as the initial RA type, they became more common over the course of an encounter. When including subsequent RAs, rather than only the initial RA in an encounter, there were a total of 54 blended RAs in the current study. Blended RAs were overwhelmingly the product of a vertical RA being added to an existing horizontal RA. Much of the bias toward horizontal RAs can be attributed to a tendency with ACAS Xu v5.0 to issue horizontal RAs slightly earlier than vertical RAs.

During development, ACAS Xu was observed to issue target heading updates up to every second during a horizontal RA. A

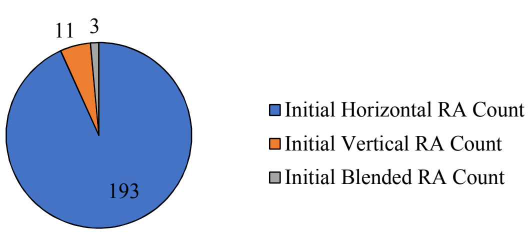

Fig. 10. Count of horizontal, vertical, and blended RAs issued as the initial RA in an encounter.

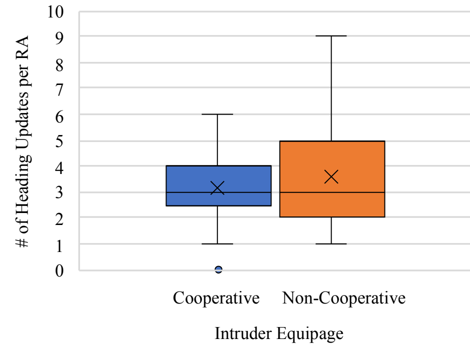

Fig. 11. Mean, median, 1st and 3rd quartiles, minimum and maximum number of target heading updates per horizontal RAs by intruder equipage (cooperative and non-cooperative).

filter was added within VSCS that limited the target heading update rate to no more than once every five seconds. As shown in Fig. 11, despite the filter, pilots still received frequent target heading updates, an average of approximately three updates per horizontal RA (for an average of four total target headings issued per horizontal RA). Non-cooperative intruders, in particular, resulted in frequent target heading updates, with a quarter of horizontal RAs leading to five or more updates. While target heading updates were extremely common, reversals were not. There were no recorded horizontal or vertical RA reversals. Unlike horizontal RAs, vertical RAs were not subject to updates of the target vertical rate.

2) RA Response Times

Average RA response times were fast in both the Standalone condition ($M = 2.88$ *s*, $SE = 0.16$ *s*) and the Integrated condition ($M = 2.69$ *s*, $SE = 0.16$ *s*). As shown in Fig. 12, pilots met the initial RA response time requirement of 5 seconds in more than 90% of RA encounters. Pilots were able to meet the subsequent RA response time requirement of 2.5 seconds 70% of the time.

3) RA Compliance Rates

a) Horizontal RA Compliance Rate

Pilot compliance with horizontal RAs decreased with the number of target heading updates (Fig. 13). Pilots complied with the initial horizontal RA target heading 94% of the time. Non-compliance with the initial target heading only means that pilots failed to upload the first heading generated by ACAS Xu; pilots

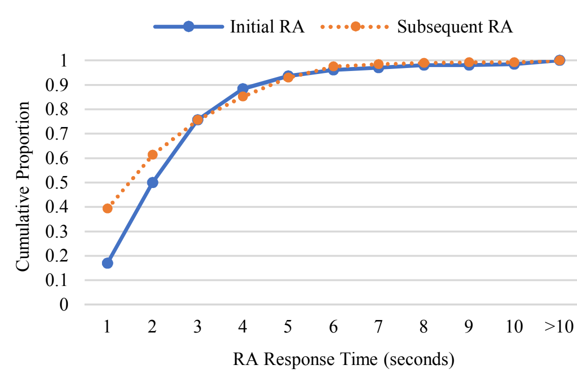

Fig. 12. Cumulative proportion of RA response times (seconds) to initial and subsequent RAs.

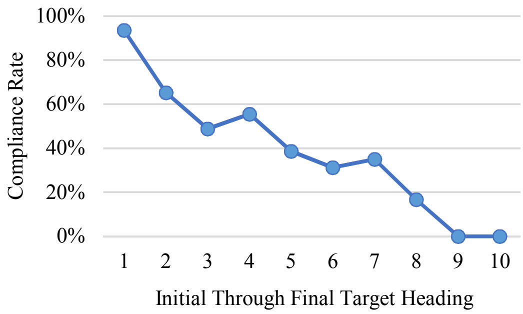

Fig. 13. Average compliance rate for each target heading issued during horizontal RAs, from the initial RA to the final heading update.

never fully non-complied (i.e., ignored the RA entirely or uploaded a target heading in the opposite direction) with a horizontal RA. Compliance rate with the first target heading update (i.e., the second target heading issued during the RA) dropped to 65%, while the second target heading update compliance rate dropped to just below 50%. Compliance rates stayed below 50% starting with the fourth update. Though this rate of non-compliance seems high relative to past research [12], cases of non-compliance for horizontal ACAS Xu RAs are less severe since pilots were turning when the updates were issued. Nonetheless, pilots are trained to fully comply with all RA guidance, and it is therefore important to capture their ability to keep up with frequent updates to the commanded maneuver.

b) Vertical RA Compliance Rate

Compliance to vertical RA guidance was consistently high, with pilots complying in 94% (64/68) of cases. The four cases of non-compliance were the result of one of two situations. In the first, pilots were already in a climb or descent in response to the preceding DAA alert and were maneuvering in a direction that was ultimately consistent with the direction of the RA. In this sense, pilots were technically complying with the vertical RAs, however, since they did not modify their target altitude, it was possible that they would not continue to climb or descend for the duration of the RA, as pilots are instructed to do. The second cause of non-compliance was a vertical RA being added to a horizontal RA late into an encounter. In rare cases, pilots found the vertical maneuver unnecessary given the lateral separation gained as a result of complying with the horizontal RA.

IV. Discussion

The current study aimed to understand pilot performance with ACAS Xu relative to previous DAA research and with respect to the unique aspects of ACAS Xu RAs. Consistent with Phase 1 results, the findings did not reveal an effect of the Display Configuration variable. Pilots were equally capable of responding to ACAS Xu guidance whether it was collocated or separated from the primary ground station display. Compared to previous research, however, pilots were much more likely to lose DAA well clear against non-cooperative traffic with ACAS Xu. This is the result of the test setup: Pilots had a smaller declaration range in the current study than they did in the Phase 1 study due to a reduction in the minimum declaration range requirement that was made at the end of the development of DO-365. Furthermore, there was also only a single non-cooperative DAA encounter geometry in the current study and it simulated the maximum-possible closure rate with this class of aircraft. In tandem, these simulation artifacts meant that pilots had far less time to resolve non-cooperative DAA threats in general than they had in previous simulations by the authors. Despite this discrepancy, the results showed that pilots were still highly effective at reducing the severity of losses of DAA well clear when using ACAS Xu. This is a function of ACAS Xu issuing RAs prior to the DAA well clear boundary. As RA results demonstrated, pilots were able to consistently comply with RAs within a few seconds, which served to avoid any high-severity losses of DAA well clear.

Despite the relatively low severity of losses of DAA well clear, there was a greater proportion of losses against cooperative intruders than had been observed in the Phase 1 study. A review of each encounter revealed that these losses were largely due to an inappropriate conversion of ACAS Xu's vertical speed DAA maneuver guidance into altitude guidance within VSCS. This misleading information was a result of not taking into account the ±1,000 feet per minute vertical rate limit modeled by VSCS when performing the conversion. This error could have been avoided if the display had added logic to "saturate" the altitude bands with Corrective-level guidance whenever the vertical rate guidance exceeded ±1,000 feet per minute. This would have informed pilots that a climb or descent in that direction would lead to a loss of DAA well clear given the vertical rate performance of their aircraft.

The RA results revealed a clear bias towards issuing horizontal RAs against the types of traffic conflicts modeled in this study. While blended RAs became more common over the course of an RA, comprising roughly one quarter of RAs overall, horizontal RAs made up nearly all of the remainder. The prevalence of horizontal RAs was amplified, from a pilot's perspective, by the frequency of target heading updates that were observed per RA. Pilots saw an average of three target heading updates per horizontal RA, with some pilots seeing as many as nine updates in a single encounter. As demonstrated by the compliance rates, pilots frequently disregarded these updated target headings since they were already complying with the initial heading issued for the RA. While pilots were still technically complying with a command to turn left or right, training with CA systems emphasize the criticality of complying with all RAs generated by the system. Results here suggest that frequent target heading updates will encourage non-compliance. This is consistent with pilot feedback reported in [18], which conveyed the sentiment that pilots perceived the target heading updates as unnecessary and redundant. Contrary to the levels of non-compliance seen for horizontal RAs, pilots were overwhelmingly likely to comply with vertical RAs. The high rate of compliance was likely influenced by the fact that the target vertical speed remained constant over the course of the encounter; no strengthened or reversed vertical RAs were observed in this study.

A major finding in the current study was the ability of pilots to routinely meet the initial RA response time requirement of five seconds. Data here showed that, when provided with a simplified control interface that only required pilots to click a "Send" button to upload the maneuver, pilots responded to the initial RA within five seconds more than 90% of the time. While the subsequent RA response time requirement of 2.5 seconds is significantly harder to meet given the keyboard and mouse interface utilized in this study, pilots still managed to achieve this response time requirement approximately 70% of the time, a substantial improvement over the RA response times reported in [15].

V. Conclusion

The present study suggests that pilots can effectively utilize ACAS Xu to manage the DAA function. In a significant departure from Class 1 and Class 2 systems, ACAS Xu (i.e., the Class 3 DAA system) removed the DAA Warning alert and guidance, as well as the regain DAA well clear guidance that appears once a loss of DAA well clear is unavoidable. The present findings demonstrated that ACAS Xu substantially minimizes the severity of losses of DAA well clear, despite the higher prevalence of losses of DAA well clear against non-cooperative traffic. ACAS Xu, in fact, resulted in less severe losses of DAA well clear, on average, than was found in the Phase 1 study. This finding is especially noteworthy given the fact that the Phase 1 study utilized perfect sensor data and simulated an 8 nautical mile RADAR declaration range, whereas the current study incorporated realistic sensor models and a RADAR declaration range of 6.7 nautical miles. Furthermore, pilots were capable of complying with initial RAs within the five second response time window and met the subsequent RA response time requirement in a majority of the cases. This was enabled by minimizing the extent to which pilots had to interact with the GCS in order to upload the RA.

The primary limitation of this version of ACAS Xu was an overreliance on horizontal RAs in general and on target heading updates in particular. The excessive updating of the target heading led to high rates of non-compliance and poor pilot feedback, as reported in [18]. While pilot non-compliance with a target heading update is not as critical as a lack of compliance with the initial RA, the findings reported here suggest that pilots consider these updates to be nuisances, which could, over time, reduce their trust in the system. Ideally, the horizontal RA guidance should behave similarly, from a pilot's point of view, to the vertical RA guidance, which is consistent (i.e., issues a nominal target vertical speed) and stable (i.e., updates to the target vertical speed are infrequent).

Following the completion of this study, updates were made to the ACAS Xu logic that are expected to address most of these issues. Future studies should continue to examine ACAS Xu, and any new ACAS X variants, in human-in-the-loop settings to better understand pilots' ability to manage the unique capabilities and features of each system.

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