Detect and Avoid and Collision Avoidance Flight Test Results with ACAS Xr

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Abstract*— In October 2023, the National Aeronautics and Space Administration (NASA) completed its Integration of Automated Systems flight test series, conducted under NASA's Advanced Air Mobility project and in partnership with Sikorsky and the Defense Advanced Research Projects Agency (DARPA). The flight test effort included two crewed rotorcraft platforms. The first, a modified S-76B helicopter, served as the "ownship" for the duration of the flight test. The second vehicle, a modified S-70, served as the intruder aircraft. One Sikorsky pilot and one NASA test pilot was onboard each aircraft for every test point, with the NASA test pilot responsible for interacting with the research systems under test. Approximately half of the flight test was devoted to assessing the Federal Aviation Administration's (FAA) next-generation collision avoidance system, the Airborne Collision Avoidance System X for Rotorcraft (ACAS Xr). The two configurations available within ACAS Xr – the Collision Avoidance System (CAS) configuration and the Detect and Avoid (DAA) configuration – were flown with an onboard pilot under Visual Flight Rules in controlled airspace over the Long Island Sound (Connecticut, USA). A total of 33 flight test cards were flown with ACAS Xr active. The ownship was equipped with ACAS Xr and the intruder was equipped with Automatic Dependent Surveillance-Broadcast (ADS-B). The test points were blocked by ACAS Xr configuration, with individual encounters varying the ownship speed (90 knots or 20 knots), the intruder designation (en-route, terminal area, or structured airspace), and method of RA execution (automated or manually executed). Results showed that the ACAS Xr alerting and guidance was largely effective and rated positively by the NASA test pilots, exemplified by zero instances of the pilots overriding an ACAS Xr Resolution Advisory (RA). Key areas of improvement, however, were noted, particularly with regards to the lack of an aural alert indicating a need to accelerate when receiving an RA at low speed and the occurrence of multiple RAs that the pilots found to be unacceptable.

***Keywords*—detect and avoid, collision avoidance, flight test, ACAS X, advanced air mobility**

I. INTRODUCTION

The concept of Advanced Air Mobility (AAM) is central to the current era of aviation-related research and development [1]. AAM is broadly understood as the introduction of advanced aircraft designs, and associated technologies, to passenger and cargo-carrying operations. One AAM use case, Urban Air Mobility (UAM), is focused on providing highly automated air transportation services in and around urban areas [2]. The AAM and UAM concepts have far-reaching consequences on the design of future airspace systems. As a result, the operators of AAM aircraft may interact with their vehicle and with the larger Air Traffic Management (ATM) ecosystem in drastically different ways than is done under the current system.

The National Aeronautics and Space Administration's (NASA) AAM project is tasked with investigating the barriers to the safe introduction of this new operational paradigm. One such barrier is the lack of validated solutions for tactical conflict management for AAM, particularly operations conducted with vehicles capable of Vertical Takeoff and Landing (VTOL). A related question is whether automation can be leveraged in support of tactical conflict management, which may become increasingly relevant as AAM operations scale. While legacy aircraft, and even large and small Uncrewed Aircraft Systems (UAS), have existing methods and systems for avoiding collisions, the requirements for VTOL aircraft operating within an AAM environment warrant dedicated study.

The Federal Aviation Administration's (FAA) Traffic Alert and Collision Avoidance System (TCAS) Program Office has developed multiple variants of a next-generation collision avoidance system. Referred to broadly as the Airborne Collision Avoidance System X (ACAS X), the logic for each variant is tuned to facilitate a particular operation type [3]. ACAS Xu, for instance, was designed for large UAS. A version of the logic, referred to as ACAS Xr, is currently being developed to support crewed and uncrewed rotorcraft [4]. Support for both crewed and uncrewed platforms will be achieved through the use of two distinct ACAS Xr confugrations.

The implementation designed for crewed rotorcraft, referred to as the Collision Avoidance System (CAS) configuration, closely matches TCAS II, the predecessor to ACAS X. This is by design, since pilots onboard the aircraft are expected to interact with ACAS Xr similarly to pilots who fly on aircraft equipped with TCAS II today. Crucially, however, the CAS configuration under ACAS Xr differs from TCAS II in the exact timing of its alerting and in the types of guidance it is capable of issuing. ACAS Xr issues its Resolution Advisories (RAs) earlier and includes maneuver commands in the horizontal dimension, whereas TCAS II is limited to issuing commands in the vertical dimension.

The ACAS Xr implementation developed for uncrewed rotorcraft is referred to as the Detect and Avoid (DAA) configuration. The DAA configuration meets existing requirements for UAS DAA systems, which specify a multi-level alerting and guidance structure that can support the remote pilot's ability to remain DAA well clear (DWC) [5]. Whereas onboard pilots can rely on their vision to "see-and-avoid" other aircraft, a DAA system quantifies well clear and uses a suite of surveillance sensors (e.g., Automatic Dependent Surveillance-Broadcast [ADS-B], active surveillance, air-to-air radar [ATAR], and ground-based surveillance systems [GBSS]) to generate alerting and guidance that the remote pilot can use to inform if, and how, to maneuver against a predicted threat. The first application of the DAA requirements to an ACAS X system occurred with ACAS Xu. ACAS Xr's DAA configuration, however, includes unique features, such as the ability to designate intruders as operating within a specific environment (e.g., within the terminal area), as well as the ability to incorporate terrain and obstacle information into its guidance.

Research – both in simulation and in flight – has been conducted with earlier ACAS X variants [6-9]. More recently, several human-in-the-loop simulations have investigated the effectiveness of ACAS Xr under a variety of conditions and under multiple levels of automation [10-11]. In the most recent study, pilots flew a variety of scenarios in a full-motion simulator, under both the CAS and DAA configurations. The test included scripted conflicts at cruise speeds and at low (near hover) speeds in order to capture both ends of the rotorcraft flight envelope. The simulation also incorporated scenarios within the terminal area. Key results from the study included the finding that pilots had higher rates of losses of DWC when flying at low speeds and when operating in the terminal environment. Pilots were also observed overriding ACAS Xr RAs at a relatively high rate. The primary justifications that participants provided for failing to comply with an RA were terrain proximity and the use of level-off RAs in situations where participants determined insufficient separation had been achieved.

The present paper reports on findings from the first flight test performed with ACAS Xr. The testing was conducted under NASA's AAM project, in partnership with Sikorsky and the Defense Advanced Research Projects Agency (DARPA). Referred to as the Integration of Automated Systems flight test series, the activity provided multiple NASA AAM research areas with access to Sikorsky and DARPA's highly-configurable vehicle platforms and advanced automation capabilities. This flight test series included multiple systems under test, with each individual system tested independently. The current paper reports on objective and subjective data collected during the ACAS Xr portion of the test, with a focus on how pilots perceived and responded to ACAS Xr alerting and guidance. Papers and reports that cover additional aspects of the flight test series, such as a Flight Path Management (FPM) tool and pilot workload data have been published separately [12-14].

TABLE I. ACAS XR TEST CARD OVERVIEW

ACAS Configuration	Ownship Speed	Intruder Designation	RA Execution	# of Cards
CAS	90	Nominal	Automated	5
CAS	90	Nominal	Manual	3
CAS	20	Nominal	Manual	4
DAA	90	Nominal	N/A	7
DAA	20	Nominal	N/A	4
DAA	90	Terminal	Automated	3
DAA	90	Terminal	Manual	2
DAA	90	Structured	Automated	4
DAA	90	Structured	Manual	1

II. METHOD

A. *Experimental Design*

The ACAS Xr test points were structured according to four key conditions: ACAS Xr Configuration, Ownship Speed, Intruder Designation, and RA Execution Type. Table 1 provides a breakdown of the 33 test cards flown with ACAS Xr.

1) *ACAS Xr Configuration*

ACAS Xr configuration determines the types of alerting and guidance that are presented to the pilot. The CAS configuration is designed for onboard pilot architectures and the DAA configuration is designed primarily for remotely piloted architectures. The core features of each configuration will be detailed later in this section.

2) *Ownship Speed*

Two different ownship speeds were flown, 90 knots indicated airspeed (IAS) and 20 knots ground speed (GS). The 90 knot encounters were intended to represent the ownship at cruise speed. The 20 knot encounters were included to capture low speed flight profiles that are achievable with rotorcraft.

3) *Intruder Designation*

The DAA configuration allows a user to designate three "types" of intruders: en-route, terminal area, and structured (e.g., high-density, UAM) airspace. The default intruder designation is en-route, which uses the largest alerting and hazard region of the three: 4000 feet horizontally, 450 feet vertically, and 35 seconds of modified Tau (approximately equivalent to closest point of approach [CPA]) [5]. The different hazard regions used by ACAS Xr is shown in Table 2. In addition to the larger alerting region, intruders designated as en-route receive all possible DAA and RA alert types, which differs significantly from the other two intruder designations.

TABLE II. DAA WELL CLEAR (DWC) & NMAC SEPARATION CRITERIA

	Separation Criteria		
Loss of Separation Type	***Horizontal Threshold***	***Vertical Threshold***	***Modified Tau***[a]
En-Route DWC	4000 feet	450 feet	35 seconds
Terminal & Structured DWC	1500 feet	450 feet	N/A
Near Midair Collision	500 feet	100 feet	N/A

[a] Modified Tau (modTau) is approximately equivalent to time to closest point of approach.

The terminal area designation is applied to any aircraft flying within the DAA terminal area (DTA). The DTA region is defined as operating within 4-5 nautical miles laterally and 2000 feet vertically of the departure or arrival runway [5]. The purpose of the terminal area intruder designation is to reduce the likelihood of nuisance alerts while UAS operators are departing or on approach, with a particular emphasis on preventing alerts against aircraft that are flying on the downwind leg of the traffic pattern. The alerting and hazard region for terminal area intruders is 1500 feet horizontally and 450 feet vertically (with no modified Tau). To further reduce the likelihood of nuisance alerts, no caution-level alerting and guidance is issued against terminal area intruders. Lastly, no horizontal maneuver commands are issued against terminal area intruders. This is done to improve operational suitability in the terminal area, where large turns made on final can be highly disruptive to tower controllers and other traffic in the area.

At the time of the flight test, criteria had not been established for when to apply the intruder designation flag for operating within structured airspace. The designation, however, is intended to capture aircraft operating within high-density, cooperative (e.g., UAM) airspace. It uses the same alerting and hazard region as the terminal area designation and also suppresses caution-level alerting and guidance. The only difference between the two designations is the use of horizontal RAs against structured airspace intruders, which may not be subject to the same operational constraints as seen in the terminal area.

4) RA Execution Type

Under default conditions, the ownship aircraft was configured to automatically fly the RA commands issued by ACAS Xr. This was achieved utilizing NASA-developed "middleware" software that was capable of translating RAs into the format required by the ownship's flight computer (i.e., 4D trajectories). The middleware software, known formally as the Expandable Variable Autonomy Architecture (EVAA), ensured that each RA, and subsequent RA update, was sent to the flight computer as a new 4D trajectory [12]. The middleware was designed to meet requirements that stipulated the commands be translated and sent to the flight computer within 1 second and that the 4D trajectories conformed to the aircraft performance assumed by the ACAS Xr logic (i.e., standard rate turns and vertical rates of 500 feet per minute). Upon receipt of a "Clear of Conflict" message from ACAS Xr, the middleware would send a final 4D trajectory to the flight computer that returned the aircraft to straight and level flight. The NASA test pilot was able to disable the auto-RA behavior at any point in the testing by pressing a dedicated button on the ACAS display or by deflecting the inceptors. To re-enable the functionality, the pilot could press the auto-RA button on the display.

While most encounters were flown with the auto-RA behavior enabled, the pilots were instructed to intentionally disable the functionality for two test points in the CAS configuration to ensure a subset of the data captured pilots' manual responses to RAs. Additionally, the auto-RA function was not available during test points that had the ownship flying at 20 knots due to the middleware being functionally out-of-the-loop for those encounters. Only RA maneuvers could be automated. Maneuvers made against caution-level alerting and guidance could only be performed manually.

B. ACAS Xr Configuration Descriptions

The IAS flight test utilized version 3 of the ACAS Xr executable libraries. Version 3 was the most up-to-date version at the time of the test. The executable libraries were made available by the FAA TCAS Program Office.

1) CAS Configuration

Designed to be consistent with the existing TCAS II, ACAS Xr's CAS configuration is designed for use by pilots onboard the aircraft. If ACAS Xr predicts that a nearby aircraft is going to become a collision threat in the CAS configuration, pilots will first see a Traffic Advisory (TA), followed by a Resolution Advisory (RA). The purpose of the TA is to cue the pilot to an imminent RA and to give them time to visually acquire the aircraft. The TA is indicated by a caution-level (i.e., yellow) traffic icon on the traffic display and a "Traffic, Traffic" aural annunciation.

Once a threat does become an RA, the increase in severity is indicated by a warning-level (i.e., red) icon on the traffic display and an aural annunciation that specifies the direction of the commanded maneuver (e.g., "Climb, Climb" or "Turn Right, Turn Right"). There are three general RA types: horizontal RAs, vertical RAs, and blended RAs. Horizontal RAs command a target track, which is indicated on the traffic display by a green "wedge" extending from the ownship to the outer range ring. Red bands on the outer range ring indicate the tracks that must be avoided. Vertical RAs command a target vertical speed, indicated by a green band on the vertical speed tape, with the red band indicating the vertical speeds to be avoided. Concurrent horizontal and vertical RAs are referred to as a blended RA. Figure 1 depicts a blended RA on the traffic display used in the current flight test. Pilots are trained to respond to initial RAs within 5 seconds.

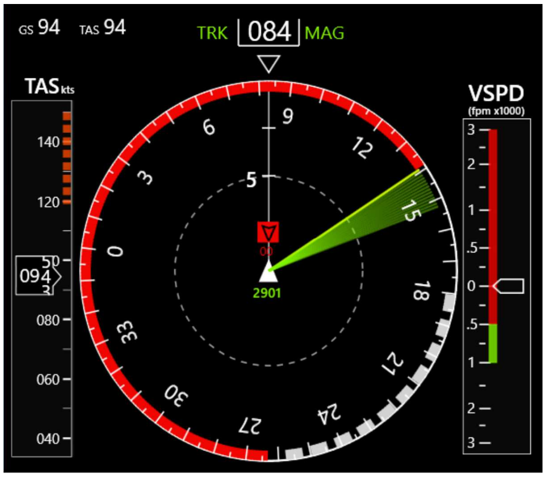

Fig. 1. Flight test traffic display during a blended RA.

2) *DAA Configuration*

The DAA configuration of ACAS Xr is designed to meet the requirements for large UAS DAA systems [5]. In addition to protecting against collision hazards, the DAA configuration also issues alerting against the DWC volume, which varies based on intruder type. There are two dedicated DAA alerts, both of which are caution-level and are only issued against intruders designated as en-route. The Preventive DAA alert is issued when a piece of traffic is more than 450 feet but fewer than 700 feet vertically separated from the ownship . This means the traffic is *outside* of the DWC volume but is close enough to warrant the remote pilot's attention. The Preventive DAA alert is indicated on the display by a hollow yellow traffic icon and a "Traffic, Monitor" aural annunciation. The Corrective DAA alert is issued when a loss of DWC is predicted to occur. When flying under Instrument Flight Rules (IFR), the pilot is required to coordinate their maneuver with ATC. The Corrective DAA alert is indicated by a yellow, filled traffic icon and a "Traffic, Avoid" aural annunciation.

Preventive and Corrective DAA alerts are accompanied by "suggestive" maneuver guidance, which is displayed as yellow arcs on the traffic display's outer range ring and vertical speed tape (see Fig. 2). A loss of DAA well clear can be avoided by ensuring the aircraft's track and/or vertical speed resides outside of the yellow banding region. While the caution-level DAA alerting and guidance was only issued against en-route intruders, RAs were issued against all intruder types in the DAA configuration.

C. *Flight Test Overview*

1) *Vehicles and Equipage*

All flight test encounters included two crewed rotorcraft. A modified S-76B helicopter, referred to as the Sikorsky Autonomous Research Aircraft (SARA), served as the "ownship" for the duration of the flight test. A modified S-70 helicopter, referred to as the Optionally Piloted Vehicle (OPV), served as the intruder aircraft for the duration of the test period. Both aircraft, shown in Fig. 3, hosted Sikorsky's MATRIX™ software package, which can support testing with advanced levels of automation.

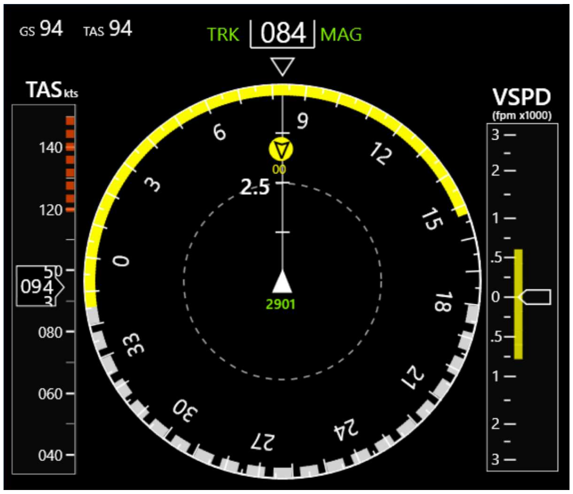

Fig. 2. Flight test traffic display during a Corrective DAA alert.

Fig. 3. Photo of the SARA aircraft (left) and the OPV aircraft (right) flying over Sikorsky Memorial Airport. Credit: NASA.

NASA's middleware software was designed to interface with the MATRIX™ systems via Sikorsky's Autonomy Mission Manager (AMM) software. This primarily took the form of the NASA middleware uploading 4D trajectories from the ground to SARA and OPV's AMM systems for each new test point. The SARA vehicle was also equipped with the ACAS Xr software, ADS-B Out, and an ADS-B receiver. The OPV aircraft was equipped with ADS-B Out but was not equipped with ACAS Xr. ACAS Xr was modified for the current test to allow the use of unvalidated ADS-B data.

2) *NASA Test Pilots*

Each aircraft had one Sikorsky pilot and one NASA test pilot onboard. The Sikorsky pilots served as safety pilots and could take full control of the aircraft at any point. Three NASA test pilots participated in the flight test series. One NASA pilot was assigned to OPV while the other two were assigned to SARA and alternated between sorties. The SARA pilots averaged 10.5 years of experience as NASA test pilots, with an average of 6500 flight hours on fixed-wing aircraft. While only one of the SARA pilots was previously rated to fly helicopters, both pilots received extensive training on the SARA platform and on the systems under test. Several rounds of classroom-based and simulator training ended with both pilots flying representative test points with SARA on the ground, connected to a training simulator. This provided the NASA SARA pilots with the opportunity to use the same inceptors, displays, and voice communications as would be used during flight.

3) *Environment and Protocol*

The Integration of Automated Systems flight test series was operated out of Sikorsky Memorial Airport in Stratford, Connecticut (USA). The current paper reports on flight testing that occurred between October 17-26, 2024. The team performed a variety of build-up flights, which allowed the team to test individual components of the overall system and then to gradually increase the functionality of the NASA test software. All test points were conducted over the Long Island Sound in Class E airspace. Operations were performed under Visual Flight Rules (VFR) and within an altitude block of 1500-3000 feet Mean Sea Level (MSL).

The mission rules and criteria complied with NASA airworthiness and flight test safety review processes, in accordance with NASA Procedure Requirement (NPR) 7900.3D [15]. All pre-scripted conflict trajectories included at least 0.1 nautical mile of separation laterally and 150 feet of separation vertically – or 0.2 nautical miles of lateral separation if co-altitude – to ensure a baseline level of separation absent any pilot corrective action. The SARA pilots were expected to receive ACAS Xr alerting and subsequently begin their avoidance maneuver with at least 1 nautical mile of lateral separation between the aircraft. The OPV aircraft was not equipped with ACAS Xr and so was not expected to make any avoidance maneuvers. A lack of visual contact at 0.75 nautical miles or a lack of increasing separation between the aircraft at 0.25 nautical miles would result in a Knock It Off (KIO), at which point both aircraft would end the test point and reset.

The 33 ACAS Xr test points were flown across 12 total sorties. Each sortie lasted approximately two hours, typically allowing for two sorties per day. NASA test pilots alternated between sorties. To reduce the chances of mode confusion, the test points were blocked – to the extent possible – by ACAS Xr configuration, and within that, by ownship speed.

4) *ACAS Xr Scenarios*

a) CAS Configuration Scenarios

A total of 12 test points were flown using the CAS configuration (see Table 1 above). Eight of those test points were flown with the ownship and intruder both at 90 knots, flying straight and level. The ownship was always established at 3000 feet MSL, with the intruder either co-altitude or separated vertically by ±150 or ±250 feet, depending on the test card. The intruder's approach angle was also varied between test cards (head-on, crossing, or overtake). During these test points, both SARA and OPV flew pre-scripted 4D trajectories. In all but two of these scenarios, the SARA aircraft was expected to auto-execute the RA. The pilot was trained to monitor the progress of the encounter, from the TA through the automated RA response, and intervene if necessary. If they did intervene, they would fly at their discretion, manually, until they cleared the conflict. Once clear, with or without prior pilot intervention, the pilot would coordinate with the test conductor to set up for the next encounter. In the other two encounters flown in the CAS configuration at cruise speed, the NASA test pilot in SARA was told to disable the auto-RA logic prior to the start of the encounter and instead execute the RAs manually.

The remaining four of the twelve CAS configuration test points were flown with the ownship at 20 knots GS and the intruder at 90 knots IAS. Since the middleware could not support 4D trajectories at this speed reliably, SARA and OPV had to fly the low-speed cards entirely manually. This required both aircraft to fly to a designated area over the Long Island Sound, at which point they would coordinate their tracks and altitudes to conform to the test conditions. As with the test points at cruise, the relative altitude and approach angles varied from test point to test point. The manual, dynamic nature of the low-speed test cards resulted in less accurate test setups, and often had to be re-flown in order to generate an acceptable RA. The pilots were instructed to accelerate to at least 40 knots GS while also complying with the guidance commanded by the RA. This instruction was arrived at through discussion with the ACAS Xr development team and may be changed. It should be noted here that the ACAS Xr aural alerts did *not* include an indication that the pilot needed to accelerate. Currently, only aural alerts for the horizontal and vertical RA components are required.

b) DAA-En-Route Configuration Scenarios

A total of 12 test points were flown using ACAS Xr's DAA configuration with the intruder designated as en-route. Seven of those were flown with the ownship and the intruder at 90 knots, flying straight and level. One key difference between the CAS and DAA-En-Route configuration test cards was the introduction of two test cards in this configuration that increased the intruder's altitude offset to 500 feet. This was intended to result in a Preventive DAA alert, rather than a Corrective DAA alert. If issued as expected, this would give the pilots a chance to gauge the utility of the Preventive alert, which is meant to draw the pilot's attention to a piece of traffic that is close in altitude but predicted to remain DAA well clear.

The other test points were intended to result in a Corrective DAA alert, which was expected to prompt a manual avoidance maneuver from the pilot that was consistent with the DAA guidance bands. If successfully flown, the pilot should avoid a loss of DAA well clear and avoid the issuance of an RA. Since pilots in this test were operating under VFR, no coordination with ATC was required. Any RAs that were issued would still have to be followed, either automatically (if the auto-RA mode had not been disengaged) or manually (if the auto-RA mode had been disengaged).

As with the CAS configuration, four of the test points in the DAA-En-Route configuration were flown with the ownship flying 20 knots GS and the intruder flying 90 knots IAS. The same procedures were used to fly the low-speed test points as were performed in the CAS configuration. Pilots were expected to respond to the Corrective DAA alerts by manually accelerating and following the maneuver guidance bands to avoid a loss of DWC and RA.

c) DAA-Terminal Configuration Scenarios

Five test points were flown in the DAA configuration with the OPV designated as flying within terminal airspace. This designation was flagged manually – neither SARA nor OPV were in truth operating within a terminal area. To mimic terminal area-type operations, SARA was in descent in three of the five test points (to approximate an approach) and in a climb in the other two (to approximate a departure). These test points were included to collect pilot feedback on the reduced alerting threshold and simplified alert schema designed for terminal area operations. All DAA-Terminal test points were flown at cruise speeds. Three of the five DAA-Terminal cards were flown with auto-RA mode enabled. Pilots disabled auto-RA mode at the start of the encounter in the remaining two.

d) DAA-Structured Configuration Scenarios

Five test points were flown in the DAA configuration with OPV designated as flying within structured airspace. As with the DAA-Terminal cards, this designation was done manually. To deviate from the DAA-Terminal test points, SARA remained level in all of the DAA-Structured cards. Instead, the intruder was in a climb or descent in three of the five cards. The DAA-Structured test cards were designed to solicit feedback from pilots on the smaller alerting threshold and simplified alert schema. All DAA-Structured test points were flown at cruise speeds, with four cards flown with auto-RA enabled and a single card flown with auto-RA disabled.

D. Reported Metrics

1) Objective Measures

Researchers utilized three data sources – ACAS Xr output logs, NASA middleware logs, and screen recordings of the traffic display – to extract the following objective metrics.

a) Alert Types

A count of the types of alerts that were generated over the course of the flight test series. Includes Preventive DAA and Corrective DAA alerts (DAA-En-Route configuration only), TAs (CAS configuration only), vertical RAs (all configurations), and horizontal-only and blended RAs (all configurations except DAA-Terminal).

b) RA Non-Compliance Rate

The rate at which pilots decided to not fully comply with an ACAS Xr RA (e.g., pilot stopped following an RA before it was cleared, pilot flew in the opposite sense or direction of what was commanded).

c) Pilot Response Times

Response times were captured in all cases where pilots manually responded to a DAA Corrective alert or an RA. It includes the time elapsed from the onset of a given alert type to the initiation of a corresponding horizontal or vertical maneuver. During low-speed test points, the time at which the ownship began to accelerate was also captured.

d) Maneuver Sizes

The average change in altitude (in feet) or track (in degrees) observed during maneuvers made in response to a Corrective DAA alert or an RA.

e) Miss Distances

The average CPA between the ownship and intruder aircraft. Any instances where the CPA fell within the established DWC thresholds or the near midair collision (NMAC) boundary (see Table 2) will be noted.

2) Subjective Feedback

Researchers collected structured and unstructured feedback from the NASA test pilots over the course of the flight test. This included post-encounter and post-sortie questionnaires, as well as comments made by the pilots while in flight or during mission debriefs. Key comments pertaining to each configuration will be reported.

III. RESULTS

The IAS flight test included 33 ACAS Xr test points. One test point had to be dropped due to an improperly flown SARA route during a low-speed CAS encounter. The remaining cards were completed successfully but were unevenly distributed between the two different NASA test pilots assigned to SARA. One of the NASA pilots participated in 22 of the cards, with the second pilot participating in 11. Descriptive, rather than inferential, statistics are provided due to the small number of test points within each configuration and condition pair.

A. Objective Metrics

1) Alert Types

As shown in Table 3, all alert types were generated over the course of the flight test. Pilots in the CAS configuration experienced 11 total RAs (out of 11 possible), with horizontal-only RAs only occurring in low-speed cards. In the DAA-En-Route configuration, pilots saw 2 Preventive DAA alerts (out of 2 expected) and 11 Corrective DAA alerts (out of 9 expected). The two unexpected Corrective DAA alerts occurred during the test cards that were developed specifically to exercise the Preventive DAA alert. During those runs, the intruder initially triggered the Preventive DAA alert but eventually generated a Corrective DAA alert. Also of note was the occurrence of a blended RA in the DAA-En-Route configuration during one low speed encounter. In all other DAA-En-Route encounters, pilots were able to avoid RAs by maneuvering during the Corrective DAA alert.

As expected, all 5 RAs in the DAA-Terminal configuration were vertical, while vertical and blended RAs were observed in the DAA-Structured configuration.

2) RA Non-Compliance Rate

Pilots were observed to comply with all RAs issued as part of this testing, resulting on a non-compliance rate of 0.

3) Response Times

a) CAS Configuration

Pilots took, on average, 2 seconds (*SD* = 0; *n* = 2) to manually respond to initial RAs in the CAS configuration while flying in cruise (see Fig. 4). In the low-speed test points, pilots took an average of 6.67 seconds (*SD* = 3.51; *n* = 3) to begin their RA response. Pilots required a similar amount of time, an average of 7 seconds (*SD* = 4.36; *n* = 3), to begin to accelerate in response to RAs in the CAS configuration while operating at a low speed.

TABLE III. COUNT OF ALERT TYPES BY CONFIGURATION

	CAS		**DAA-En-Route**		**DAA-Term.**	**DAA-Struct.**
Alert Type	***Cruise***	***Low-Speed***	***Cruise***	***Low-Speed***	***Cruise***	***Cruise***
Preventive DAA	N/A	N/A	2	0	N/A	N/A
Corrective DAA	N/A	N/A	7	4	N/A	N/A
Traffic Advisory	6	2	N/A	N/A	N/A	N/A
Vertical-only RA	4	3	0	0	5	2
Horizontal-only RA	0	0	0	0	N/A	0
Blended RA	4	0	0	1	N/A	3

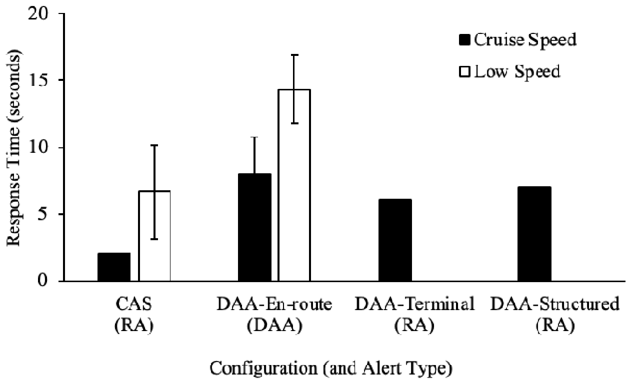

Fig. 4. Average response times (and standard deviations) to RA and Corrective DAA alerts across configuration and speed condition.

b) DAA-En-Route Configuration

Pilots spent, on average, 8 seconds (*SD* = 2.77; *n* = 7) responding to Corrective DAA alerts while in cruise (see Fig. 4). In low-speed encounters, pilots spent an average of 14.33 seconds (*SD* = 2.52; *n* = 3) beginning their maneuver and an average of 19.33 seconds (*SD* = 7.23; *n* = 3) initiating their acceleration.

c) DAA-Terminal Configuration

Pilots spent an average of 6 seconds (*SD* = 0; *n* = 2) responding to RAs in the DAA-Terminal configuration.

d) DAA-Structured Configuration

The NASA test pilot spent 7 seconds (*n* = 1) manually responding to an RA in the DAA-Structured configuration.

4) Maneuver Sizes

The average size (and *SD*) of the altitude and track changes made by the pilots across each configuration are shown in Table 4. The maneuvers were made in response to RAs in the CAS, DAA-Terminal, and DAA-Structured configurations, whereas the maneuvers were in response to the Corrective DAA alert in the DAA-En-route configuration.

5) Miss Distances

The average horizontal miss distances (HMD; in nautical miles) and average vertical miss distances (VMD; in feet) are shown (with *SD*) in Table 5. There were zero NMACs in the flight test. There were zero en-route losses of DAA Well Clear observed during the cruise cards in the DAA-En-Route configuration. There was a single loss of en-route DWC observed during a low-speed DAA-En-Route test point. In that instance, the intruder was in an overtake geometry and the pilot inadvertently climbed into the intruder before correcting the mistake and beginning a descent.

TABLE IV. AVERAGE ALTITUDE AND TRACK CHANGE SIZES (AND STANDARD DEVIATIONS) BY CONFIGURATION

	CAS		**DAA-En-route**		**DAA-Term.**	**DAA-Struct.**
Deviation Type	***Cruise***	***Low-Speed***	***Cruise***	***Low-Speed***	***Cruise***	***Cruise***
Altitude (ft)	304 (±85)	N/A	104 (±105)	98 (±125)	208 (±200)	250 (±125)
Track (°)	80 (±38)	95 (±31)	29 (±15)	46 (±25)	N/A	28 (±20)

TABLE V. AVERAGE MISS DISTANCES (AND STANDARD DEVIATIONS) BY CONFIGURATION

	CAS		**DAA-En-route**		**DAA-Term.**	**DAA-Struct.**
Dimension	***Cruise***	***Low-Speed***	***Cruise***	***Low-Speed***	***Cruise***	***Cruise***
HMD (nm)	0.5 (±0.46)	1.1 (±0.04)	1.8 (±0.86)	1.3 (±0.67)	0.09 (±0.04)	0.09 (±0.03)
VMD (ft)	438 (±155)	222 (±5.8)	389 (±225)	377 (±246)	567 (±72)	671 (±188)

The horizontal miss distances in the DAA-Terminal and DAA-Structured configurations were drastically reduced compared to all other configurations, averaging 0.09 nautical miles of lateral separation (approximately 500 feet). The vertical miss distances in these configurations, however, remained above 500 feet, on average, avoiding any instances where a loss of terminal-area DWC was flagged. However, a KIO was called by the test conductor during a DAA-Structured test point. The KIO occurred during a head-on encounter with the intruder descending into the ownship. ACAS Xr initially commanded a descent (which the pilot complied with) but then commanded a level off while the intruder was still descending into SARA's altitude.

B. Subjective Feedback

1) CAS Configuration

During the test cards spent in cruise, the pilots' comments were largely positive regarding the automated RA functionality. They reported no cases of the auto-RA behavior lagging or incorrectly translating an ACAS Xr command. However, there was one case where the automation failed to stop turning when a horizontal RA was removed from a blended RA. The pilot caught this in real time and reported the issue over the radio.

The pilots pointed to three encounters in the cruise portion of the CAS configuration test cards where they interpreted the ACAS Xr guidance as inappropriate. In one case, an especially large right turn was commanded by ACAS Xr, which resulted in a total track change of 122°. This occurred in a crossing encounter, with the intruder co-altitude with the ownship. The RA started with a climb and the right turn was added to the maneuver to create a blended RA. The vertical RA component was quickly removed, while the right turn lasted an additional 30 seconds, with the ownship commanded to fly in the same direction as the intruder.

The other two encounters flagged by the pilots as unacceptable started with a climb RA only to switch after a few seconds to a level off RA. Several seconds later, the RA commands switched again to a climb RA. The pilots commented, in both encounters, that insufficient separation had been achieved to warrant a weakening of the vertical RA from an active climb to a level off. They also commented that frequently alternating between the two maneuver types left them with the impression that ACAS Xr was unreliable.

The final key piece of feedback we received from pilots in the CAS configuration occurred during the low-speed test cards. Both pilots commented that a dedicated aural alert that cued pilots to accelerate – such as "Accelerate and.." at the start of the annunciation - would have been advantageous.

2) *DAA-En-Route Configuration*

Pilots in the DAA-En-Route configuration felt strongly that the Corrective DAA alert and associated suggestive maneuver guidance was a valuable addition onboard the aircraft. The NASA pilots commented that the DAA guidance increased their general awareness of the airspace and resulted in greater confidence in their maneuver decisions.

Despite the general improvement experienced with the DAA-En-Route configuration, the pilots noted that the maneuver guidance bands had a tendency to "follow" the ownship's track on the traffic display as they turned. The guidance bands would then recede once the ownship stopped its turn. The pilots reported that this was generally frustrating and reduced their trust in ACAS Xr. They also reported that it led to larger horizontal maneuvers than they would have otherwise made.

3) *DAA-Terminal and -Structured Configurations*

Pilots offered minimal comments regarding the DAA-Terminal and DAA-Structured configuration test points. This is in large part due to the test conditions not truly reflecting terminal area or structured/dense airspace operations. As a result, pilots found it difficult to remark on the appropriateness of the terminal and structured airspace alerting schema.

Pilots did, however, notice the smaller alerting region applied against the terminal and structured airspace-designated intruders. Pilots commented that the delayed RA timing removed any buffer they had in executing their response. The pilots argued that, without that buffer, a slight delay in their response, or an improper initial response, could lead to more severe losses of separation than were observed in the flight test.

IV. DISCUSSION

For this flight test effort, NASA test pilots flew onboard the Sikorsky Autonomous Research Aircraft. SARA was equipped with ACAS Xr and an associated traffic display, and completed 33 scripted traffic encounters against a live, ADS-B equipped intruder. Variables included ACAS Xr Configuration, Ownship Speed, Intruder Designation, and RA Execution Type. This paper reported on the types of alerts generated over the course of the flight test, RA non-compliance rates, response times, maneuver sizes, miss distances, and key comments made by the pilots.

A. CAS Configuration

Pilots successfully completed a total of eight RA encounters at cruise speed, and a total of three RA encounters at low speed, while flying with the CAS configuration. Unlike previous simulations by the authors, the pilots were found to comply with all RAs issued in the CAS configuration. The stark difference – 0% presently compared to a maximum non-compliance rate of 40% in [10] – can be explained, in part, by the lack of low-altitude test points in the current flight test. Proximity to terrain was the most common cause of non-compliance in the previous study. Low-altitude flights could not be accommodated in the current flight test given a minimum mission altitude of 1500 feet MSL. As a result, terrain proximity could not become a factor. It is noteworthy, however, that pilots did not decide to override the RA in the small number of cases where pilots reported the guidance as being unacceptable (i.e., an encounter with an excessively large turn and two encounters where the RA rapidly switched between climb and level-off RAs). In all three cases, it is possible that safety never degraded to the point where the NASA pilots in SARA found it necessary to intervene. The large right turn, while inefficient, did eventually command a turn large enough to ensure that the two aircraft were gaining separation. Likewise, the fluctuating vertical RA cases were considered unacceptable while the level-off RA was briefly commanded, but in both cases, it was quickly followed by a climb RA, which the pilots ultimately agreed was appropriate. The formal nature of a flight test environment may have also contributed to the lack of non-compliance with RAs. While their training and the flight test mission rules stipulated that pilots could override ACAS Xr guidance if deemed necessary, their awareness of the test conditions, and having the intruder in sight, may have made them more comfortable with allowing ACAS Xr guidance to play out over time.

The middleware consistently met its requirements to translate the ACAS Xr RAs into 4D trajectories within 1 second and conforming to nominal aircraft performance during test cards that utilized the auto-RA functionality. There was one case where pilots noticed the middleware failed to stop a turn once a horizontal RA was cleared. A fix for this specific issue was quickly identified. No other cases were observed where the automation failed to accurately translate an RA. The two cruise speed test cards that called for a manual RA response showed an average response time of 2 seconds to the initial RA, which is well within the 5-second response time assumption utilized by TCAS II and the different ACAS X variants. Average response times slightly exceeded the 5-second assumption, however, when pilots were responding to RAs at low speeds. In those cases, pilots averaged approximately 7 seconds to respond to RAs (i.e., to start their turn) and 7 seconds to begin to accelerate. The slower response times reflect the greater level of workload the pilots were under in the low-speed cards. As opposed to the cards flown at cruise speed, the pilots had to manually fly the setup to the encounter, which required real-time coordination over the radio with the pilots in the intruder aircraft. This increased workload, and the lack of an aural alert that indicated a need to accelerate, resulted in pilots struggling to prioritize how they should respond to the RA. While more data is certainly needed, the findings here suggest that an aural alert to "accelerate," appended to the other elements of the RA aural alert (e.g., "Accelerate and Turn Right"), could help clarify the required response during a critical phase of flight, where consistently slow response times could be especially problematic.

Vertical RAs were found to result in average altitude deviations of approximately 300 feet, while horizontal RAs were found to result in an average track change of 80° in cruise and 95° at low speeds. The maximum track changes, however, were 122° in cruise and 131° at low speeds. Large track changes have been seen in previous simulations and have been frequently identified by pilots as an area needing improvement. The excessive turn cases typically arise during crossing encounters, where a horizontal RA results in the pilot turning with the intruding aircraft.

The RAs issued in the CAS configuration were found to consistently ensure a minimum of 500 feet of vertical separation in cases where a vertical RA was issued and at least 0.66 nautical miles (4000 feet) of lateral separation when a horizontal RA was issued. Pilots reported no issues with the size of the miss distances achieved in the CAS configuration.

B. *DAA-En-Route Configuration*

Pilots in the DAA-En-Route configuration experienced a total of 2 Preventive DAA alerts and 7 Corrective DAA alerts during the test cards flown at cruise speed and 4 Corrective DAA alerts and 1 blended RA during the cards flown at low speed. At cruise, pilots were always able to avoid the issuance of an RA by responding, on average, 8 seconds after the Corrective DAA alert was issued. This is approximately half as long as remote pilots were found to take, on average, when responding to Corrective DAA alerts in previous simulations with ACAS Xu [8]. The faster times here can be explained by a lack of ATC coordination and the use of inceptors for their response (earlier studies relied on mouse and keyboard inputs). The NASA test pilots executed maneuvers that were consistent with the suggestive maneuver guidance and, as a result, they never lost DAA well clear. During the low-speed cards, pilots started their turn, climb, and/or descent an average of 14 seconds after the Corrective DAA alert had been issued, and started to accelerate an average of 19 seconds after the alert. Both response times are consistent with the amount of time remote pilots typically spend when responding to a Corrective DAA alert.

There was one encounter in the DAA-En-Route configuration where the pilot failed to respond to the Corrective DAA alert entirely. Occurring during a low-speed test point, the pilot commented that the high level of workload required to manually set up the encounter caused him to miss the Corrective DAA aural alert. As a result, the pilot was not sure how to proceed and decided to wait until the RA was issued to take action. When the RA was eventually issued, the pilot quickly complied with the guidance. Surprisingly, there was a single loss of DAA well clear recorded during the DAA-En-Route configuration test points, and it did not occur in the case where the pilot failed to respond to the Corrective DAA alert. Instead, the loss of DAA well clear occurred when the pilot temporarily climbed into the intruder's altitude (before ultimately correcting their mistake). Previous research with ACAS Xr has shown that quickly responding to an RA can result in pilots avoiding losses of DAA well clear, in addition to avoiding NMACs [10-11].

Pilots were found to make smaller deviations in the DAA-En-Route configuration, compared to the CAS configuration. The average change in altitude was 104 feet while in cruise and 98 feet while at low speed. The average change in track was 29° while in cruise and 46° in the low-speed cards. The smaller deviations demonstrate the expected benefit of maneuvering earlier in an encounter's progression. Pilots were observed to maneuver in both axes in 10 out of 11 encounters in the DAA-En-Route configuration, revealing a preference to gain separation in both dimensions when given the choice.

Pilots were found to achieve 1.3-1.8 nautical miles of horizontal separation and approximately 400 feet of vertical separation. Since pilots overwhelming maneuvered in two axes in the DAA-En-Route configuration, they did not typically require 450 feet of vertical separation in order to remain DAA well clear.

Pilot feedback was particularly strong regarding the Corrective DAA alert and corresponding maneuver guidance. The NASA test pilots that participated in the flight test had previously seen the Corrective DAA alert and guidance in a simulation setting. At the conclusion of the flight test, the pilots commented that it was not until they were flying with the system onboard SARA that they appreciated the ability to cross-check their desired maneuver with what was depicted on the DAA display. As a result, they reported that they were much more comfortable making their maneuvers than they would have been without the ACAS Xr traffic display on board. The pilots did note a distracting tendency of the maneuver guidance bands to maneuver along with the ownship as they turned. This resulted in larger maneuvers than may have otherwise been performed. Pilots argued that it also reduced their trust in the system. In discussions with ACAS Xr developers, and other experts in DAA systems, this behavior may be unavoidable. Regardless, this behavior should be mitigated to the extent possible, given the indication that it reduced pilot trust in the information being provided by the DAA system.

Two encounters were designed to exercise the Preventive DAA alert, which is designed primarily for cases where a VFR intruder is 500 feet above or below ownship and level. The alert is therefore not intended to prompt a maneuver from the pilot but to instead cue the pilot to a nearby piece of traffic that could potentially become a legitimate DAA well clear threat. Both Preventive DAA alerts in the current flight test eventually triggered a Corrective DAA alert. In one case the switch to a Corrective DAA alert occurred very close to CPA (0.7 nautical miles) and in the other it occurred almost immediately after the Preventive DAA alert had been issued (3 nautical miles). The IFR-VFR vertical separation minima (500 feet) and the vertical threshold used for the Corrective DAA alert (450 feet) differ by only 50 feet. The fact that both Preventive DAA alerts failed to remain at their original, expected threat level caused the pilots to doubt its reliability and purpose.

C. *DAA-Terminal and -Structured Configurations*

Pilots experienced 5 vertical-only RAs in the terminal area test cards and 2 horizontal-only RAs and 3 blended RAs in the structured airspace test cards. As reported in the CAS configuration, there were no instances of the pilots failing to comply with an RA in the DAA-Terminal or DAA-Structured test cards. This deviated from a previous simulation, where pilots were found to disregard level-off RAs issued while the ownship was on approach, preferring instead to climb [10]. Surprisingly, no level-off RAs were issued while the ownship was on "approach" (i.e., in a descent) in the current flight test. Instead, only climb and descend RAs were issued against terminal area-designated intruders, which the pilots were comfortable following.

Pilot response times averaged 6 seconds and 7 seconds in the DAA-Terminal and DAA-Structured configurations, respectively. Pilots' maneuver sizes were considerably smaller in these configurations. In the DAA-Terminal configuration, the average change in altitude was 200 feet, with the average change in altitude only slightly larger - 240 feet – in the DAA-Structured configuration. Matching this trend, the average change in track was only 28° in the DAA-Structured test condition (no horizontal RAs were issued in the DAA-Terminal condition). The smaller deviation sizes reflect the reduced alerting region applied to terminal area and structured airspace-designated intruders. While no terminal area or structured airspace losses of DAA well clear were recorded, the pilots did note that they perceived the onset of the RAs as late. RAs were issued with approximately 1 nautical mile of lateral separation with the intruder. Pilots argued that this left them with no room for error, which is reflected in the minimum average horizontal miss distance of 0.09 nautical miles (~550 feet) observed in both the DAA-Terminal and DAA-Structured test points. Losses of terminal area DAA well clear were avoided due to the aircraft never coming within 450 feet vertically of one another. The lack of any losses of DAA well clear suggests that the system worked as intended, but the pilots warned that operating with such small margins is inherently risky and that the level of performance seen in a controlled flight test is likely going to be better than what can be expected in real-world operations.

V. CONCLUSION

The NASA AAM project's Integration of Automated Systems flight test series was a successful demonstration of multiple organizations – NASA, Sikorsky, and DARPA – coordinating on a series of challenging research activities involving multiple systems under test. The portion of IAS that utilized ACAS Xr highlighted the utility of flight testing software that is still under development. A variety of software bugs were identified as part of the integration process (which have since been addressed) and the key findings of the flight test have been shared with the ACAS Xr team and the broader DAA community in an effort to improve the robustness and pilot-acceptability of this vital piece of software. While the authors feel the data collected as part of this flight test have been valuable, much more simulation and flight test data are needed to fully validate ACAS Xr. The current flight test series did not incorporate non-cooperative sensors and did not test the terminal-area logic in an actual terminal environment. Low-altitude flight profiles and the integration of terrain and obstacle information were also out of scope of this flight test series. These areas, and more, warrant thorough study.

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