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UAS Integration in the NAS Flight Test 6: Full Mission Results

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Table of Contents

List of Figures

List of Tables

Acronym List

ADS-B	Automatic Dependent Surveillance-Broadcast
AFRC	NASA Armstrong Flight Research Center
ARC	NASA Ames Research Center
ATC	Air Traffic Control
DAA	Detect-and-Avoid
DAIDALUS	Detect-and-Avoid Logic for Unmanned Systems
DoD	Department of Defense
DWC	DAA Well-Clear
FOR	Field of Regard
FT6	Flight Test 6
h*	Height Threshold for DAA Well-Clear Definition
HITL	Human-in-the-Loop
hmd*	Horizontal distance threshold for DAA Well-Clear Definition
kts	Knots
LoDWC	Loss of Well-Clear
LVC-DE	Live-Virtual-Constructed Distributed Environment
M	Mean
MIR	Maneuver Initiation Range
MOC	NASC Mobile Operations Center
MOF5	NASA Mobile Operations Facility 5
MOPS	Minimum Operational Performance Standards
MSL	Mean Sea Level Altitude
N	Number of Subjects
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NASA TLX	National Aeronautics and Space Administration Task Load Index
NASC	Navmar Applied Sciences Corporation
NMAC	Near Mid-Air Collision
nmi	Nautical Miles
RADAR	Radio Detection and Ranging
RDR	RADAR Declaration Range
RGCS	Research Ground Control Station
RT	Reaction Time
SC-228	RTCA Inc. Special Committee 228
SD	Standard Deviation
SPUT	Subject Pilot Under Test
SWaP	Size, Weight, and Power
TCAS	Traffic Collision Avoidance System
*t*LoDWC	Time to Loss of Well-Clear

t_{mod}*	Time Threshold of the DAA Well-Clear Definition
VSCS	Vigilant Spirit Control Station
WAAS	Wide Area Augmentation System

Abstract

Recent standards development efforts for the integration of Unmanned Aircraft Systems (UAS) into the National Airspace System (NAS), such as those in RTCA Inc. Special Committee 228 (SC-228), have focused on relatively large UAS transitioning to and from Class A airspace. To expand the range of vehicle classes that can access the NAS, the NASA UAS Integration in the NAS project has investigated Low Size, Weight, and Power (Low SWaP) technologies that would allow smaller UAS to detect-and-avoid (DAA) traffic. Through batch and human in the loop (HITL) simulation studies, the UAS Integration in the NAS DAA subproject has identified candidate performance standards that would contribute to enabling extended Low SWaP, UAS operations under 10,000 feet. These candidate performance standards include minimum field of regard (FOR) values for Low SWaP air surveillance sensors as well as a DAA well-clear (DWC) definition which can be applied to non-cooperative traffic to reduce the required maneuver initiation range.

To test the assumptions of the project's simulation studies and validate the candidate performance standards, a live flight research event was executed at NASA Armstrong Flight Research Center. The UAS Integration in the NAS Project Flight Test 6 Full Mission sought to characterize UAS pilot responses to traffic conflicts using a representative Low SWAP DAA system in an operational NAS environment. To achieve this live, virtual and constructive distributed environment (LVC-DE), elements were combined to simulate a sector of Oakland center airspace and induce encounters with a live, manned aircraft. A NAVMAR Applied Sciences Tigershark XP was used as the UAS ownship and was integrated into the test architecture to enable it to be controlled from a Vigilant Spirit Control Station (VSCS) research ground control station. Qualified UAS pilots were recruited to act as subject pilots under test (SPUT) to control the Tigershark XP in a simulated mission while coordinating with a participating air traffic controller in simulated airspace. The intruder speed, intruder equipage and encounter geometry were varied between six scripted encounters per SPUT. Various metrics were collected including pilot reaction time from the onset of DAA alert, ATC coordination rate, probability and severity of losses of DAA well clear, and subjective ratings of system acceptability.

Flight Test 6 Full Mission was successfully executed in October and November 2019. Results indicated that the subject pilots completed the simulated missions with zero losses of well-clear and generally low workload ratings, although avoidance maneuvers were larger and reaction times were longer than was found in HITL lab studies. In the post-flight subjective questionnaire, subject pilots indicated that the sensor FOR would not allow coordination with ATC and would have preferred a longer sensor range if flying in the NAS. The implications of these results on the development of standards for Low SWAP DAA systems will be discussed.

1. Introduction

As demand for allowing routine access for Unmanned Aircraft Systems (UAS) to the National Airspace System (NAS) increases, so too does the demand for diversifying the range of vehicles and operations. Previous research efforts of the RTCA Inc. Special Committee 228 (SC-228) and the NASA UAS Integration in the NAS project focused on developing performance standards for large and relatively capable unmanned vehicle operations which transition between the terminal area and Class A airspace. [1] This effort resulted in Minimum Operational Performance Standards (MOPS) for UAS Detect-and-Avoid (DAA) Systems and Air-to-Air RADAR for Traffic Surveillance. [2] These MOPS, however, excluded smaller, less-capable vehicles conducting extended operations in airspace with both transponder equipped (i.e., cooperative) traffic and non-transponder equipped (i.e., non-cooperative) traffic; similar to that which would be found in Class E airspace below 10,000 feet.

One of the primary limiting factors for smaller size UAS to operate in this environment is their ability to be equipped with sensors capable of detecting non-cooperative traffic at distances that allow a human UAS operator to maneuver to remain well-clear. DAA systems integrated onboard smaller, less capable UAS are generally expected to have a reduced level of performance in comparison to more capable vehicles. However they will still be required comply with existing federal aviation regulations that require aircraft to remain well-clear of other aircraft and maintain safe separation from other vehicles in the airspace. [3] Sensor performance will likely be limited by the available electrical power, the payload carrying capacity and the aerodynamic sensitivity of the vehicle; with declaration range, field of regard, and accuracy being the performance metrics impacted by these limitations. To address these concerns, the NASA UAS Integration in the NAS DAA subproject performed a series of studies to determine requirements for smaller UAS and Low Size, Weight and Power (Low SWaP) sensors and DAA systems.

Sensor declaration range is especially crucial in enabling DAA for UAS, as it increases the time available for a human operator to either contact Air Traffic Control (ATC) or command an avoidance maneuver before safe separation is lost between a UAS and another aircraft One method to reduce the minimum maneuver initiation range (MIR) and by extension, the minimum required sensor declaration range, is to limit the speed envelope and to maximize the turn rate of the UAS. A combination of limiting the speed of the UAS to under 75 knots (kts) and increasing the turn rate of the UAS to seven degrees-per-second or greater may significantly reduce the minimum MIR for UAS using the Phase 1 DAA MOPS well-clear definition. [4] Additional reductions in minimum required sensor declaration range may be accomplished by defining a DAA well-clear definition specifically for non-transponder equipped, or non-cooperative aircraft in the NAS. Reducing the size of the DAA well-clear (DWC) definition for non-cooperative aircraft is possible because of the lack of the need to interoperate with the existing Traffic Collision Avoidance System (TCAS) onboard many cooperative aircraft. A fast-time airspace simulation identified two potential non-cooperative well-clear definitions which minimized the probability of a near mid-air collision (NMAC) given a loss of well-clear and minimized the MIR needed to avoid a loss of well-clear. Both DWC definitions were found to have been suitable for vehicles with the performance of a Low SWaP UAS, however the study did not include a pilot model. [5]

To evaluate this well-clear definition with a live human operator, a human-in-the-loop (HITL) simulation study was conducted which compared the two candidate DWC definitions in a realistic Low SWaP UAS mission scenario. [6] The first candidate DWC definition was comprised of a horizontal miss distance threshold (hmd*) of 2200 feet (ft), a vertical height threshold (h*) of 450 ft, and a modified tau threshold[1] (τmod*) of 0 seconds. The second DWC definition candidate had a hmd* of 2000 ft and a τmod* of 15 seconds. Pilot performance in reaction time (RT) and ability to remain well-clear between the DWC candidates were similar, however the DWC candidate without the τmod* component produced longer caution-level corrective alerts and allowed the UAS operators to notify ATC before their maneuver in more cases than the candidate with the τmod* component. Allowing a UAS operator to notify ATC prior to a maneuver could avoid traffic disruptions and reduce the risk of further losses of separation between aircraft, as it would direct the controller's attention to the situation sooner.

[1] Modified tau (τmod) is the time function of the DAA well-clear definition and is defined as the time to penetration of the horizontal and vertical distance thresholds.

Of note from this study was the relatively low number of losses of well-clear, which suggested that the selected sensor declaration range of 3.5 nmi provided ample time for the UAS operators to maneuver to remain well-clear was significantly higher than the minimum safe value. A repeat study was conducted using the 2200 ft DWC definition to investigate the sensor declaration range at which UAS operators' remain-well-clear performance degrades. [6, 7] Determining which sensor declaration ranges induce more losses of well-clear and NMAC incursions would help identify a potential minimum sensor declaration range. Sensor declaration ranges of 3.0, 2.5, 2.0, and 1.5 nmi were tested with UAS operators in a simulated mission identical to one of the scenarios used in the previous encounter. The results indicated that the 1.5 and 2.0 nmi surveillance declaration ranges rarely allowed for corrective level alerts to be presented during an encounter with a non-cooperative aircraft and never allowed enough time for a UAS operator to respond to a corrective alert before progressing to a warning alert. In some cases, these declaration ranges did not allow for a full warning alert timeline. Declaration ranges of 2.5 and 3.0 nmi almost always provided for a full warning alert timeline, however short duration corrective alerts were still common. The rate of losses of well-clear and NMAC incursions increased dramatically for the 2.0 and 1.5 nmi surveillance declaration range conditions compared to the 2.5 and 3.0 nmi conditions. This suggests that it would be difficult to coordinate a DAA maneuver with ATC with a DAA system with declaration ranges of 2.0 nmi or less. Additionally, it appears that the risk of losing well-clear and having an NMAC incursion may increase at declaration ranges below 2.5 nmi.

While simulation studies provided candidate minimum aircraft performance characteristics, DAA well-clear definitions for non-cooperative aircraft, and sensor declaration range limits, the question remains of how a UAS integrated with a candidate DAA system would perform in the NAS. Several real-world factors may impact the performance of the human-machine system that were not present in the simulation studies. The simulation studies used a simplified vehicle model which assumed an instantaneous turn rate. However, because most fixed wing aircraft must first roll about its longitudinal axis before a change in heading is achieved, potentially resulting in lower separation between aircraft during DAA maneuvers. Furthermore, subjects in a HITL simulation usually know that they are participating in a simulation as opposed to a real-world scenario, which may encourage subjects to make riskier maneuver decisions in simulation than they would in the NAS. Finally, weather conditions such as changing winds or turbulence that can affect vehicle performance are difficult to realistically simulate. To provide validation of the minimum requirements elicited from simulation studies, the NASA UAS Integration in the NAS project conducted a flight test with a Department of Defense (DoD) group 3 category UAS with a prototype low SWaP DAA system in a mixed live-virtual-constructive simulation of the NAS.

2. **Test Architecture**

The following section will detail the apparatus used in the execution of FT6 Full Mission including the aircraft, DAA system, and the software which enabled a shared live and virtual environment. The aircraft section outlines the capabilities, performance and modifications made to the NASC Tigershark XP aircraft as well as the manned intruder aircraft. The DAA system section outlines the DWC definition sizes used for cooperative and non-cooperative aircraft, the method used to emulate a non-cooperative surveillance system and the workstation where the subject pilots interacted with the DAA system. The Live-Virtual-Constructive Distributed Environment (LVC-DE) section explains the LVC-DE concept and the systems which were used to generate the NAS simulation.

2.1 Aircraft

The NAVMAR Applied Sciences Corporation (NASC) Tigershark XP UAS was selected as the ownship vehicle for FT6. The Tigershark XP is a DoD Group 3 UAS with a maximum airspeed of 80 knots, and maximum operating altitude of greater than 14,000 ft MSL. The Tigershark XP is also capable of carrying an 80 lb. payload with 900 Watts of electrical power. The vehicle used for FT6 was modified to carry a Low SWaP DAA system which included a nose structure to house a 3 panel RADAR system developed by

Honeywell. Other modifications to the Tigershark XP included a payload tray to house an ADS-B In and Out system, and an exhaust injection smoke generating system for visual identification. Figure 1 shows the Tigershark XP with the FT6 modifications.

Figure 1 The NAVMAR Applied Sciences Corporation (NASC) Tigershark XP UAS

The Tigershark XP was controlled by the Piccolo Ground Control Station software located within the NASC Mobile Operations Center (MOC) for launch and recovery phases of flight, before control was transferred to the NASA Mobile Operations Facility 5 (MOF5) for the data collection phases of flight. During the Full Mission phase of the flight test the Tigershark XP was controlled by a subject pilot under test from the Vigilant Spirit Control Station (VSCS) while being monitored by a NASA safety pilot which had the capability to take control of the vehicle in the event of an off nominal situation.

A NASA Armstrong Beechcraft T-34C Mentor was used as the live, manned intruder for FT6. The T-34C was flown by a pilot and an observer to aid in maintaining visual contact with the Tigershark and any other nearby traffic. The T-34C equipped with an ADS-B In/Out system and a Stratus 3 ADS-B In system which aided the flight crew in setting up encounters with the UAS and also provided WAAS quality flight data which was used as a source of "truth" flight state data in post-flight analysis.

2.2 Detect-and-Avoid System

Early test flights to characterize the performance of the RADAR system found that the sensor declaration range achieved was not sufficient for DAA operations. In response to this, a Low SWaP surveillance system was emulated by filtering ADS-B tracks to replicate the field of regard (FOR) of a Low SWaP RADAR system. As ADS-B tracks were received by the DAA system, their range, bearing and elevation were calculated and hidden from the DAA display (and therefore the subject pilots) until the tracks were inside of the specified FOR. The FOR selected for FT6 Full Mission consisted of a range of 2.5 nmi., +/-110° azimuth and +/- 15° elevation from the nose of the aircraft. Non-cooperative traffic was differentiated from cooperative manually by applying a software "flag" to the aircraft track which was read by the filtering software. The RADAR emulation however did not include an uncertainty model of a RADAR system which resulted in the detected traffic having the positional uncertainty and stability of the ADS-B system.

Live ADS-B tracks were downlinked to the Live-Virtual-Constructive network before they were published to the research ground control station (RGCS). The RGCS was a workstation within the MOF5 that was isolated from the flight operations personnel and was configured with the VSCS software for vehicle control. [8] The workstation used in FT6 Full Mission is shown in Figure 2. The VSCS allowed the subject pilots under test to command the autopilot onboard the Tigershark XP, navigate using electronic sectional charts, and view and respond to DAA alerting and guidance. A headset and push-to-talk switch allowed the subject pilot to communicate with the virtual ATC. The VSCS software allowed the subject pilots to toggle between either NAV mode where the UAS follows the active flight plan loaded in the autopilot or the heading hold mode which commands the UAS to hold a specific heading.

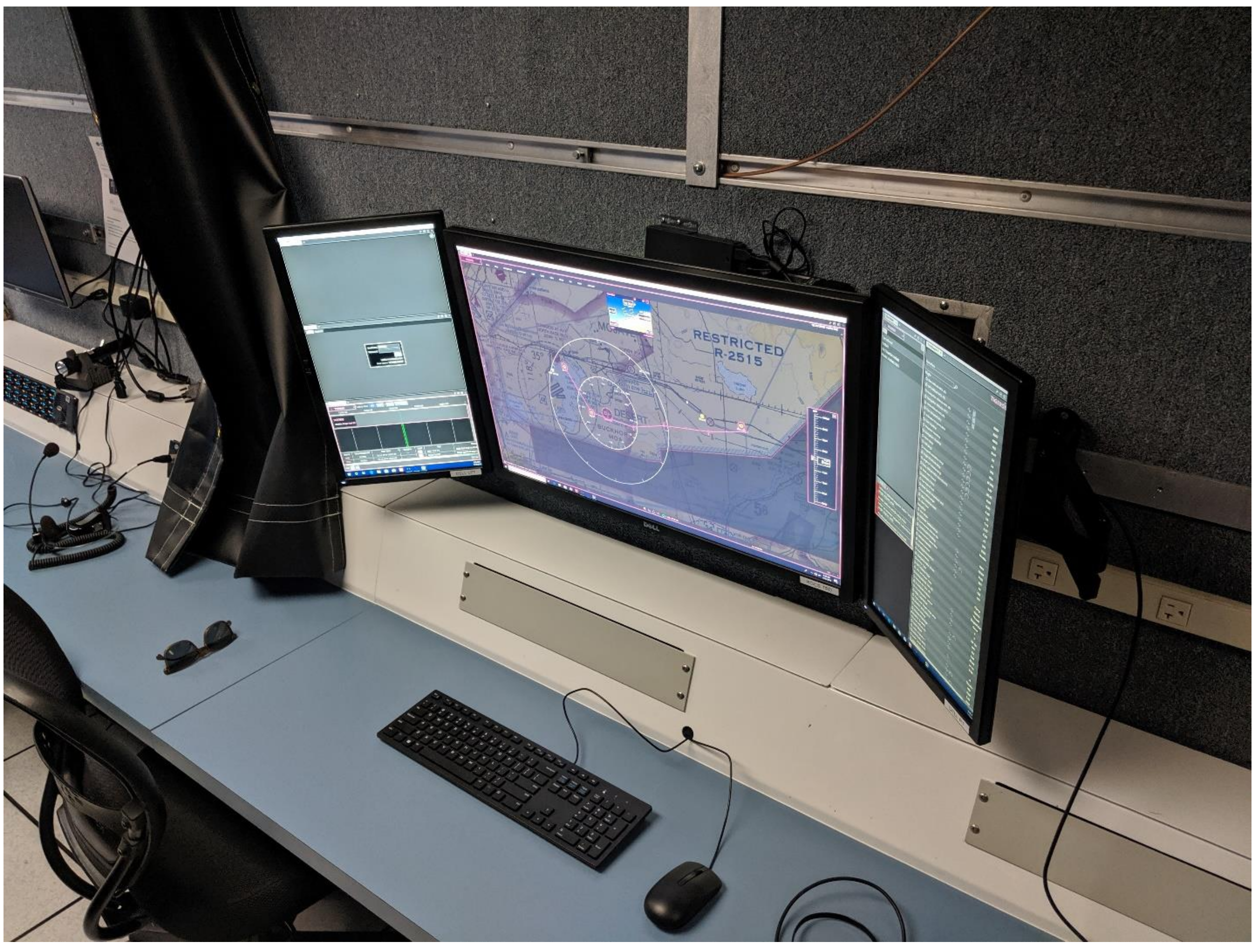


Figure 2: FT6 Full Mission subject pilot workstation with VSCS software.

The Detect and Avoid Logic for Unmanned Systems (DAIDALUS) algorithm was integrated into the VSCS to provide DAA well-clear alerting and guidance to the subject pilots. [9] The well-clear and alerting definitions for cooperative and non-cooperative aircraft used in FT6 are listed in Table 1. DAIDALUS determined when to present each type of alert depending on the calculated time to penetration of the well-clear volume. When an aircraft was projected to penetrate the well-clear volume, DAIDALUS would also generate heading "bands" which represented a range of headings that would result in a loss of well-clear. For the UAS to remain well-clear, the subject pilots would need to command the heading of the UAS to be outside of the bands. When DAIDALUS determined that a loss of well-clear was physically unavoidable, directive recovery guidance was displayed in the form of a green "wedge" shape on the VSCS.

Table 1: DAA well-clear and alerting definition for FT6 Full Mission

Traffic Aircraft Type	DAA Well-Clear Definition			Alert Time	
	hmd^*	h^*	τ_{mod}^*	Corrective	Warning
Cooperative	4000 ft	450 ft	35 seconds	60 seconds	30 seconds
Non-Cooperative	2200 ft	450 ft	0 seconds		

2.3 Live-Virtual-Constructive Distributed Environment

The Live-Virtual-Constructive Distributed Environment (LVC-DE) network connected geographically distributed flight test assets and merged simulated and live flight assets into an immersive simulated environment. In FT6 Full Mission, the LVC-DE allowed the researchers to connect the simulation assets located in laboratories at NASA Ames Research Center (ARC) to the live flight assets located at NASA Armstrong Flight Research Center (AFRC). To create a realistic simulation, a sector of the Oakland airspace was adapted using actual routes and navigational data.

The simulation elements generated from ARC included the virtual ATC, virtual traffic, and constructive traffic. The confederate virtual ATC was a retired human controller who was trained on the methods and goals of FT6. The virtual ATC was responsible for controlling the airspace sector being simulated for FT6. The virtual ATC would act as if controlling a real airspace sector during the data collection apart from being instructed to not provide traffic alerts to the subject pilots. This allowed a better evaluation of how an actual encounter would play out with a non-cooperative aircraft with the DAA system under test. Virtual traffic was controlled by human pilots working from pseudo-cockpits and were responsible for the navigation of simulated aircraft and communicating with the virtual ATC. The combination of communications from the virtual pilots and virtual ATC created a realistic "party line" communications environment for the subject pilots. Constructive traffic was a set of simulated aircraft that followed a prescribed route and required no human intervention. In FT6, the constructive traffic were programmed to fly in adjacent sectors and served the purpose of added visual noise. Both virtual and constructive traffic were programmed to fly along actual Oakland airspace airways.

The live elements located at AFRC included the manned intruder pilot and the Tigershark XP UAS being controlled by the subject pilots. The manned intruder aircraft acted as a simulated non-cooperative aircraft in the airspace that was not communicating over the virtual controller's frequency.

3. Research Methods

The following section will describe the subject selection criteria, the tasks that the subjects were asked to perform during the flight test, the design of the encounters with the manned intruder aircraft, and the metrics that will be used to measure the performance of the system. The Subject Pilots Under-Test section details the selection criteria as well as the flying experience, qualifications, and familiarity of the subject pilots with RADAR systems. The Primary and Secondary Tasks section details the flying, communication, and navigation tasks as well as the secondary chat window tasks that were asked of the subject pilots. The Encounter Design section details the geometry and kinematic profiles of the DAA encounters between the Tigershark XP and the manned intruders. The Metrics section will provide an definition and rationale for each of the performance metrics used to evaluate the DAA system.

3.1 Subject Pilots Under-Test

Seven active duty, fixed wing UAS pilots were recruited to participate in FT6 as subject pilots. Subject pilots were required to have been actively flying UAS within the past year, have at minimum a private pilot certificate and a current FAA medical or U.S. military equivalent. To ensure the results were not influenced by exposure to previous iterations of the DAA system, subject pilots were required to have no previous experience with the UAS Integration in the NAS Project simulations or flight tests.

The average age of the subject pilots in FT6 was 32 and all subjects had previous experience in civilian manned aircraft with an average of 130 flight hours. Three of the subject pilots had earned a commercial pilot's certificate with an instrument rating. All subject pilots had UAS experience with either the General Atomics Inc. MQ-1 or MQ-9. None of the pilots had previous experience with the VSCS system. Of note is the low number of subject pilots who rated their familiarity level with airborne and ground air surveillance RADAR as "very familiar" or "expert." Table 2 shows the self-rated familiarity level with RADAR and TCAS systems.

The subject pilots were provided training before flights to ensure they could complete the primary and secondary tasks. Training modules were focused on the performance characteristics of the Tigershark XP and the detect-and-avoid system, as well as modules on the VSCS interface, and the aspects of the simulated mission. Due to the scheduled early launch time for data collection, the training was split between two days. The day before the data collection flight involved the intake of the subject pilots, classroom training on the purpose of the test and the background of the motivation of the research. Each training module was reinforced with part-task simulation scenarios designed to demonstrate the concepts in each module. The subject pilots were provided with a training packet that they could review at their own convenience after the classroom training was provided. The morning of the data collection flight, a refresher simulation session was provided, and subject pilots were given the chance to ask the researchers questions before the flight was initiated.

Table 2: Subject pilot familiarity with various aviation systems

Familiarity Level	Number of Pilots Familiar with Various Aviation Systems					
	Traffic Alert and Collision Avoidance System (TCAS II)	Airborne air surveillance RADAR	Ground-based air surveillance RADAR	Airborne weather RADAR	Ground-based weather RADAR	Airborne ground surveillance RADAR
Expert	0	0	0	0	0	0
Very Familiar	3	0	0	2	1	0
Familiar	1	2	1	1	2	2
Some	2	3	5	1	3	2
Not Familiar	1	2	1	3	1	3

3.2 Primary and Secondary Tasks

The primary tasks of the subject pilots were to control and monitor the UAS as it completed the preplanned flight circuit, monitor the DAA display for traffic, and monitor ATC communications. Subject pilots were instructed to use the autopilot's NAV mode when they were not actively executing a DAA maneuver. The actions of the subject pilots when a DAA conflict was detected depended on the alert displayed. Subject pilots were trained to contact ATC to negotiate an avoidance maneuver when the corrective alert was displayed by the DAA system. The meaning and expected pilot actions associated with each alert level is illustrated in Figure 3. Once the virtual ATC provided clearance to maneuver, the subject pilot would execute a turn which placed the heading of the UAS outside of the heading bands. Subject pilots were trained to execute a maneuver immediately without contacting ATC if the warning DAA alert was displayed first. The subject pilots could use a text window to enter a specific heading or a graphical heading bug on the VSCS display to command heading changes. After the subject pilots determined that the UAS was clear of conflict, they could rejoin the flight plan by commanding the UAS to fly direct-to the next waypoint.

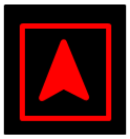
Symbol	Name	Time to LoDWC	Pilot Action	Aural Alert Verbiage
	DAA Warning Alert	30 sec	• ***Immediate action required to remain DAA well clear*** • Prior ATC coordination not required	"Traffic, Maneuver Now, Traffic, Maneuver Now"
	Corrective DAA Alert	60 sec	• On current course, ***corrective action required to remain DAA well clear*** • Coordinate with ATC	"Traffic, Avoid"
	Preventive DAA Alert	N/A	• **No action required to remain DAA well clear** • Not currently a threat; monitor for potential increase in threat level • Between 500 – 700 ft vertically	"Traffic, Monitor"
	Guidance Traffic	N/A	• **No action required to remain DAA well clear** • Traffic generating guidance bands outside of current course	N/A
	"Other"	N/A	• **No action required to remain DAA well clear** • No coordination required	N/A

Figure 3: DAA alert levels and required pilot actions.

The secondary task of the subject pilots was to execute and respond to automated scripted tasks through a chat application on the VSCS. The tasks required the subject pilots to reference either the vehicle state or the vehicle's position relative to landmarks labeled on the sectional chart overlay and type in a response in the chat window. Examples of tasks from the chat script included reporting current fuel endurance of the UAS and reporting distance and bearing to a nearby airport. Responses to the questions varied between subject depending on the position and vehicle state of the Tigershark UAS. Further examples of secondary tasks can be found in Table 3.

Table 3: Subject Pilot Secondary Task Questions

Start Time	Chat Message
0:06:41	*TIGER50 please provide a wind check.*
0:17:01	*TIGER50 what is the current bearing and range to your next waypoint?*
0:25:20	*TIGER50 what is the current fuel burn rate per hour?*
0:33:29	*TIGER50 what is the current ETE to your next waypoint?*
0:41:24	*TIGER50 what is your current mission route?*
0:49:03	*TIGER50 what is the current bearing and range to loiter point CHARLIE?*
0:56:51	*TIGER50 please provide a wind check.*
1:05:57	*TIGER50 what is the current bearing and range to loiter point ALPHA?*
1:13:41	*TIGER50 what is the current fuel burn rate per hour?*

1:21:50	*TIGER50 what is the current ETE to your next waypoint?*
1:31:49	*TIGER50 what is the current bearing and range to your next waypoint?*
1:41:06	*TIGER50 what is your current mission route?*
1:50:43	*TIGER50 what is the current bearing and range to loiter point CHARLIE?*
2:00:18	*TIGER50 please provide a wind check.*
2:09:37	*TIGER50 what is the current fuel burn rate per hour?*
2:19:34	*TIGER50 what is the current ETE to your next waypoint?*
2:28:54	*TIGER50 what is the current ETE to your next waypoint?*

3.3 Encounter Design

During data collection each subject pilot encountered 6 live DAA encounters with "intruder" aircraft at either 100 kts. or 170 kts. ground speed and either a 90° crossing, head-on, or 45° crossing geometry. The UAS maintained 60 kts. ground speed throughout the data collection. Two of the encounters were designated as cooperative traffic targets and used the cooperative DAA well-clear definition, while the remaining 4 encounters used the non-cooperative DWC definition. Two encounters were presented to the subject pilots per circuit of the mission flight plan. Figure 4 shows the geometries of each encounter on each circuit.

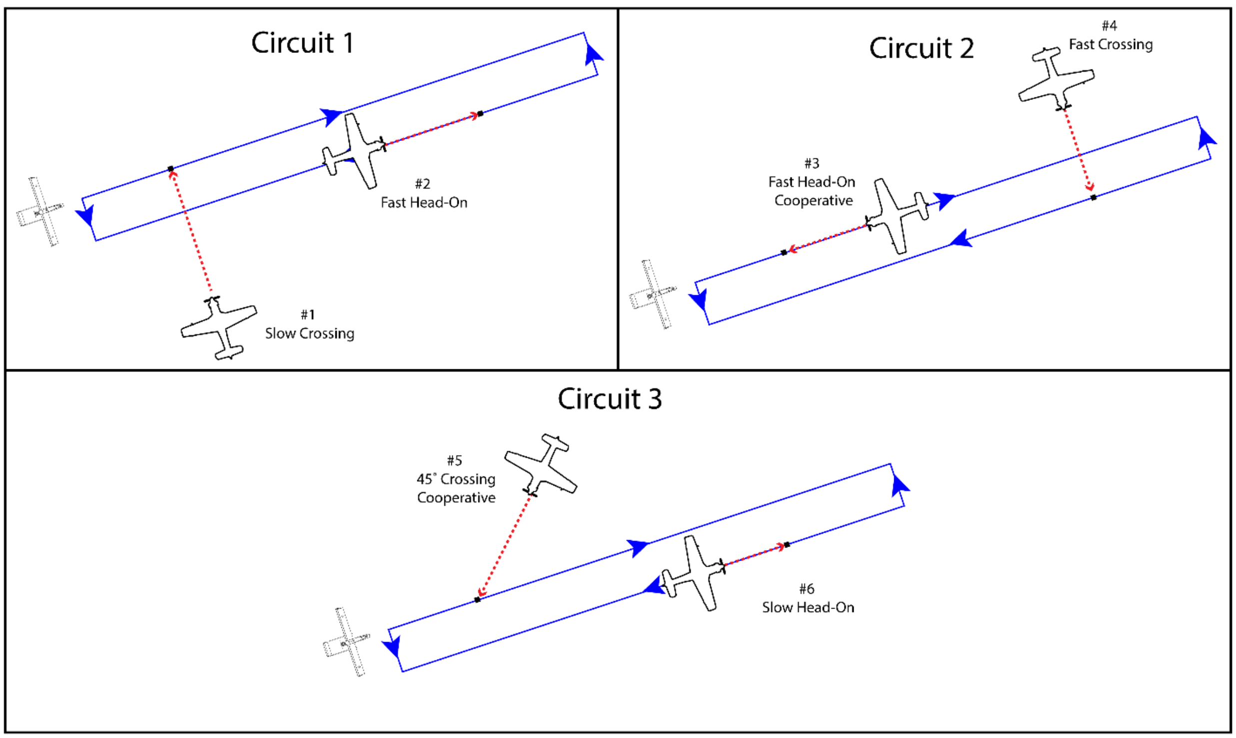


Figure 4: Encounter geometries and speeds for each circuit.

The order of the presentation of the circuits were counterbalanced across subject pilots to control for order effects. The counterbalancing schedule can be found in Table 4.

Table 4: Circuit order presentation counterbalancing schedule

Subject Pilot #	Circuit # Order		
	First	Second	Third
1	Circuit 1	Circuit 2	Circuit 3
2	Circuit 3	Circuit 2	Circuit 1
3	Circuit 2	Circuit 1	Circuit 3
4	Circuit 3	Circuit 1	Circuit 2
5	Circuit 1	Circuit 2	Circuit 3
6	Circuit 3	Circuit 2	Circuit 1
7	Circuit 2	Circuit 1	Circuit 3
8	Circuit 3	Circuit 1	Circuit 2
9	Circuit 1	Circuit 2	Circuit 3
10	Circuit 3	Circuit 2	Circuit 1

For each encounter a researcher observer monitored the trajectories of the UAS and the live intruder as well as the alerting and guidance generated during the encounter for anomalies. If the observer or the test director noted a significant change in the flight state of the encounter, it was aborted, and an identical backup encounter was executed. Similarly, if the encounter did not generate the expected alert time before loss of well-clear, no alerting occurred, or the alerting and guidance was unstable and changing continuously, the encounter was aborted, and a backup encounter was executed. Backup flight plans for the UAS were designed if the test airspace became unavailable or encounters were missed or deemed unacceptable. The profile of the backup flight plans remained as similar as possible to the primary flight plan and the order of the encounters would not change if the backup flight plans was utilized. The backup flight plan profiles can be found in Appendix A. The data collection concluded once six encounters were successfully executed. There were no planned encounters with virtual or constructive traffic during the data collection.

3.4 Metrics

Subjective and objective data were collected from the subject pilot during FT6 before, during, and after the data collection flights. The subject pilots were asked to complete a pilot background/demographics questionnaire before subject pilot training began. During the data collection flights the interactions with the VSCS display, algorithm output, and flight state data were collected in addition to a post-encounter questionnaire that subject pilots were asked to complete after each encounter was resolved. After the flight the subject pilots were asked to complete a post-simulation questionnaire before being interviewed by the researchers about the events that took place during the flight. The complete contents of the questionnaires can be found in the Appendices B through D.

The background/demographics questionnaire was provided to the subject pilots as soon as they completed the informed consent form. The questionnaire covered the subject pilot's experience with both manned and unmanned aircraft in flight hours, types of aircraft flown, and ratings/certificates earned. The subject pilots were also asked about expertise level with TCAS, cockpit multifunction displays, and technically advanced aircraft. Subject pilots were also asked about their expertise level with RADAR systems, as advanced knowledge of the characteristics of RADAR technology may lead subjects to notice simulation artifacts present in the emulation of a Low SWaP RADAR system. Additionally, subject pilots were asked about their experience with the VSCS display and flight simulation.

After each encounter subject pilots were asked to complete an adaptation of Hart and Stavelands NASA Task Load Index (NASA TLX) questionnaire pertaining to their perceived workload during the encounter. [10] The NASA TLX assesses perceived workload across seven facets: mental demand, physical demand, temporal demand, performance, effort, and frustration. Workload measures were used to both determine if the flight test results correlate to previous simulation results and to identify individual encounters during the flight test campaign that may have been qualitatively dissimilar to the other encounters. Identifying outlier encounters is particularly important for a human-in-the-loop flight test since it is impossible to replicate the same flying conditions for each subject pilot due to weather and aircraft performance. The post encounter questionnaire also presented the subject pilots with several adjective rating scale questions pertaining to alerting time and stability, ability to maintain a safe separation from the intruder aircraft, usefulness and accuracy of the alerting and guidance, and the impact of winds and interactions with ATC on maintaining separation from the intruder.

Flight state data including the position, speed, altitude, heading, and vertical speed was collected for the ownship UAS, the live intruder, and the constructive and virtual targets. The aircraft flight state data allows post-hoc recreation of each encounter, as well as determination of the separation at closest point of approach between the UAS and the live intruder, number and severity of losses of well-clear, and closure rates. The VSCS was also configured to log interactions the subject pilot initiated with the graphical user interface. This allows a determination of maneuver timing after a DAA alert is generated and maneuver choice and magnitude. The output of the DAIDALUS algorithm was logged to determine the start and end times of each type of alert to determine alerting time before the subject pilots initiated a maneuver.

The post-simulation questionnaire was provided after the completion of the final mission plan circuit and asked the subject pilots to rate the quality and realism of the training and simulation by the researchers and the overall simulation. The subject pilots were then asked to rate the presentation of the each of alert icons and auditory alerts as well as their usefulness and how they responded to them. The subject pilots were also asked about the discriminability between a simulated RADAR target and a cooperative target and the acceptability of the RADAR surveillance volume used. The final section included open-ended questions about what influenced the subject pilot's decision during the flight, the realism of the simulated airspace, what elements of the ground station and DAA system which were useful, the data link latency, and the acceptability of the system as a whole for integration into the NAS.

The debriefing interview was conducted after a short break away from the ground control station to provide a quiet environment for conversation. In this interview the subject pilots were given the opportunity to speak freely about the conditions of the test. The researchers inquired about the surveillance sensor performance, the DAA alerting and guidance, the data link latency, and any other topics about the flight in which they were interested.

4. Results

The following section is divided into sections which describe the FT6 results. The alerting performance section describes how the DAA system alerted the subject pilots when compared to the Low SWaP HITL 2 laboratory study. The aircraft response time section describes how long it took the subject pilots to execute an avoidance maneuver after an alert was issued and compares these results to the Low SWaP HITL 2 laboratory study. The ATC coordination section describes how often subject pilots coordinated with ATC when executing a maneuver as opposed to maneuvering without coordination. The separation performance section provides an overview of the number of losses of well-clear and near mid-air collisions. The field of regard section provides details on the phenomena of intruder aircraft flying out of the limits of the surveillance sensor's field of regard limits as a result of the maneuvering of the UAS. The subjective workload and acceptability sections provide an overview of the results of the NASA TLX and post-encounter questionnaires administered to the subject pilots after each encounter and at the completion of the flight test.

4.1 Alerting Performance

Time to loss of DAA well-clear (*t*LoDWC) at first alert can be used to both verify the similarity of encounters in FT6 to encounters flown in the HITL simulation studies and to evaluate the amount of alerting time that the surveillance declaration range allows. A high *t*LoDWC indicates a longer alert timeline and lower closure rates between the UAS and the manned intruder. Figure 5 shows the average *t*LoDWC at first alert for each of the encounter types for non-cooperative encounters.

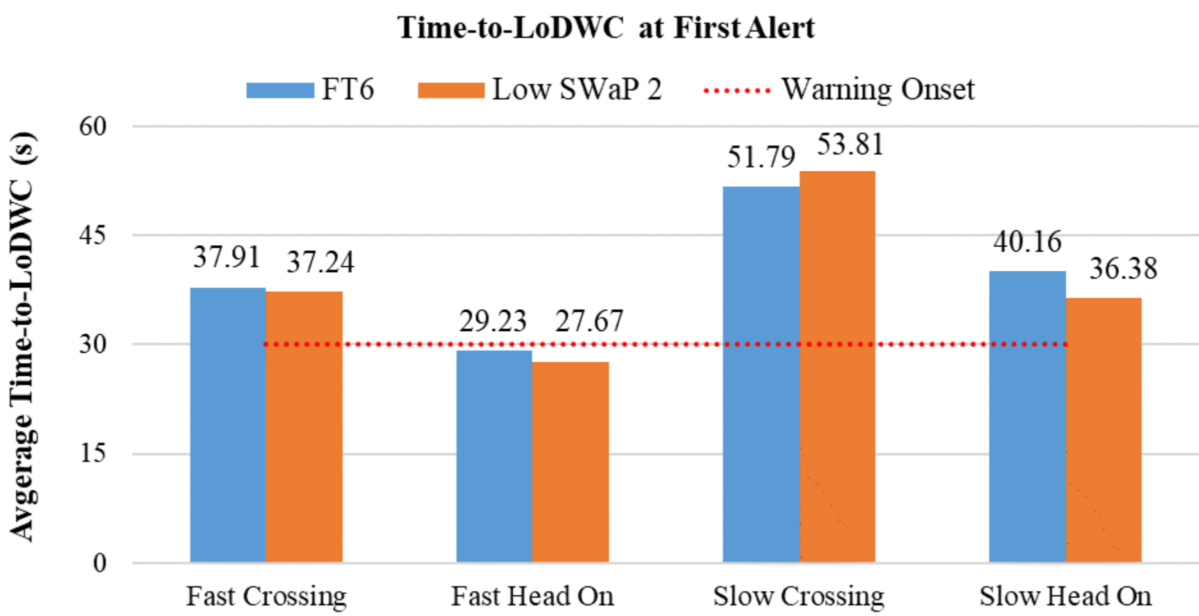


Figure 5: Comparison of time to loss of DAA well-clear at onset of first alert by encounter type between Low SWaP 2 HITL and FT6.

Overall the average *t*LoDWC between FT6 and the second Low SWaP HITL simulation study were similar, with the FT6 times being slightly higher than the Low SWaP HITL for all except the slow crossing encounters. The differences in *t*LoDWC at first alert can be accounted for by variations in the UAS's and intruder's airspeed during the encounters. At times during the execution of FT6 the manned intruder needed to adjust ground speed to arrive at the encounter start location in time to trigger the DAA alerting and guidance at the predefined time. Additionally, the intruder pilots were forced to adjust ground speed manually due to changing wind conditions on some days. As can be seen in Table 5, the average varied from the speeds originally listed on the flight cards (100 and 170 kts ground speed). Time to loss of DWC at first alert values above 30 seconds suggest a full warning alert timeline, while values above 60 seconds suggest a full corrective alert timeline. In FT6, all non-cooperative encounters except for the fast head-on geometries had a *t*LoDWC above 30 seconds which allowed, at minimum, a partial corrective alert timeline.

Table 5: Average ownship and intruder speeds and mean time to loss of DAA well-clear by encounter type

Encounter Type	**Encounter Characteristics**		
	Ownship Speed *M*	Intruder Speed *M*	*t*LoDWC *M*
Slow Crossing	71 kts	115 kts	51.8*s*
Slow Head On	64 kts	107 kts	40.2*s*
Fast Crossing	61 kts	173 kts	37.9*s*
Fast Head On	64 kts	170 kts	29.2*s*

Corrective alerts were generated for 81% of non-cooperative conflicts, however only 32% of corrective alerts lasted 15 seconds or longer, which suggests that many of the alerts may have progressed to a warning level alert before the end of the encounter. This is confirmed when investigating how the alerts progressed during the encounter timelines. Figure 6 shows the proportion of warning and corrective alerts at three different events in the encounter timeline: first alert displayed, first maneuver uploaded, and the last alert displayed.

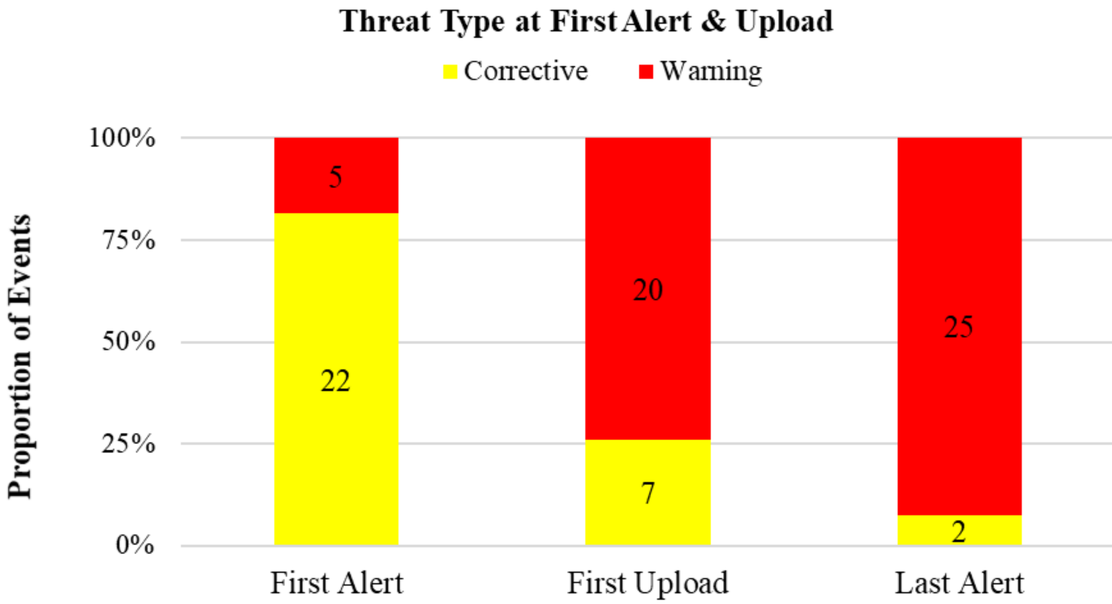


Figure 6: Proportion of alert types at onset of first alert, first maneuver upload and the last alert displayed.

By the time the subject pilots uploaded the first maneuver, 74% of the encounters had progressed to warning level alerts. Warning level alerts were the last alert displayed to the subject pilots before the alerting was extinguished for all but 2 encounters. This means that in many cases subject pilots were in the middle of coordinating with ATC when the alert displayed changed from corrective level to warning level. All but 2 encounters progressed to a warning level alert by the time the encounter ended.

4.2 Aircraft Response Time

Aircraft response time is defined as the time elapsed from the onset of the first alert to the time the first avoidance maneuver is uploaded in the VSCS. This time is useful in modeling the performance of a DAA system in the NAS as well as determining how long of an alert time threshold is needed in a DAA system for pilots to initiate a maneuver. Figure 7 shows the response times against non-cooperative intruders generating corrective and warning alerts for FT6 and the Low SWaP HITL simulation study. The mean aircraft response time for non-cooperative corrective alerts in FT6 was 13.25 seconds (*N*=20, *SD*=3.36) which was notably slower than was observed in the Low SWaP HITL simulation (*M*=9.42). This effect may be due to fluctuating closure rates between the UAS and the manned intruder aircraft in FT6 which resulted in lower overall closure rates when compared to the scripted virtual intruders in the HITL study. Additionally, pilots in FT6 may have placed more emphasis on coordinating with ATC because they knew they were commanding a live aircraft and therefore had a greater desire to obtain concurrence from a controller. The aircraft response time for non-cooperative warning alerts was shorter than the corrective response time at 8.00 seconds (*N*=8, *SD*=2.00) and only slightly slower than was observed in the Low SWaP HITL study (*M*=7.12).

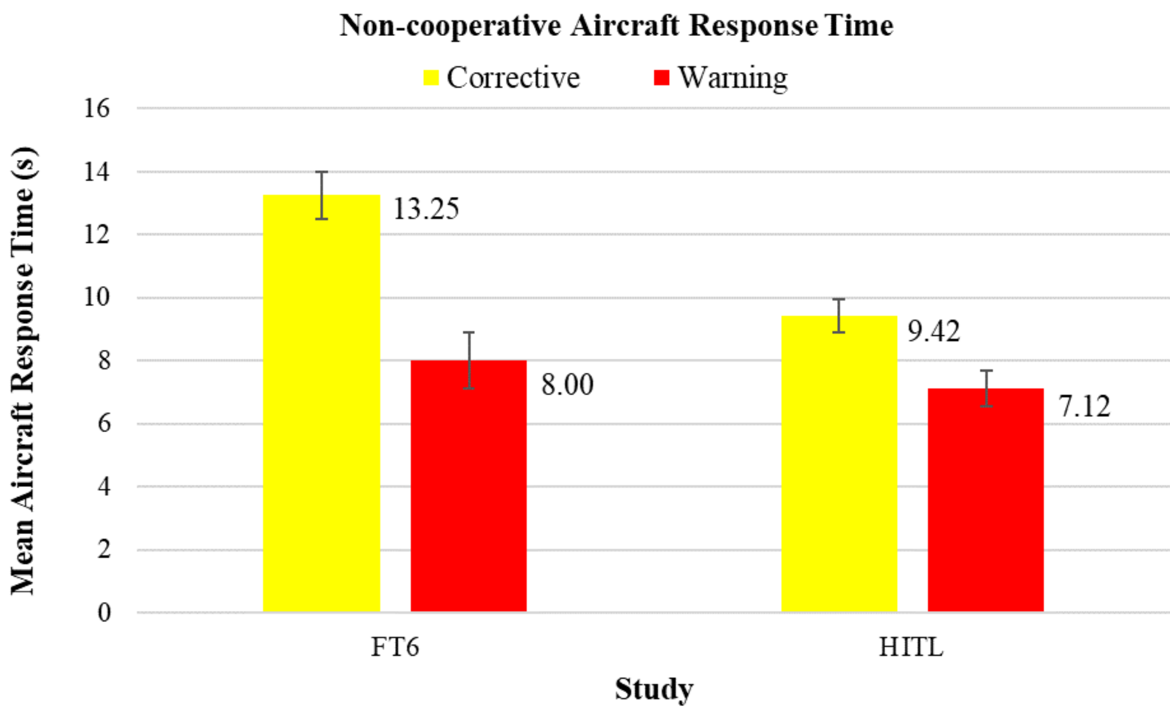


Figure 7: Non-cooperative aircraft response times between FT6 and the Low SWaP 2 HITL.

Figure 8 shows the aircraft response time between alert level and intruder equipage. The mean aircraft response time for cooperative intruders was predictably higher (*M*=17.875, *SD*=6.96, *N*=8) as the unrestricted declaration range allowed a full corrective and warning alert timeline which resulted in maneuver decisions being made at greater distances and with less perceived urgency by the subject pilots.

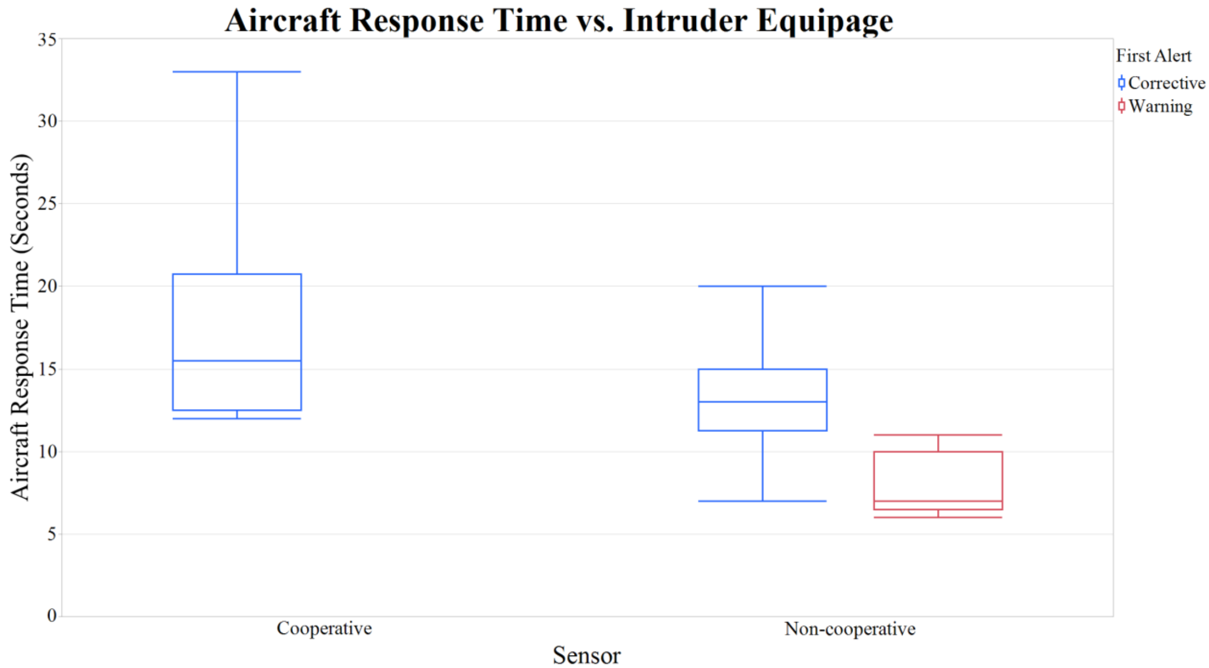


Figure 8: Aircraft response times and sensor selections for cooperative and non-cooperative intruders.

4.3 ATC Coordination

The rate of subject pilot coordination with ATC provides an estimate of how often UAS pilots in the NAS would maneuver without prior approval from an ATC. Figure 9 shows the proportion of maneuvers executed with prior approval from ATC in FT6 compared to the Low SWaP 2 HITL. In FT6 the subject pilots obtained prior approval from ATC 70% of the time compared to only 61% of the time in the Low SWaP HITL study. The discrepancy between live flight and simulation can likely be attributed to longer corrective alert times in FT6 compared to the Low SWaP HITL, as the average corrective alert times in FT6 were over 10 seconds longer than in the HITL. Subject pilots may have also been more reluctant to execute a maneuver without prior approval in a live flight environment than they would be in a laboratory study out of concern for safety.

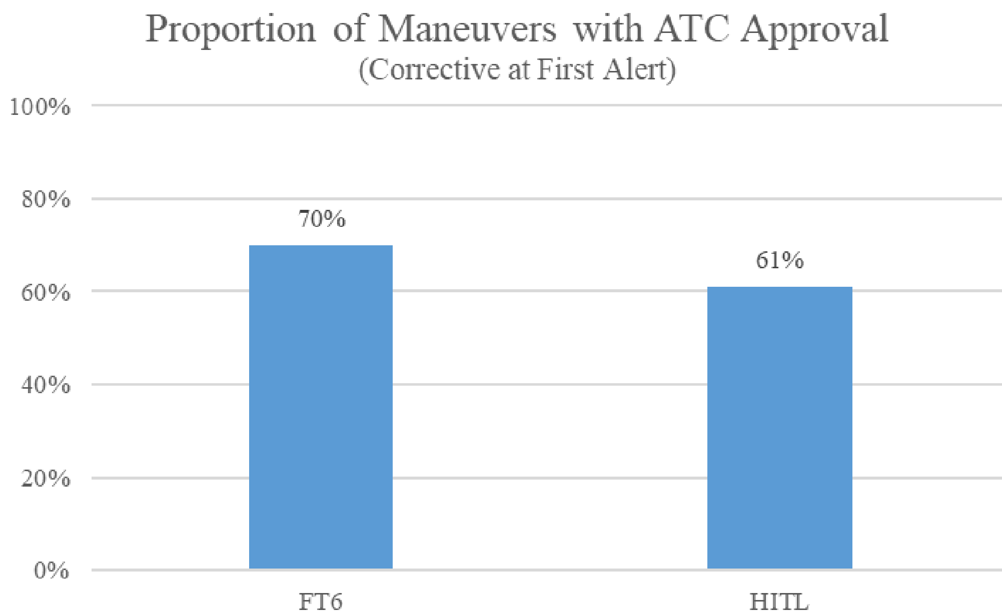


Figure 9: Proportion of maneuvers with prior ATC approval.

4.4 Separation Performance

Subject pilots were able to avoid losses of well clear in all encounters in both FT6 and the Low SWaP 2 HITL. Mean minimum separation between the UAS and the intruder for cooperative encounters was 1.42 nmi while mean minimum separation for non-cooperative encounters was lower at 0.77 nmi due to the restricted surveillance range and alerting time available to the subject pilots. The lowest separation during an encounter was 2871.5 ft during a non-cooperative encounter with a fast crossing intruder. Non-cooperative encounters with a fast intruder had only a slightly lower mean minimum separation (0.73 nmi) than non-cooperative encounters with a slow intruder (0.82 nmi). This small difference in minimum separation indicates that the subject pilots were able to achieve similar separation with higher closure rate encounters.

4.5 Field of Regard Considerations

An unexpected difference in the results between FT6 and the HITL was in the frequency of intruders exiting the azimuth limits of the field of regard of the emulated non-cooperative sensor before the UAS and intruder were clear of conflict. The non-cooperative sensor emulation limited the azimuth of the field of regard to a limit of +/- 110° on either side of the nose of the vehicle. This means that if a subject pilot commanded a maneuver which resulted in the intruder being at a bearing relative to the nose of the vehicle greater than

110°, the intruder would not appear on the DAA display. This event occurred in 41% of non-cooperative encounters in FT6 compared to 25% in the Low SWaP 2 HITL. Subject pilots also executed larger maneuvers compared to the Low SWaP 2 HITL with a mean turn size (change in heading) of 128° in FT6 and 90° in the HITL. This increase in number of field-of-regard drop-offs and turn size between the simulation and flight environment could have been caused from unsteady intruder aircraft states (e.g. changing airspeed or heading to compensate for wind) resulting in constantly changing guidance bands. Alternatively, the subject pilots may have been motivated to maneuver beyond what was required to stay separated from the intruder aircraft as a precautionary measure.

4.6 Subjective Workload

Subject pilots rated subjective workload through an abbreviated form of the NASA TLX (i.e., with ratings ranging from '1' to '7', with '1' being the lowest workload and '7' being the highest workload) following each encounter. Figure 10 displays the averages for each NASA TLX dimension across the various non-cooperative encounter types. Mental demand peaked with the Fast Crossing encounter (*M*=4.14, *SD*=2.12) and was the lowest for the Slow Head On encounter (*M*=3, *SD*=2.16). As expected, physical demand in general was especially low for the subject pilots. Temporal demand was similar for both the Fast Head On (*M*=4.14, *SD*=2.04) and the Fast Crossing encounters (*M*=4.43, *SD*=2.23). Both the Slow Head On (*M*=3.14, *SD*=1.77) and the Slow Crossing encounters (*M*=3.71, *SD*=1.50) promoted slightly less temporal demand than encounters featuring a fast intruder speed. Subjects piloted viewed their performance as being slightly better with the Slow Head On encounter (*M*=1.86, *SD*=.90) compared to other encounter types, including the Slow Crossing (*M*=2.43, *SD*=1.40), Fast Head On (*M*=2.57, *SD*=.96), and Fast Crossing (*M*=2.29, *SD*=.76). Perceived effort held constant for both the Fast Head On (*M*=3.29, *SD*=2.14) and Fast Crossing encounters (*M*=3.29, *SD*=1.95). The Slow Crossing encounter produced slightly more effort (*M*=2.86, *SD*=1.89) compared to the Slow Head On encounter (*M*=2.57, *SD*=1.81). Finally, frustration was lowest for the Slow Head On encounter (*M*=1.86, *SD*=1.46) compared to the Slow Crossing (*M*=2.43, *SD*=1.81) and Fast Head On encounters (*M*=2.57, *SD*=1.81).

Composite scores were calculated by totaling all dimension scores for each subject pilot. NASA TLX composite scores could range from a lowest value of '7' to a highest value of '42'. All average composite scores for the four encounter types all fell below a score of '20'. General workload peaked with the Fast Crossing encounter (M=18.43, SD=8.73), followed by the Fast Head On (M=17.29, SD=8.48), Slow Crossing (M=15.57, SD=8.42), Slow Head On encounters (M=13.14, SD=7.34) (see Figure 10).

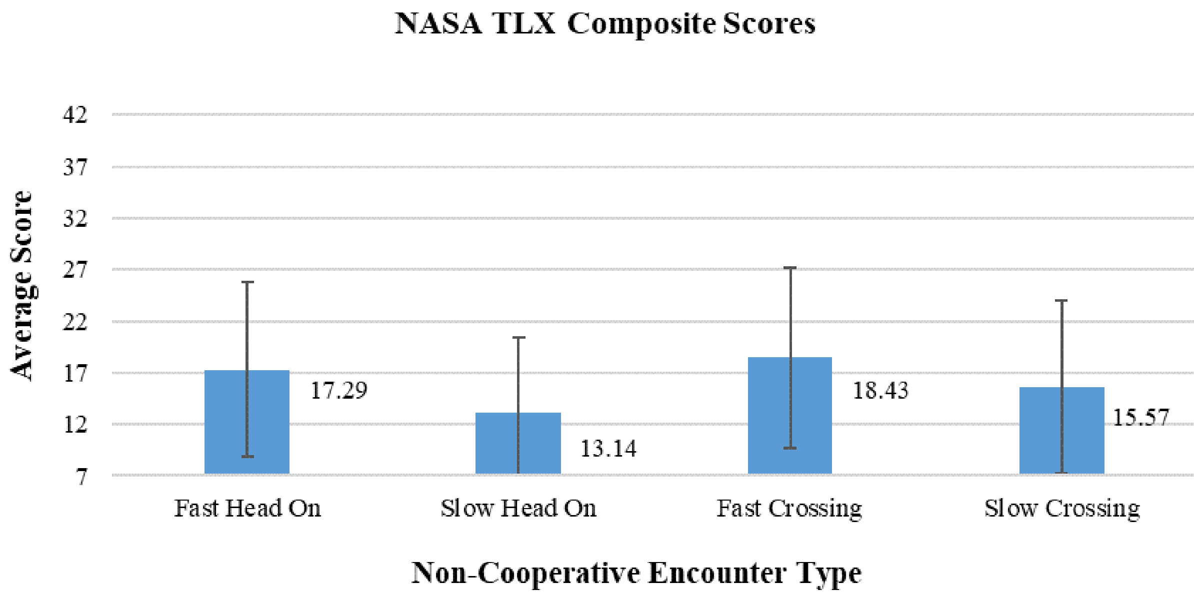


Figure 10: Composited NASA TLX Workload Ratings across all encounter types.

4.7 Subjective Acceptability

4.7.1 Post-Run Questionnaire Results

Following the successful resolution of each planned encounter, pilots completed a short questionnaire meant to query opinions on the encounter and systems. The questionnaire featured various statements regarding both the DAA system, interactions with ATC, and other environmental factors and participants responded with their level of agreement with the statement along a scale of 1 to 5 (i.e., rating of '1' representing strong disagreement and '5' indicating strong agreement). Only the ratings for non-cooperative encounters (i.e., those said to be detected by the Low SWaP sensor) will be detailed for the purposes of this report.

When asked to rate their agreement with whether the DAA alerting provided sufficient time to resolve an encounter (i.e., 'The DAA alerting provided sufficient time to resolve this encounter'), subject pilots rated the Slow Head On encounter (M=4.57, SD=.53) higher than all other non-cooperative encounter types. Encounters with a fast intruder speed featured similar average ratings, including the Fast Head On (M=3.71, SD=.76), Fast Crossing (M=3.71, SD=1.38) and Slow Crossing encounters (M=4, SD=1.15) (see Figure 11).

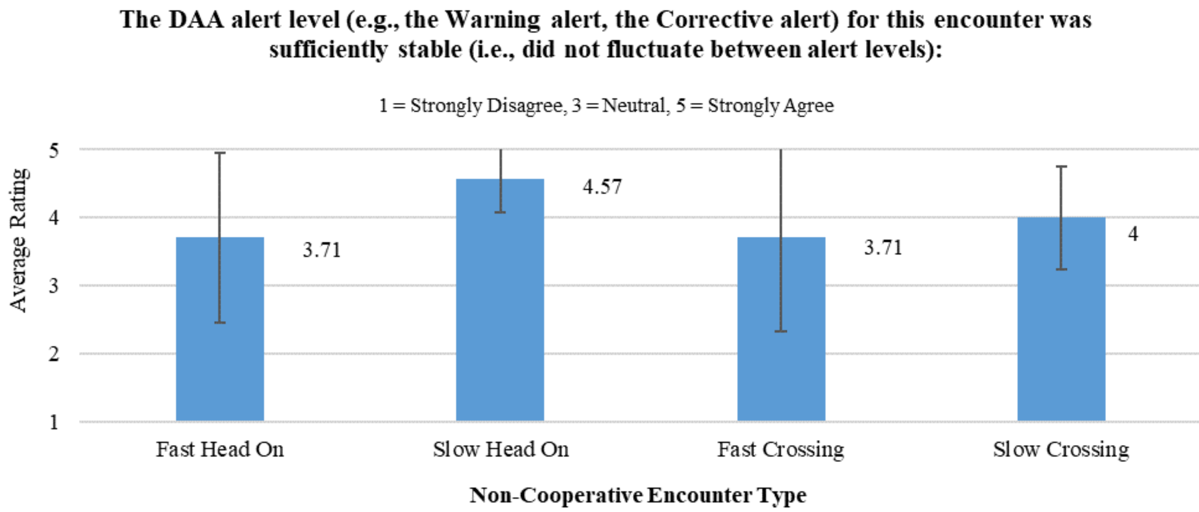


Figure 11: Average agreement ratings for whether DAA alerting was stable.

The stability of DAA alerts (i.e., 'The DAA alert level (e.g., the Warning alert, the Corrective alert) for this encounter was sufficiently stable (i.e., it did not fluctuate between alert levels)') was seen as greater in the Slowing Crossing (*M*=4.29, *SD*=.76) and Slow Head On encounters (*M*=4.71, *SD*=.49). Encounters that featured a faster intruder speed resulted in slightly lower agreement ratings on whether the DAA alerts were stable, including the Fast Head On (*M*=3.71, *SD*=1.25) and Fast Crossing encounters (*M*=3.71, *SD*=1.38) (see Figure 12).

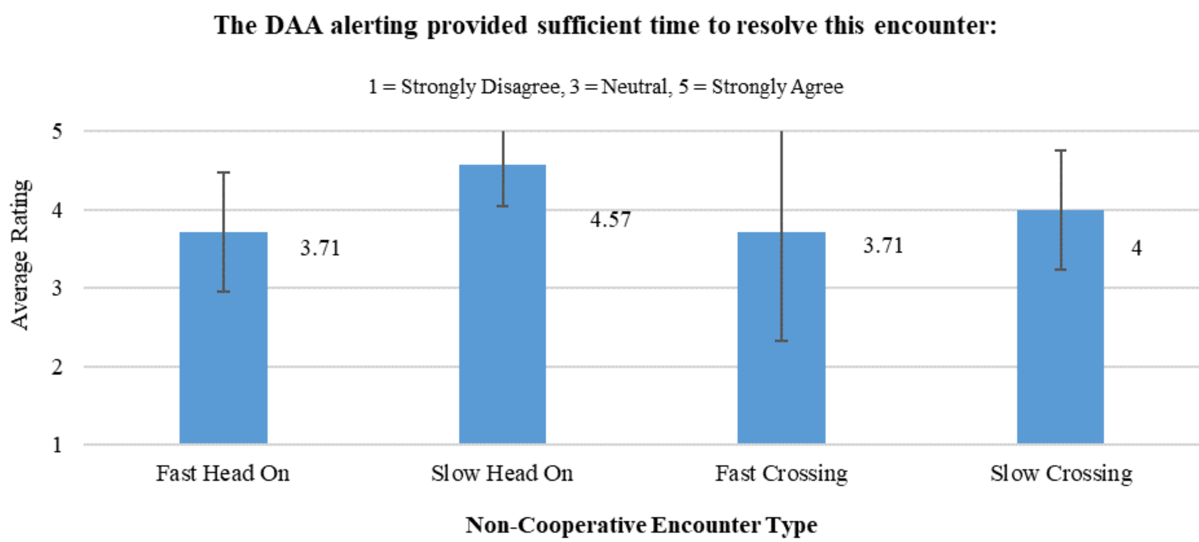


Figure 12: Average agreement ratings for whether DAA alerting and guidance provided sufficient time to resolve encounters.

Regarding the stability of guidance bands (i.e., 'The display of guidance bands was sufficiently stable (i.e., did not "jump around" excessively):'), a similar trend of greater acceptability for the guidance band behavior during the slow ownship speed encounters, including Slow Head On (*M*=4.57, *SD*=.79) and Slow Crossing (*M*=4.57, *SD*=.53), was observed across participants. Encounters featuring a fast intruder speed had a negative impact on the acceptability of guidance bands, with the Fast Crossing encounter producing slightly lower average scores (*M*=3.43, *SD*=1.62) compared to the Fast Head On encounter (*M*=3.57, *SD*=1.81) (see Figure 13).

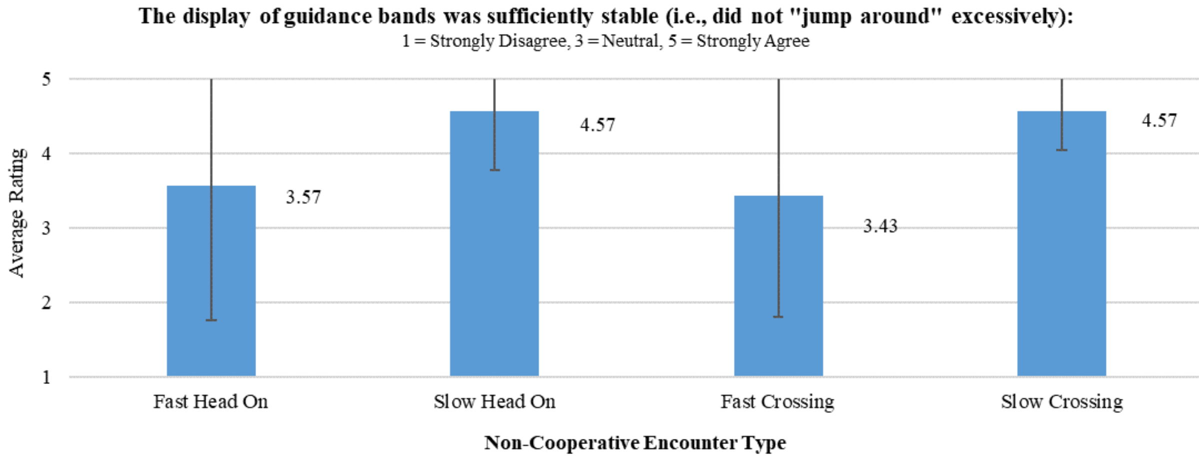


Figure 13: Agreement ratings for whether guidance bands were stable and usable.

When asked whether they were able to achieve separation across the various encounters (i.e., 'I was able to achieve sufficient separation from the intruder aircraft(s) using the alerting and guidance in this encounter:'), responses were generally favorable across all encounters. The Slow Head On encounter produced the greatest agreement amongst participants (*M*=4.86, *SD*=.38), followed by the Fast Head On (*M*=4.57, *SD*=.53), Slow Crossing (*M*=4.29, *SD*=1.11), and Fast Crossing (*M*=4.14, *SD*=.90) encounters respectively (see Figure 14).

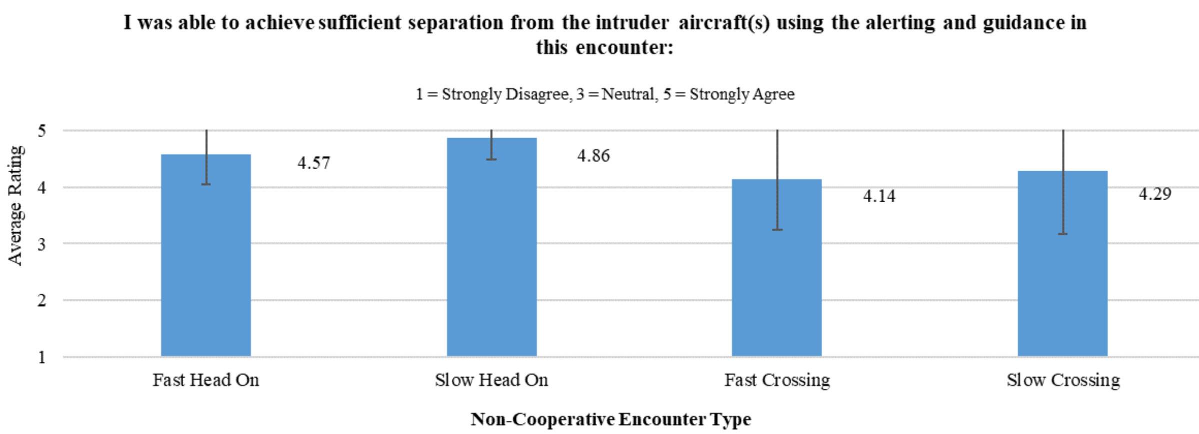


Figure 14: Agreement ratings for whether subject pilots were able to achieve sufficient separation.

When queried about the relative usefulness of the DAA guidance bands (i.e., 'The DAA guidance bands were useful for solving this encounter'), responses were again generally high across all four encounter types. The Slow Head On encounter again produced the highest rate of agreement across all participants (*M*=4.86, *SD*=.38) followed by the Fast Crossing encounter (*M*=4.71, *SD*=.49). Both the Fast Head On (*M*=4.57, *SD*=.79) and Slow Crossing encounters (*M*=4.57, *SD*=.79) featured equivalent agreement ratings (see Figure 15).

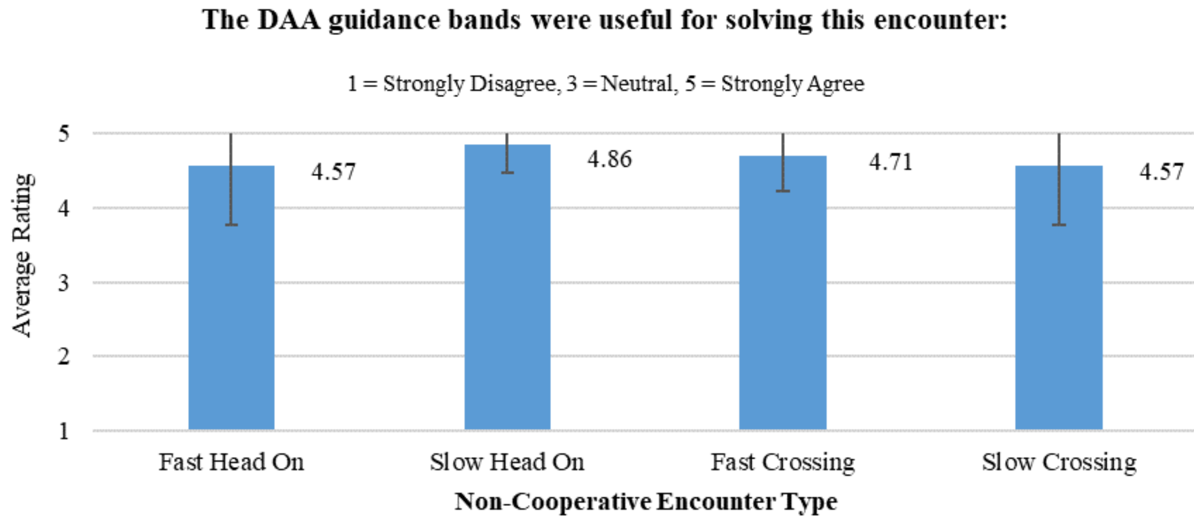


Figure 15: Average agreement ratings for whether DAA guidance bands were useful.

Most subject pilots felt that sensor noise did not impact their ability to maintain sufficient separation from all four encounter types (i.e., 'Sensor noise or alerting and guidance instability did not impact my ability to maintain sufficient separation from traffic'). Average agreement ratings were highest in both the Slow Head On (*M*=4.86, *SD*=.38) and the Fast Crossing encounters (*M*=4.86, *SD*=.38). Meanwhile, agreement ratings were equal for both the Fast Head On (*M*=4.57, *SD*=.53) and Slow Crossing encounters (*M*=4.57, *SD*=.79) (see Figure 16).

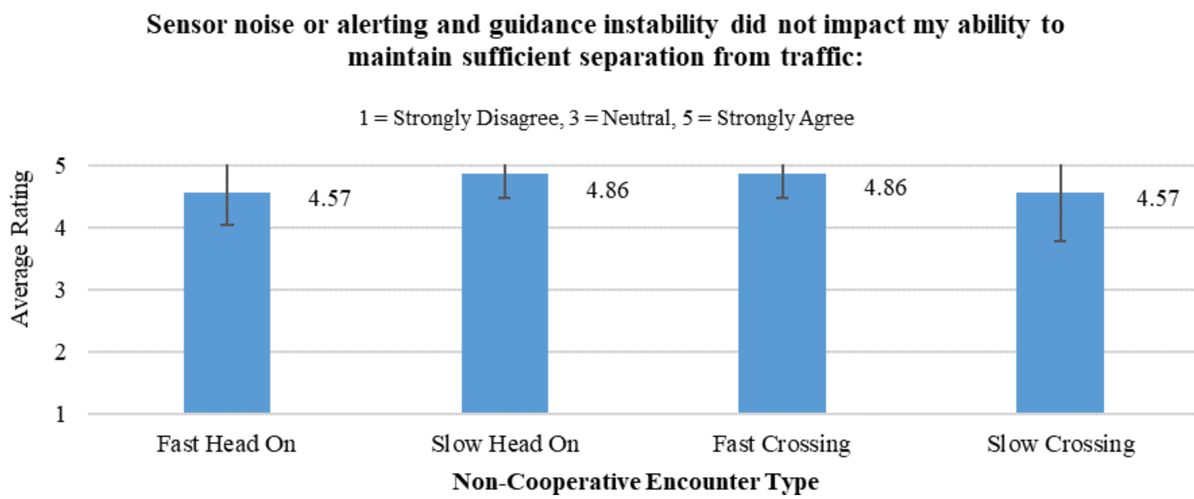


Figure 16: Average agreement ratings for whether alerting/guidance instability did not negatively impact separation ability.

Generally, subject pilots did not feel that there was a significant impact of winds aloft on ability to maintain separation across all four non-cooperative encounter types (i.e., 'Winds aloft did not impact my ability to maintain sufficient separation from traffic'). Agreement was generally the highest for both crossing encounters, including the Fast Crossing (*M*=4.71, *SD*=.49) and Slow Crossing (*M*=4.71, *SD*=.49) encounters, followed by both the Fast Head On (*M*=4.57, *SD*=.79), Slow Head On (*M*=4.43, *SD*=1.13) encounters (see Figure 17).

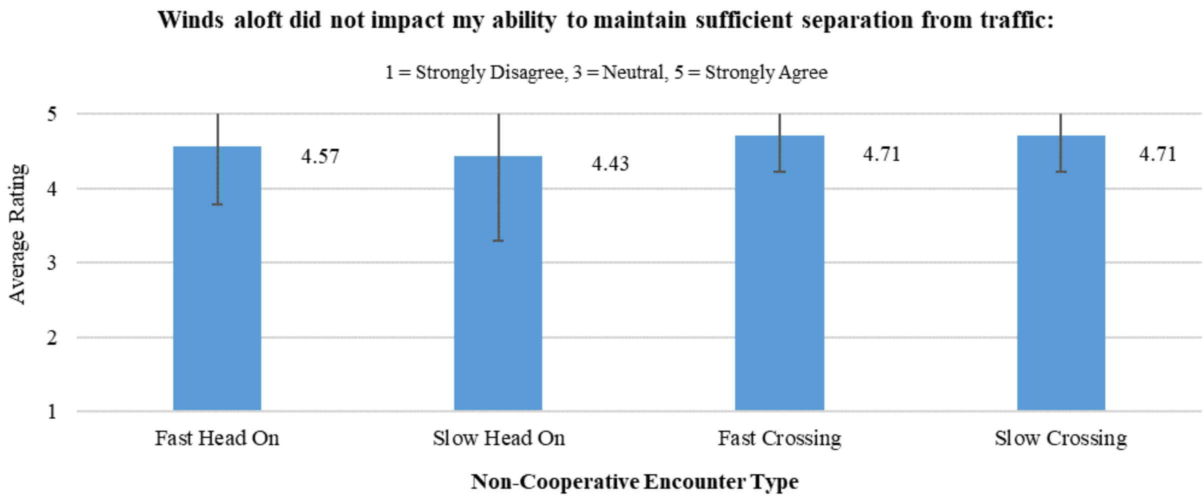


Figure 17: Average agreement rating for whether winds aloft impacted separation ability.

When queried on whether ATC interaction had an impact on separation ability (i.e., 'My interactions with ATC did not impact my ability to maintain sufficient separation from traffic:'), agreement ratings for the Fast Head On encounters were the highest (*M*=4.57, *SD*=.53), followed by the Slow Head On (*M*=4.14, *SD*=.69), Slow Crossing (*M*=3.86, *SD*=1.35), and Fast Crossing encounters (*M*=3.43, *SD*=1.13) (see Figure 18).

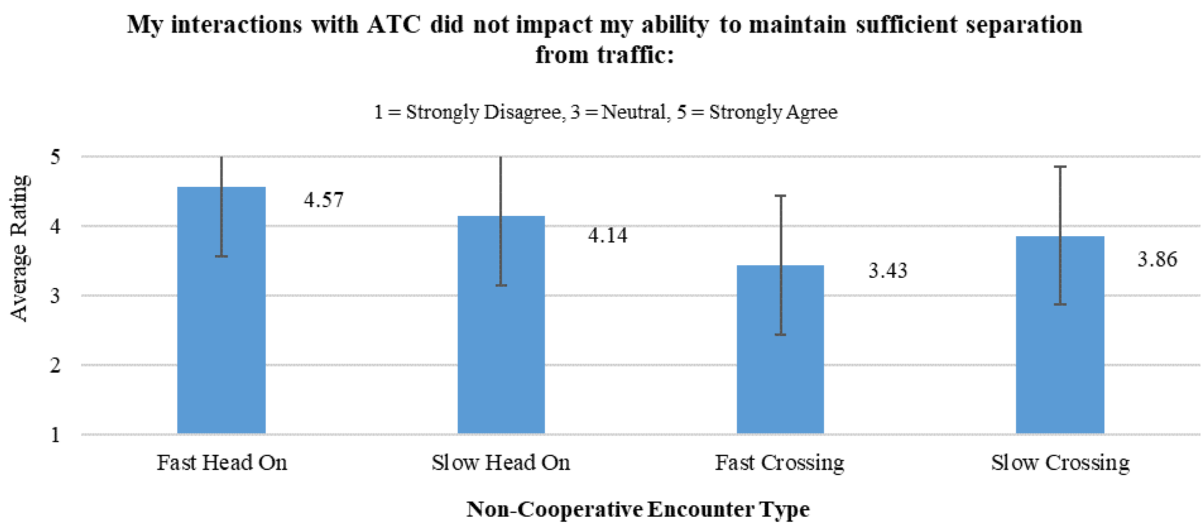


Figure 18: Average agreement ratings for whether ATC interactions impacted separation ability.

When asked about how trustful they were in the accuracy of the DAA alerting and guidance (i.e., 'I trusted the accuracy of the alerting and guidance generated by the DAA display'), responses were generally equivalent for all four encounter types. The Slow Head On encounter (*M*=4.71, *SD*=.49) featured a slightly higher average agreement rating than both the Fast Head On (*M*=4.57, *SD*=.53) and Fast Crossing encounters (*M*=4.57, *SD*=.53). The Slow Crossing encounter featured the lowest average agreement rating (*M*=4.29, *SD*=.76) (see Figure 19).

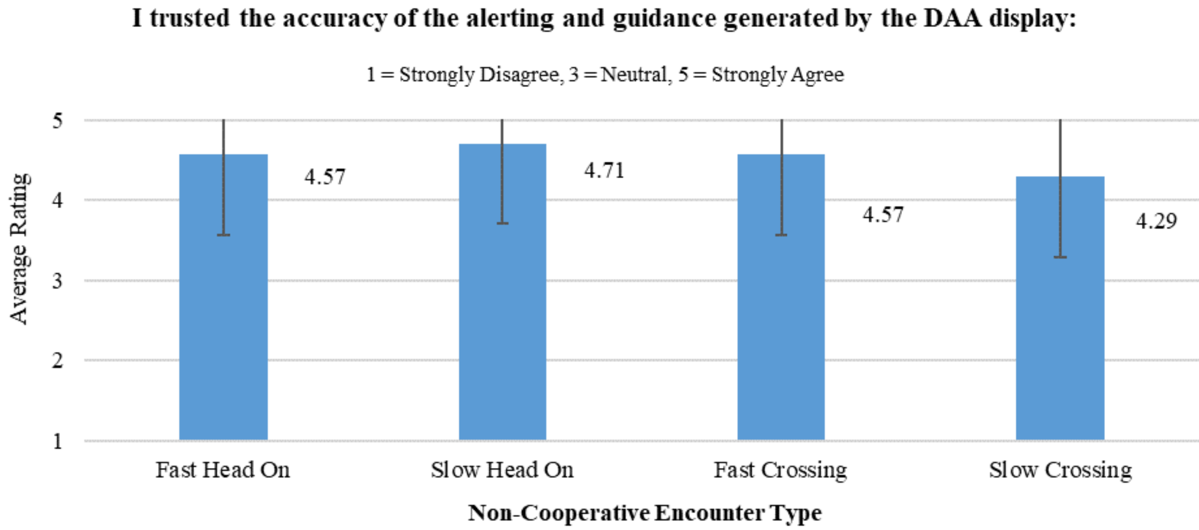


Figure 19: Average agreement ratings for whether subject pilots trusted the accuracy of the DAA alerting and guidance

4.7.2 Post-Test Questionnaire Results

The post-test questionnaire revealed that all subject pilots believed they had sufficient training on the ground control station and the DAA system to perform the flight test (*N*=7). Most thought that the RGCS display provided enough information to maintain situational awareness, with the majority selecting 'Somewhat Agree' (*N*=2) and 'Strongly Agree' (*N*=5). ATC communications and interactions were 'Moderately Realistic' (*N*=6), with only one subject pilot believing them to be 'Neither Unrealistic nor Realistic' (*N*=1). Similarly, radio traffic was rated as being 'Very Realistic' by the majority (*N*=5) and a smaller minority rating them as 'Somewhat Realistic' (*N*=2). Regarding perceived realism of the UAS mission profile, opinions were split between ratings of 'Very Realistic' (*N*=3) and 'Somewhat Realistic' (*N*=4). During debrief, several participants expressed the desire to see more complicated mission profiles but also understood the constraints of the airspace the test was operating within. However, the majority found the RGCS environment to be acceptable (*N*=6), with only one subject pilot providing a rating of 'Somewhat Agree' (*N*=1). Most found datalink latency between RGCS and UAV to be 'Acceptable' (*N*=6), with only one subject pilot providing a 'Somewhat Agree' (*N*=1) rating.

When asked about the usefulness of maneuver guidance bands (i.e., banding on the tactical situation display) for maintaining DAA well clear, the majority of subject pilots believe them to be useful (i.e., either a rating of 'Strongly Agree' or 'Somewhat Agree') and also trusted the guidance being shown (i.e., ' I trusted the maneuver guidance generated by the DAA system:'). Additionally, the recovery guidance shown to help remain well clear was generally perceived as useful (i.e., 'The recovery guidance (a green wedge on traffic situation display) was useful in regaining DAA well clear'), with the majority of subject pilots providing either a rating of 'Strongly Agree' (*N*=3) or 'Somewhat Agree' (*N*=3) and only one subject pilot providing a rating of 'Neutral'.

When asked regarding their experience with cooperative versus non-cooperative conflicts, most subject pilots felt the encounters were distinct (i.e., 'I was able to differentiate between cooperative (ADS-B) and non-cooperative (RADAR):'), with five subject pilots giving a rating of 'Strongly Agree' and the rest providing a rating of 'Somewhat Agree' (*N*=2). However, opinions were somewhat split regarding whether each encounter type was treated differently (i.e., 'I responded to differently to cooperative and non-cooperative DAA conflicts'). Most subject pilots gave a rating of 'Somewhat Agree' (*N*=4), but the three remaining each provided either a rating of 'Strongly Disagree', 'Somewhat Disagree', or 'Strongly Agree'. Some subject pilots felt neutral (*N*=3) to the idea of providing an indicator for intruder equipage (i.e., 'I would prefer that the display distinguish between cooperative traffic and non-cooperative traffic'), whereas others were favorable to the idea and provided a rating of either 'Somewhat Agree' (*N*=2) or 'Strongly Agree' (*N*=2).

Opinions were again split when asked whether the RDR used in the flight test provided enough to asses DAA conflicts (i.e., 'The RADAR surveillance volume was sufficiently large to assess DAA conflicts'). Most subject pilots provided a rating of 'Somewhat Agree' (*N*=4), while the other three subject pilots provided a rating of 'Strongly Disagree', 'Somewhat Agree', and 'Strongly Agree' respectively. When asked whether the RDR allowed for timely resolution of DAA conflicts (i.e., 'The RADAR surveillance volume was sufficiently large for timely resolution of DAA conflicts'), the majority provided a rating of 'Somewhat Agree' (*N*=4), while the three other subject pilots gave ratings either of 'Strongly Disagree', 'Somewhat Disagree', or 'Neutral'. Finally, subject pilots generally viewed the size of the radar surveillance volume as 'Somewhat smaller than necessary' (N=5), with only two subject pilots viewing the RDR size as being 'Just right' or 'Much smaller than necessary'.

Following the post-test questionnaire, subject pilots were led through a verbal debrief to collect final thoughts on the test. While all subject pilots expressed favorable opinions of the DAA system used for the test, subject pilots expressed a clear desire to see a larger minimum acceptable range than the 2.5 nmi used, especially when considering traffic conflicts with intruders at faster speeds. Acceptable ranges expressed by participants fell between a minimum of 3 to 8 nmi, with most responses falling around 3 to 4 nmi. Several subject pilots noted that the 2.5 nmi range escalated quickly from the DAA Corrective level alert to a Warning DAA alert and did not allow for consistent ability to effectively coordinate with ATC prior to an avoidance maneuver. This was especially true when encounters were at faster speeds than ownship. One subject pilot noted that noted that the short response windows generated with a fast, head on encounter could lead to accidental blunders into the path of other aircraft that are not currently within range. Another subject pilot commented that it would be "unrealistic" for a pilot to be extremely vigilant throughout an entire 3 to 4-hour shift and be in a ready state to respond to "sudden pop-ups." The sentiment was also echoed in a later subject pilot under test's debrief, where the pilot commented that the subject pilots for the study are primed and expecting intruders. The subject pilot further elaborated that for normal UAS operations, a pilot may be focused on other operational tasks and expecting a pilot to be able to immediately jump into an encounter. The vigilance issue could further negatively create issues in a situation where a pilot is less experienced as mentioned by an additional subject pilot.

5. Conclusions

The UAS Integration in the NAS Flight Test 6 Full Mission successfully demonstrated the efficacy minimum surveillance requirements for a Low Size, Weight and Power UAS Detect-and-Avoid system by flying a medium-sized vehicle with human subjects in a simulated National Airspace System scenario. Human subject UAS pilots were able to complete the simulated UAS mission while controlling the NASC Tigershark XP vehicle from the research ground control station and were also able to effectively use the DAA alerting and guidance to avoid non-cooperative traffic with an emulated non-cooperative air-to-air surveillance sensor. The results suggest that a 2.5 nmi surveillance range for a non-cooperative surveillance sensor would provide sufficient time for UAS pilots to remain well-clear of other traffic and avoid near mid-air collisions. The results however suggest that a 2.5 nmi surveillance range would not be sufficient for a corrective alert timeline or ATC coordination.

The encounters flown in the FT6 Full Mission scenario were comparable to the scenarios generated in the Low SWaP HITL study, although the ground speed and track of the manned intruder aircraft in FT6 varied throughout the encounters due to pilots compensating for wind by adjusting heading and groundspeed. The wind compensation by the pilots likely resulted in longer alert times compared to the HITL. The loss of well-clear performance data was comparable to the Low SWaP HITL study with no recorded penetrations of the non-cooperative well-clear volume during the data collection. However, the response times of the subject pilots in FT6 were slower than observed in the laboratory study with an average aircraft response time of 9.42 seconds for warning alert time in FT6 compared to 7.12 seconds compared to the HITL. The difference between FT6 and HITL responses to the corrective level alerts were more pronounced at 13.25 seconds aircraft response time for corrective level alerts in FT6 compared to 8 seconds in the HITL. This longer reaction time was accompanied by a higher rate of coordination with ATC in FT6 compared to the HITL. Lower closure rates between the UAS and manned intruder could explain these differences by allowing a longer corrective alert time, and therefore a longer window to contact ATC, and creating a less urgent encounter as perceived by the subject pilots. While a longer corrective alert timeline and higher rate of ATC coordination might appear to lend support to the inclusion of a corrective alert timeline in the Low SWaP DAA performance standards, analysis of the alert level at key events in the encounter found that by the time the subject pilots commanded the first DAA maneuver a majority of a alerts had progressed to the warning level. This suggests that a corrective alert timeline paired with a 2.5 nmi surveillance range would not allow UAS pilots to coordinate a maneuver with ATC in higher closure rate encounters with non-cooperative traffic before the alert level would change to a warning level, which would negate the need to coordinate with ATC.

The increased maneuver size and number of occurrences of the intruder exiting the field of regard of the sensor emulation is a result which should be investigated further in batch simulation to determine if the minimum surveillance volume requirements should be revisited. Losing surveillance and DAA alerting and guidance removed during a conflict could result in a hazardous situation for the manned pilot or bystanders on the ground. The increased maneuver sizes compared to the HITL was likely due to changing intruder trajectories causing the guidance bands to fluctuate in size or an abundance of caution in maneuver selection by the subject pilots. The need to investigate this issue further is compounded by the fact that an operational non-cooperative surveillance system will likely have additional sensor uncertainty than the ADS-B based state information in FT6. Increasing the azimuth surveillance limits of the non-cooperative sensor would allow DAA alerting and guidance to continue to be displayed during large turns. Increasing the range of the non-cooperative sensor would alternatively allow turns to be made earlier and further away from the DWC boundaries, reducing the minimum required turn.

Predictably, encounters with higher speed intruders resulted in higher NASA TLX workload ratings in mental and temporal demand than encounters with slow intruders. This corresponded with higher perceived performance and lower frustration on encounters with slow intruders. This result seems to indicate that either additional decision support (e.g. ground speed readouts on the DAA display) and/or training for fast intruders may be beneficial in an operational environment, although not necessarily a minimum requirement. This additional support would be especially important in encounters with fast intruders that may be more difficult for a non-cooperative surveillance system to detect, such as a single engine piston aircraft with composite construction that are capable of high cruise speeds. On the subjective ratings, the subject pilots rated the timeliness of the alerting for non-cooperative encounters higher for encounters with a slow intruder than encounters with fast intruders, which corresponds with the longer alerting times that slow intruder encounters expected with lower closure rates. Additionally, subject pilots rated the stability of the encounters with a slow intruder higher than the encounters with fast intruders. This further reinforces the potential benefit of providing additional decision support or training to UAS operators.

Subject pilots found the DAA guidance bands to be helpful in all types of encounters and generally stated that they trusted the guidance that was displayed to them during FT6. This indicates that the concept of guidance bands for operational UAS missions is viable and should be used as a model for future certified DAA systems. Future research into display requirements for ground control stations could be expanded to investigate how the guidance band concept be used in other UAS functions such as guidance for avoiding terrain, obstacle, weather and restricted airspace.

Acceptability of the 2.5 nmi RDR in the questionnaire and debrief interviews indicate that the subject pilots desired a greater surveillance range. Pilots felt that this range allowed them to avoid traffic conflicts, it did not allow for coordination with ATC and a longer range would provide earlier notification of conflicts during periods of either task saturation or reduced vigilance. Future research could investigate whether the extension of the DAA warning alert timeline and removal of the corrective DAA alert would allow for a 2.5 nmi RDR to be acceptable to pilots and ATC. While the focus of the current effort was to determine minimum performance standards, these responses from subject pilots should be taken into consideration in the development of Low SWaP surveillance systems as longer RDR would allow a greater margin of safety and potentially less interference with traffic flow.

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Appendix A. Primary and Backup Flight Plan Profiles

Figure 20: Nominal Flight Plan

Figure 21: Four Corners Alternate Flight Plan

Figure 22:Mercury Spin Alternate Flight Plan

Appendix B. Post-Encounter Questionnaire

Post-Encounter Questionnaire

<u>This section to be completed by researcher</u> **Pilot #:**

<u>ENCOUNTER 1</u>

NASA Task Load Index (TLX):

Hart and Stavelands NASA Task Load Index (TLX) assesses workload on a 7-point scale, ranging from Very Low to Very High.

Please select the tick mark that best represents your workload in each of the dimensions below:

<u>Mental Demand</u>: *How mentally demanding was the task?*

Very Low | | | | | | Very High

<u>Physical Demand</u>: *How physically demanding was the task?*

Very Low | | | | | | Very High

<u>Temporal Demand</u>: *How hurried or rush was the pace of the task?*

Very Low | | | | | | Very High

<u>Performance</u>: *How successful were you in accomplishing what you were asked to do?*

Perfect | | | | | | Failure

<u>Effort</u>: *How hard did you have to work to accomplish your level of performance?*

Very Low | | | | | | Very High

<u>Frustration</u>: *How insecure, discouraged, irritated, stressed, and annoyed were you?*

Very Low | | | | | | Very High

Please select the response that best represents your answer:

1. The DAA alerting provided sufficient time to resolve this encounter:

Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree

2. The DAA alert level (e.g., the Warning alert, the Corrective alert) for this encounter was sufficiently stable (i.e., it did not fluctuate between alert levels):

Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree

3. The display of the DAA guidance bands was sufficiently stable for this encounter (i.e., the banding did not "jump around" excessively):

Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree

4. I was able to achieve sufficient separation from the intruder aircraft(s) using the alerting and guidance in this encounter:

Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree

5. The DAA guidance bands were useful for solving this encounter:

Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree

6. Sensor noise or alerting and guidance instability **did not** impact my ability to maintain sufficient separation from traffic:

Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree

7. Winds aloft **did not** impact my ability to maintain sufficient separation from traffic:

Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree

8. My interactions with ATC **did not** impact my ability to maintain sufficient separation from traffic:

Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree

9. I trusted the accuracy of the alerting and guidance generated by the DAA display:

Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree

Appendix C. Post-Simulation Questionnaire

Post-Flight Test Questionnaire

<u>This section to be completed by researcher</u> **Pilot #:**

Section I – Basics

Please select the response that best represents your answer:

1. I received sufficient training on the ground control station and the DAA system to perform today's flight test:

Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree

2. The ground control station display provided enough information to maintain situation awareness throughout the flight test:

Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree

3. How realistic were the chat questions?

Very Unrealistic	Somewhat Unrealistic	Neither Unrealistic nor Realistic	Somewhat Realistic	Very Realistic

4. I could easily manage chat questions without negatively impacting mission performance:

Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree

5. How realistic was the Air Traffic Controller in the simulation?

Very Unrealistic	Somewhat Unrealistic	Neither Unrealistic nor Realistic	Somewhat Realistic	Very Realistic

6. How realistic was the radio traffic in the simulation?

Very Unrealistic	Somewhat Unrealistic	Neither Unrealistic nor Realistic	Somewhat Realistic	Very Realistic

7. How realistic was the UAS mission profile?

Very Unrealistic	Somewhat Unrealistic	Neither Unrealistic nor Realistic	Somewhat Realistic	Very Realistic
If not, please explain:				

8. The GCS environment (lighting, temperature, ambient noise) was acceptable:

Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree
If not, please explain:				

9. The datalink latency between the GCS and the UAV was acceptable:

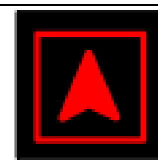
Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree

---

Section II – DAA Alerting & Guidance

Please select the response that best represents your answer:

Refer to the scale provided in the top left of the table.
Please circle the appropriate number for each cell:

Scale 1 = Strongly Disagree 2 = Somewhat Disagree 3 = Neither Agree nor Disagree 4 = Somewhat Agree 5 = Strongly Agree			
	Preventive DAA Alert *"Traffic, Monitor"*	***Corrective DAA Alert*** *"Traffic, Avoid"*	***Warning DAA Alert*** *"Traffic, Maneuver Now"*
1. The visual display of this alert (i.e., icon color, shape, etc.) was easy to understand	**1 2 3 4 5**	**1 2 3 4 5**	**1 2 3 4 5**
2. The visual display of this alert was clearly distinguishable from the other visual alerts	**1 2 3 4 5**	**1 2 3 4 5**	**1 2 3 4 5**
3. The auditory message associated with this alert was clearly distinguishable from other auditory alerts	**1 2 3 4 5**	**1 2 3 4 5**	**1 2 3 4 5**
4. This icon was useful for maintaining DAA Well-Clear	**1 2 3 4 5**	**1 2 3 4 5**	**1 2 3 4 5**
5. Based on this alert, I would contact ATC and *then* maneuver	**1 2 3 4 5**	**1 2 3 4 5**	**1 2 3 4 5**

6. Based on this alert, I would maneuver *prior* to contacting ATC	**1 2 3 4 5**	**1 2 3 4 5**	**1 2 3 4 5**

7. The maneuver guidance bands (i.e., banding on the tactical situation display) were useful for maintaining DAA well clear:

Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree

8. I trusted the maneuver guidance generated by the DAA system:

Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree

9. The maneuver resolutions generated by the DAA systemwere reasonable:

Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree

10. The recovery guidance (a green wedge on traffic situation display) was useful in regaining DAA well-clear:

Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree	N/A

Section III – RADAR System

Please select the response that best represents your answer:

1. I was able to differentiate between cooperative (ADS-B) and non-cooperative (RADAR) traffic:

Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree

2. I responded to differently to cooperative and non-cooperative DAA conflicts:

Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree

3. I would prefer that the display distinguish between cooperative traffic and non-cooperative traffic:

Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree

4. The RADAR surveillance volume was sufficiently large to assess DAA conflicts:

Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree

5. The RADAR surveillance volume was sufficiently large for timely resolution of DAA conflicts:

Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree

6. The size of the RADAR surveillance volume was:

Much Larger Than Necessary	Somewhat Larger Than Necessary	Just Right	Much Smaller Than Necessary	Somewhat Smaller Than Necessary

7. What would you consider the minimally acceptable RADAR detection range for the types of encounters you experienced today? (*Please write your response in the field below, in nautical miles*)

Section IV – Overall Impressions

1. Which factors were most influential when deciding how to maneuver against DAA intruders?

2. Were there any aspects of the ground control station (e.g., moving map, vehicle control interfaces, traffic alerting and guidance) that negatively impacted your ability to perform the task?

3. Were there any information elements that you believe the ground control station lacked that are necessary for the performance of today's task?

4. Did any aspects of the simulated environment (e.g., the translated Oakland Center map, the virtual ATC and background traffic) affect your performance today, either negatively or positively?

5. Was the datalink latency between the GCS and UAV noticeable? Did it influence your decision making?

6. Would you feel comfortable flying with this DAA system in the National Airspace System today?

Appendix D. Pilot Demographics and Background Questionnaire

Pilot Demographics

Please fill in the blanks or circle your response to each question below

Age: ___________

PART I – Manned Pilot Experience
(Please do not include experience with unmanned/remote systems in your responses to the questions in Part I)

1. Do you have manned flying experience? Yes No

   If "Yes," please complete the following by circling or filling in the appropriate answer:

   a. Military: Yes No

   b. Approximate flight hours for the following types:

      Civilian: ______ Military Non-Combat: ________ Military Combat:______

2. Are you IFR rated? Yes No

   a. Other ratings: ____

   b. Aircraft Types: ____

3. Rate your familiarity with the following systems:

   a. The Traffic Alert and Collision Avoidance System (TCAS II), which provides Traffic Advisories and Resolution Advisories against potential threats:

Not Familiar	Somewhat Familiar	Familiar	Very Familiar	Expert

   b. Other traffic displays, such as a multifunction display or tablet?

Not Familiar	Somewhat Familiar	Familiar	Very Familiar	Expert

   c. "Technically advanced aircraft" - i.e., aircraft with GPS, moving map display, autopilot, etc.:

Not Familiar	Somewhat Familiar	Familiar	Very Familiar	Expert

   d. Airborne air surveillance RADAR:

Not Familiar	Somewhat Familiar	Familiar	Very Familiar	Expert

e. Ground-based air surveillance RADAR:

Not Familiar	Somewhat Familiar	Familiar	Very Familiar	Expert

f. Airborne weather RADAR:

Not Familiar	Somewhat Familiar	Familiar	Very Familiar	Expert

g. Ground based weather RADAR:

Not Familiar	Somewhat Familiar	Familiar	Very Familiar	Expert

h. Airborne ground surveillance RADAR:

Not Familiar	Somewhat Familiar	Familiar	Very Familiar	Expert

4. Have you ever utilized the full flight-planning functionality of the Flight Management System or GPS in aircraft you have flown? Yes No

5. How familiar are you with using computer graphical interfaces with a mouse and keyboard?

Not Familiar	Somewhat Familiar	Familiar	Very Familiar	Expert

PART II – Unmanned/Remote Pilot Experience

6. Do you have unmanned/remote flying experience? Yes No

   If "Yes," please complete the following by circling or filling in the appropriate answer:

   a. Training: 18X Undergraduate Pilot Training Other:_______

   b. Military: Yes No

   c. Approximate flight hours for the following types:

   Civilian: ______ Military Non-Combat: _______ Military Combat:______

7. How would you rate your familiarity with flying into Class D airports (with unmanned/remote aircraft)?

Not Familiar	Somewhat Familiar	Familiar	Very Familiar	Expert

8. Unmanned/remote aircraft Types:

PART III – Flight Simulator Experience

9. Do you have any desktop flight simulation experience on programs such as MS Flight Sim? Yes No

10. Do you have any flight simulation experience on certified rated flight training simulators? Yes No

11. Do you have any flight simulation experience using Vigilant Spirit Control Station? Yes No

Appendix E. NASA TLX Workload Ratings Across All Encounters and Elements

Table 6: Average NASA TLX Scores Across Encounter Types

	Non-Cooperative Encounter Type			
	Fast Head On	Slow Head On	Fast Crossing	Slow Crossing
NASA TLX Dimension	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)
Mental	3.57 (1.90)	2.57 (1.72)	4.14 (2.12)	3.00 (2.16)
Physical	1.14 (0.38)	1.14 (0.38)	1.14 (0.38)	1.14 (0.38)
Temporal	4.14 (2.04)	3.14 (1.77)	4.43 (2.23)	3.71 (1.50)
Performance	2.57 (0.96)	1.86 (0.90)	2.29 (0.76)	2.43 (1.40)
Effort	3.29 (2.14)	2.57 (1.81)	3.29 (1.95)	2.86 (1.89)
Frustration	2.57 (1.81)	1.86 (1.46)	3.14 (2.12)	2.43 (1.81)

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14. ABSTRACT

Recent standards development efforts for the integration of Unmanned Aircraft Systems (UAS) into the National Airspace System (NAS) such as those in RTCA Inc. Special Committee 228 (SC-228) have focused on relatively large UAS transitioning to and from Class A airspace. In an effort to expand the range of vehicle classes that can access the NAS, the NASA UAS Integration in the NAS project has investigated Low Size, Weight, and Power (Low SWaP) technologies that would allow smaller UAS to detect-and-avoid (DAA) traffic. Through batch and human in the loop (HITL) simulation stu

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