Unmanned Aircraft System Flight-test Approach Supporting the Development of Regulatory Recommendations for Integration with the National Airspace System

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ABSTRACT

The National Aeronautics and Space Administration Unmanned Aircraft Systems Integration in the National Airspace System Project performed research that was critical to developing minimum operational performance standards for systems that will enable unmanned aircraft systems to routinely access the National Airspace System. As part of this research effort the project conducted a series of flight tests that validated several technologies and procedures which were key to developing the minimum operational performance standards, which will in turn guide industry in certifying unmanned aircraft systems. Flight Test Series 3 and Series 4 focused on unmanned aircraft systems operations using larger vehicles, with performance characteristics similar to transport category manned aircraft, transitioning through Class E airspace. The Flight Test 3 and Flight Test 4 efforts utilized the NASA Ikhana unmanned aircraft system, a civilianized General Atomics – Aeronautical Systems Inc. (San Diego, California, U.S.A.) MQ-9 Predator/Reaper, outfitted with a General Atomics developed detect and avoid system

that included an air-to-air radar providing non-cooperative sensing capability to validate the detect and avoid algorithms and separation criteria. These flight tests also enabled the development and testing of a test architecture and infrastructure needed for subsequent flight tests.

The flight test series conducted by the Unmanned Aircraft Systems Integration in the National Airspace System Project culminated with the Flight Test 6 effort that used a Navmar Applied Sciences Corporation (Warminster, Pennsylvania, U.S.A.) TigerShark XP unmanned aircraft system to investigate low cost, size, weight, and power operations in the National Airspace System. The Flight Test 6 effort incorporated lessons learned from all the earlier flight-test activities, including Flight Test 3 and Flight Test 4, and implemented a "full mission" simulation of low cost, size, weight, and power unmanned aircraft systems operations in a representative airspace environment. The full mission simulation allowed a number of metrics to be collected that were valuable to the minimum operational performance standards development process, including human response times, performance in remaining well-clear of aircraft, and the acceptability of the complete unmanned aircraft system. To create a representative airspace environment, the NASA live virtual constructive distributed environment was utilized to combine multiple assets from across NASA into a single, coherent simulation.

1.0 INTRODUCTION TO THE INTEGRATION OF UNMANNED AIRCRAFT SYSTEMS IN THE NATIONAL AIRSPACE SYSTEM

At the beginning of this century, acknowledging an increasing need to be able to fly unmanned aircraft systems (UAS) in the United States National Airspace System (NAS) to perform missions of vital importance to national security and defense, emergency management, science, and to enable commercial applications, the National Aeronautics and Space Administration (NASA) took on the challenge to enable routine access by UAS in the NAS. Beginning in 2011, the NASA Aeronautics Research Mission Directorate (ARMD) established the UAS Integration in the NAS (or UAS-NAS) Project to help address the key challenges to safe UAS access and integration into the NAS.

1.1 The History of Unmanned Aircraft Systems at NASA

Early on, NASA took into consideration inputs from various sources in the UAS community that indicated opportunities where the Agency could be uniquely helpful. For example, the 2006 Decadal Survey identified a future increase in commercial applications of UAS and pointed out how these new applications "should be integrated" into the NAS. Other documents, including the Fiscal Year 2009 NASA Authorization Bill, called for NASA to cooperate with other United States federal government agencies, academia, and industry in advancing UAS access to the NAS.

Why NASA should lead such research was evidenced by the Agency's own history. The NASA has been key in advancing the development and use of remotely piloted airplanes, from line-of-sight (LOS) flight tests, to routine beyond line-of-sight (BLOS) operations, to pre-programmed and semi-autonomous flight demonstrations. The NASA has also been the catalyst for moving UAS from their unique science and research applications to commercial and emergency applications and has led the way in moving their research and science missions and operations from restricted, well segregated airspace, into the more general NAS – effectively demonstrating how to safely share the airspace with commercial and private operators.

From the 1990s and into the early 2000s, NASA was actively involved with the Environmental Research Aircraft and Sensor Technology (ERAST) program, led by the NASA Science Mission Directorate (SMD), which advanced the development of UAS and sensor technologies. Among the aircraft that were developed under the

ERAST program were the solar-powered aircraft from AeroVironment Inc. (Arlington, Virginia, U.S.A.), including Pathfinder, Pathfinder Plus, and Helios; and the General Atomics - Aeronautical Systems Inc. (GA-ASI) (San Diego, California) Altus and Altair, the predecessors to their Predator, Reaper and SkyGuardian UAS.

The NASA and the Federal Aviation Administration (FAA) have a rich history of collaboration. There are several examples of early research partnerships between these two agencies that involved unmanned aircraft operations. A notable early collaboration was the Controlled Impact Demonstration (CID) conducted in 1984 on a Boeing 720 (B-720) (The Boeing Company, Chicago, Illinois) to test a kerosene-based fuel additive. Laboratory testing had indicated that the fuel additive would inhibit flames in the passenger compartment in the event of a crash. A B-720 aircraft was modified to be flown as an unmanned, remotely piloted vehicle, and flown to crash land at Edwards Air Force Base (EAFB). The spectacular explosion during the demonstration proved the kerosene-based fuel additive performed in the opposite manner than anticipated, and the fuel additive was not approved for use by the FAA.

In 1991 NASA and the FAA began collaboration on the Center-Terminal Radar Approach Control Facility (TRACON) Automation System, or CTAS, project. This project was initiated by the FAA Field Office at the NASA Ames Research Center (ARC) (Moffett Field, California. U.S.A.) and was the first attempt to formalize long-term research collaboration between the two agencies. Substantial interactions between NASA and the FAA ensued under the Advanced Air Transport Technology (AATT) project. Elements from the AATT project were later captured under the other ARMD programs and projects.

Between 2001 and 2006, the NASA Aeronautics Research Mission Directorate (ARMD) established an FAA Partnership Manager position, which increased collaborations and led to formalized partnership under the FAA Coordinating Committee, established in 2007. Several Research Transition Teams (RTT) have been established since, beginning with an RTT focused on Flow Based Trajectory Management and continuing to the UAS Integration RTT that concluded shortly after the UAS-NAS project.

The NASA insights into UAS development, together with the historical interactions with the FAA, provided the framework for the UAS-NAS Project collaboration that followed, and in particular helped cement and focus the path for the subsequent UAS-NAS Project research activities.

1.2 The Development of the UAS-NAS Project

A "Meeting of Experts" was hosted by the Agency in 2010. These subject matter experts (SMEs) addressed what NASA involvement with UAS integration ought to be. The plan for the UAS-NAS project was already vetted with the UAS community at this point, and feedback from this interface led to the approval for the initial formulation of the project. The UAS-NAS project formally began its initial formulation by assembling experts from the different NASA aeronautics Centers: ARC; the NASA Langley Research Center (LARC) (Hampton, Virginia, U.S.A.); the NASA Glenn Research Center (GRC) (Cleveland, Ohio), and the NASA Armstrong Flight Research Center (AFRC) (then, the NASA Dryden Flight Research Center, DFRC) (Edwards, California, U.S.A) to collaborate in the formulation effort in partnership with the FAA. The deliberate emphasis was to obtain routine access of UAS in the NAS for civil and commercial purposes. This focus helped determine what technical areas to address - those areas that were necessary to obtain UAS access to the NAS in which NASA had unique capabilities to support. The Project defined Technical Challenges (TCs) for each of the technical areas with quantitative metrics that were appropriate to capture progress and technology maturation.

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The technical areas that were identified for NASA contributions included separation assurance, collision avoidance, detect and avoid (DAA), pilot aircraft interface, certification requirements, and communications. Technical Challenges and research activities were identified to address key aspects of these technical areas. Eventually those TCs consisted of Command and Control (C2); DAA, which included Human Systems Integration (HSI); and Systems Integration and Operationalization (SIO).

Through all of the formulation activity, in addition to working closely with the FAA, NASA sought and obtained inputs from the UAS community at large through different forums comprised of critical stakeholders.

The project consisted of two phases: Phase 1 (2011 to 2016); and Phase 2 (2016 to 2020). For Phase 1, the UAS-NAS project focused on DAA aspects during the transitioning of a Group 5 UAS through Class E to Class A airspace. A Group 5 UAS is one the maximum gross take-off weight (MGTOW) of which is greater than 1320 lb, and that can fly above flight level (FL) 180. For Phase 2, the DAA research focus was expanded to include sustained operations of a Group 3 UAS at lower altitudes, from above 500 ft above ground level (AGL), up to approximately 10,000 ft mean sea level (MSL); where there is higher preponderance of non-cooperative traffic, making the on-board DAA system more critical. A Group 3 UAS is one whose MGTOW is less than 1,320 lb, that cannot fly above FL 180, and flies at speeds slower than 250 kn.

Specific operating environments were also identified for the Phase 1 and Phase 2 C2 TC work. In Phase 1, the C2 efforts, as with DAA, involved transition through Class E airspace to Class A airspace. In Phase 2, the C2 efforts expanded to include low size, weight, and power (SWaP) radios. The emphasis was sustained operation in what was termed a “visual flight rules -like” (“VFR-like”) environment - an environment in which an aircraft with a pilot on board would operate under VFR. Phase 2 work also included studies on satellite and long-term evolution (LTE) communications for UAS C2.

The DAA flight-test operations were primarily performed from the AFRC located on EAFB in the high desert of California. Phase 1 flight-test activities collected data supporting the development and integration of system-level key concepts, technologies, and procedures based on UAS stakeholder and community needs collected during UAS-NAS project formulation. The Phase 1 flight-test activity also provided a means by which to demonstrate those key concepts, technologies, and procedures as integrated technologies flown in operationally relevant environments.

The primary focus of the Phase 1 effort aligned with the development of RTCA Special Committee (SC)-228 minimum operational performance standards (MOPS) for DAA and C2 data-link equipment. The SC-228 Phase I MOPS development focused on civil UAS equipped to operate in Class A airspace under instrument flight rules (IFR) and using L-band terrestrial and C-band terrestrial data links. The SC-228 Phase I MOPS operational environment was defined as the transitioning of a UAS to and from Class A airspace, or special use airspace, and traversing Class D, Class E, and Class G airspace. The UAS-NAS Phase 1 research findings contributed to the development of the RTCA SC-228 Phase I final DAA, Air-to-Air Radar (ATAR), and C2 data-link MOPS, and provided foundational research associated with full integration of UAS into the NAS. The DAA activity in Phase 1 of the UAS-NAS project culminated with the No-Chase COA (Certificate of Waiver Authorization), or NCC, demonstration. This flight demonstrated the application of DAA MOPS to achieve approval for and to perform a UAS flight traversing from Class A airspace to Class E airspace.

Phase 2 of the UAS-NAS project continued to focus on DAA and C2, and added the SIO activity to address demonstrations of commercial applications. The focus of the DAA and C2 TCs in Phase 2 again aligned efforts with the RTCA SC-228 Phase II MOPS development. The RTCA Phase II MOPS development expanded on the Phase I MOPS to specify DAA equipment to support extended UAS operations in Class D, Class E, and Class G airspace, to provide standards for the use of satellite communications (SATCOM) in multiple bands as a C2 data link to support UAS, and to include low-SWaP equipment to enable mid-size UAS operations.

This paper summarizes some of the key initial flight tests performed under the UAS-NAS project, and provides a closer focus on the final flight-test activity, Flight Test 6 (FT6), which involved considerable HSI test planning and execution. The data collected from the NASA flight tests were instrumental in the analyses performed by NASA and its partners helping inform the development of RTCA MOPS that in turn helped with the development by the FAA of Technical Standard Orders (TSOs).

1.3 Key Initial Flight Tests

Over the life of the UAS-NAS project the flight tests evolved with increasing complexity and capability. Hundreds of encounters were performed in numerous flights that comprised six distinct flight-test campaigns, grouped into two programmatic phases. Flight tests involved encounters between the research UAS, or "ownship," and one or more "intruder" manned aircraft. The Phase 1 flight tests were primarily conducted using the NASA-owned Ikhana UAS, a civilianized MQ-9 Predator B or Reaper UAS, as the ownship. The Phase 2 activity culminated with the use of a TigerShark XP UAS from Navmar Applied Sciences Corporation (NASC) (Warminster, Pennsylvania, U.S.A.) as the ownship. The series of flight tests included carefully planned and "scripted" encounters between the ownship and different (and at times multiple) "intruder" aircraft. The intruder aircraft were primarily other NASA aircraft that were instrumented as needed for the particular flight test. During Phase 2, flight-test activity reached its climax with the "full mission" capability, which used what the teams had developed and learned in early flight-test campaigns to support a comprehensive HSI data gathering. The following discussion addresses the purpose and results from key flight tests that contributed toward informing the development of MOPS. Particular attention is given to the accomplishment of "full mission" goals during the final flight-test campaign.

1.3.1 Flight Test 3

The purpose of Flight Test 3 (FT3) was primarily to validate the results of previously completed simulations using live data. Additionally, FT3 evaluated the Traffic Collision Avoidance System (TCAS) II / Self Separation (SS) interoperability and tested a fully integrated DAA system on a UAS in a relevant flight environment, thus reducing the risk for Flight Test 4 (FT4).

The approach taken for FT3 was to increase the complexity used in simulated encounters in laboratory testing, such as with the integrated human-in-the-loop (IHITL) work, to improve the MOPS definition. The scenarios for the encounters focused on testing the DAA pilot workload, sensitivity and maneuver negotiation. The flight test encounters designed for FT3 were assessed during the performance of the flights, as were candidate pilot displays. The flight tests assessed the end-to-end performance during traffic encounters, including pilot performance and pilot guidance generated by the systems under test (SUT), namely the SS and collision avoidance (CA) algorithms that considered ownship, TCAS II inputs, and total system latency.

1.3.1.1 Flight-test Assets

The ownship used for FT3 was the NASA-owned Ikhana UAS equipped with an ATAR that was part of the DAA system developed by GA-ASI, in collaboration with Honeywell (Charlotte, North Carolina, U.S.A.), both partners to NASA for this activity. The Ikhana UAS was piloted from its ground control station (GCS) equipped to provide pilots with the competing displays showing the DAA information generated from the SUT.

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The intruder aircraft was primarily a Honeywell-owned King Air C90 aircraft. The King Air was equipped with TCAS II and had an onboard TCAS recording capability. For some encounters, a NASA owned T-34C Turbo Mentor (Beech Aircraft Company, now Raytheon Technologies, Waltham, Massachusetts, U.S.A.) was used as the intruder, and for high speed encounters a NASA F/A-18 (McDonnell Douglas, now The Boeing Company, Chicago, Illinois, U.S.A.) was used as the intruder.

On the ground, separate locations were used for collecting and observing engineering data and for providing flight test control and coordination for each of the encounters. All flight tests were conducted in sanitized airspace inside the EAFB complex.

1.3.1.2 Flight-test Performance

For all the flights, the Ikhana UAS was the ownship flying against one or two intruders. Data to evaluate SS and CA algorithms were collected during these flights. Some encounters were designed for the ownship pilot to use data from the SUT to generate a response, these were termed “mitigated” encounters. The mitigated encounters were designed to evaluate the ownship pilot response to SUT-generated alerts commanding ownship to maneuver away from the Collision Avoidance Threshold (CAT) or Near Mid-Air Collision (NMAC) thresholds to maintain a well clear distance between participating aircraft.

Similarly, encounters in which the ownship pilot was not to use the data generated by the SUT for maneuvering, but rather fly the planned path for that encounter were termed “unmitigated” encounters. The unmitigated encounters required that pilots not respond to alerts generated by the SUT, which allowed evaluation of the ability of the SUT to maintain the correct alerting displayed through the encounter.

The SUT included the Java Architecture for DAA Extensibility and Modelling (JADAM)[1], the Stratway +[2], the Conflict Prediction and Display System (CPDS)[3], the ATAR[4] and TCAS. All SUT supported the mitigated encounters, except for the ATAR. All SUT supported the unmitigated encounters, except for the CPDS and TCAS.

The encounters addressed a variety of scenarios. The test parameters included the speed at which the participants approached each other, the altitude at which the ownship flew, the vertical separation at the closest point of approach (CPA), and the angle at which the intruder aircraft flew toward the path of the ownship.

It is important to note that careful planning and adherence to rules took place in order to safely execute these encounters. All encounters were vertically offset by at least 200 ft at CPA, and for flights in which encounters within 500 ft of vertical separation were to be flown, an in-air calibration of the ownship altimeter and the intruder aircraft altimeter was performed at the start of the flight. Additionally, in order to proceed with an encounter, the intruder aircraft pilot had to confirm visual acquisition of the ownship and other intruder aircraft within certain minimum separation limits for the given encounters.

1.3.1.3 Flight-test Results

The flight data provided sufficient data to evaluate, validate, and demonstrate DAA operations in a flight environment, allowing for validation of the simulation data. Together, the live and simulated data contributed to

[1] Developed by the NASA Ames Research Center, Moffett Field, California, U.S.A.
[2] Developed by the NASA Langley Research Center, Hampton, Virginia, U.S.A.
[3] Developed by GA-ASI (San Diego, California, U.S,A., and TU Delft (Delft University of Technology, Delft, Netherlands).
[4] Developed by GA-ASI, San Diego, California, U.S.A.

the development of recommended distances at which avoidance maneuvers are necessary to maintain a safe separation.

The flight-test approach followed for FT3 supported the development and improvement in the scripting of encounters for FT4. The JADAM and CPDS were selected as pilot display algorithms to pursue for further testing.

1.3.2 Flight Test 4

The primary purpose of FT4 was to collect data to inform the development of DAA and ATAR MOPS by RTCA. Specific areas of interest were:

- To validate the DAA requirements in stressing cases that drive the DAA MOPS requirements, including, high-speed cooperative intruder, low-speed non-cooperative intruder, high vertical closure rate encounter and Mode C/S-only intruder — that is, without Automatic Dependent Surveillance-Broadcast (ADS-B).
- To validate the TCAS/DAA alerting and guidance interoperability concept in the presence of realistic sensor, tracking, and navigational errors, and in multiple-intruder encounters against both cooperative and non-cooperative intruders.
- To validate Well-Clear Recovery (WCR) guidance in the presence of realistic sensor, tracking, and navigational errors.
- To validate DAA alerting and guidance requirements in the presence of realistic sensor, tracking, and navigational errors.
- To collect data to support development and validation of trajectories specified in the DAA MOPS for DAA system acceptance testing.

As with FT3, FT4 involved end-to-end traffic encounter evaluation of pilot guidance generated by the SUT. The scripted encounters for FT4 built on the FT3 work but added several types of aircraft, as well as scenarios with multiple intruder encounters.

1.3.2.1 Flight-test Assets

As with FT3, the ownship used for FT4 was the NASA-owned Ikhana UAS equipped with an improved ATAR that was part of the DAA system developed by GA-ASI, in collaboration with Honeywell, both partners to NASA for this activity. The Ikhana UAS was piloted from its own GCS, equipped to provide pilots with the competing displays showing the DAA information generated from the SUT. Competing displays were not used simultaneously by pilots on the same flights, but rather distinct flights were dedicated to assess specific displays.

The intruder aircraft was primarily a Honeywell-owned King Air C90 aircraft. The King Air was equipped with TCAS II and had an onboard TCAS recording capability. The secondary intruders were the NASA T-34C used in FT3, and a NASA-owned King Air. A NASA G-II (Gulfstream Aerospace Corporation, Savannah, Georgia, U.S.A.) was the high-speed intruder, and a NASA TG-14 was the low-speed intruder. A USAF C-12 (Beechcraft, Wichita, Kansas, U.S.A.) was used as a Mode-C-only intruder.

Ground assets were similar to those used in FT3; separate locations for data collection, mission control, and flight control were used for FT4, but with improved capabilities. Data collection and engineering observations were conducted from a separate site, the Live Virtual Constructive (LVC) laboratory. Flight-test control was provided and coordinated for Mission Control Center 3, a NASA control room. The Ikhana was flown from its own GCS. All flight tests were conducted in sanitized airspace inside the EAFB complex.

1.3.2.2 Flight-test Performance

For all the flights, the Ikhana UAS was the ownship flying scripted encounters against one, two, or four intruder aircraft. Data collected supported the evaluation of SS and CA algorithms that were active during these flights.

As was the case with FT3, mitigated and unmitigated encounters were designed for each of the participating aircraft. The SUT for FT4 included the JADAM, the Detect and AvoID Alerting Logic for Unmanned Systems (DAIDALUS)[5] software, the GA-ASI CPDS, the GA-ASI ATAR, TCAS, the Honeywell Tracker Fusion software, and the SS algorithms. All SUT supported the mitigated encounters, except for the ATAR and the Tracker. All SUT supported the unmitigated encounters, except for the CPDS and TCAS.

A flight-test matrix was used in developing the different encounters. The matrix addressed the different combinations of aircraft, as well as aircraft software and hardware combinations supporting each of the SUT; encounter geometries, with specific objectives for that encounter for each research team; evaluation criteria; success criteria; and expected results. This information helped the test team schedule aircraft and aircraft configurations for flight days, as well as organize the flight day encounters to maximize flight-test execution efficiency.

To improve effective use of airspace available for UAS work on the day of flight, alternate encounters were also developed. These were encounters that could be performed in reduced airspace but still satisfy minimum success criteria for a subset of objectives.

As with FT3, careful planning and adherence to rules took place in order to safely execute these encounters. All encounters were vertically offset by at least 200 ft at CPA, and for flights in which encounters within 500 ft of vertical separation were to be flown, an in-air calibration of the ownship altimeter and the intruder aircraft altimeter was performed at the start of the flight. Additionally, in order to proceed with an encounter, the intruder aircraft pilot had to confirm visual observation of the ownship and other intruder aircraft within certain minimum separation limits for the given encounters.

1.3.2.3 Flight-test Results

Flight Test 4 concluded the data collection for Phase 1 of the UAS-NAS project. The data were used for analyses and reports that informed the development of the RTCA SC-228 Phase I DAA MOPS. Significant results were:

- Alert timing was determined to be largely acceptable, providing ample time for a UAS pilot to evaluate guidance and maneuver aircraft in most encounters.
- Well-Clear Recovery guidance was found to be of limited utility for intruders lacking ADS-B.
- Stability of guidance for Mode C intruders appeared adequate, but further investigation was deemed warranted due to the limited sample size, particularly for high-speed, Mode C intruders.
- Unexpected TCAS resolution advisories (RAs) were possible due to differences in predicted horizontal missed distances (HMD) for DAA and TCAS.

2.0 FLIGHT TEST 6

As a follow-on to previous UAS-NAS Flight Test Series and in response to new technical challenges being addressed project-wide, the Flight Test 6 (FT6) flight-research activity was conceived. Flight Test 6 was designed to be a final verification of simulation work conducted by the UAS-NAS DAA subproject which informed the candidate MOPS for low SWaP sensors and a DAA Well-Clear (DWC) definition for non-cooperative vehicles proposed by RTCA SC-228.

Flight Test 6 was conducted in three phases to independently evaluate different objectives and utilized an NASC TigerShark UAS (a Group 3 UAS). The first phase focused on characterizing the performance of a low-SWaP non-cooperative sensor mounted onboard the TigerShark. The second phase evaluated the performance of the candidate non-cooperative DWC in scripted encounters with live manned aircraft. The final phase of the flight test was termed "full mission" and focused on the total human-system performance. The full mission phase incorporated a naïve subject pilot flying the TigerShark in a simulated mission into a mixed live-virtual airspace environment that included simulated and live manned aircraft in addition to a live air traffic control (ATC) element. The resulting flight test validated previous research and simulation work in sensor requirements, DWC sizing, UAS performance, and HSI.

2.1 Non-cooperative Detect-and-Avoid Well-Clear

Designed to interoperate with TCAS, the DWC threshold for transponder-equipped aircraft was characterized as 4000 ft horizontal miss distance (hmd*) and 450 ft vertical height threshold (h*) with 35 s modified tau threshold (τmod*) (Ref. 1). Alternate DAA system requirements with a reduced DWC criteria were explored to accommodate the surveillance range limitations of small-to-medium aircraft with non-cooperative, low SWaP sensors. A fast-time simulation study distinguished two candidate non-cooperative DWC definitions that would minimize the necessary maneuver initiation range (MIR), while also preserving existing alerting and guidance requirements that supported safe and timely conflict avoidance in Phase 1 research studies (Ref. 2). A subsequent human-in-the-loop (HITL) simulation was conducted to evaluate the two candidate DWC definitions in a representative UAS mission scenario with a low SWaP sensor range of 3.5 nmi (Ref. 3). The static DWC definition candidate was comprised of an hmd* of 2200 ft, an h* of 450 ft, and a τmod* of 0 s, whereas the dynamic DWC definition candidate had an hmd* of 2000 ft and a τmod* of 15 s. While objective performance indicated that pilots could consistently remain DWC using either definition with a 3.5-nmi range, encounters with higher closure rates were twice as likely to progress to a warning-level alert when using the DWC definition with the τmod* component. Ultimately, the increased time for caution alerting and ATC coordination enabled by the static hazard zone without τmod* deemed it more suitable for reductions to the radar range requirement on low SWaP sensors.

2.2 Non-cooperative Detect-and-Avoid Sensor

As part of the effort to integrate smaller UAS with more limitations on available SWaP into the NAS, the range and field of regard requirements for non-cooperative sensors were revisited by RTCA SC-228 and the UAS-NAS DAA subproject. Ideally the detection range would be longer than the range required by the DAA alerting system, but not so much to require an unrealistic power supply for the class of UAS. After discussions with industry stakeholders and researchers, a candidate field of regard (FOR) with a target detection range of 2.5 nmi, elevation range of +/-15°, and an azimuth range of +/-110° was recommended.

To evaluate the effectiveness of the candidate FOR parameters in a way that afforded flexibility and avoided sensor noise and uncertainty, an emulation of a low-SWaP sensor was developed. This sensor emulation received live ADS-B aircraft state messages and filtered them so that only aircraft within the simulated FOR were passed on to the research ground control station (RGCS) where they were displayed to the subject pilot. This approach allowed the research team to separate what was seen by the subject pilot and what was seen by the flight-test operations team, which resulted in improved situational awareness.

2.3 Human-Systems Full Mission Integration

Prior to FT6, the HSI Division at NASA ARC conducted a HITL study to inform the minimum detection range needed to maintain sufficient separation performance with the 2200-ft non-cooperative DWC definition (Refs. 3 and 4]. The HITL sought to verify the human performance implications of results from a preceding fast-time simulation (Ref. 2), which revealed that warning alert look-ahead times begin to degrade at approximately 2.0-2.3 nmi when applied to the representative encounter set that would also be tested in FT6. Subject pilots in the follow-up HITL were instructed to remain DWC against scripted encounters with a simulated UAS using a sensor range of 1.5 nmi, 2.0 nmi, 2.5 nmi, or 3.0 nmi. The HITL results confirmed that 2.5 nmi was the minimum range necessary to preserve the full warning alert timeline (that is, 25-30 s) and resolve conflicts without automation support in the worst-case scenarios. In line with Phase 1 research studies, pilot performance degraded when pilots had fewer than 25 s to avoid a conflict. The rate of separation violations significantly rose at ranges below 2.5 nmi. Additionally, variable-duration corrective (caution) alerting was available in most encounters with a 2.5-nmi and 3.0-nmi sensor range, which enabled higher ATC coordination rates prior to DAA maneuvers. These findings supported a minimum detection range of 2.5 nmi for the ATAR emulation and the test encounter set utilized in FT6 (Ref. 5).

2.4 Methods

Execution of the FT6 full mission phase required several geographically distant elements working in concert to create a coherent simulation of the NAS. These elements included aircraft, ground control, and range safety assets from NASA AFRC, the Airspace Operations Laboratory (AOL) at NASA ARC, and the NASC TigerShark UAS. To ensure the smooth execution of the flight test, several rehearsals took place including one with a subject pilot. The rehearsals were crucial to identifying contingency plans and building expectations among the flight operations team. Data collection took place over seven separate flight days in October and November of 2019.

The primary objectives of FT6 full mission were to validate the results of previous HITL studies and to evaluate the total system performance of a Group 3 UAS in a realistic airspace environment. These objectives can only be achieved with human subjects who are qualified UAS operators, have limited or no exposure to previous research on DAA, and are not privy to the goals of the research to avoid potential biases. To meet these requirements, seven UAS operators from outside NASA were recruited to participate. The UAS operators were screened for previous exposure to the UAS-NAS project and other related research efforts. Subject pilots arrived at AFRC the day before their flights and completed informed consent forms and a background questionnaire. Training on the DAA concept, TigerShark UAS, and the Vigilant Spirit Control Station (VSCS) interface was provided in a classroom setting. Subjects were also given exposure to the tasks they were expected to execute in two separate simulation sessions: one the day before the flight and one the morning of the flight. Each research flight lasted between three and four hours and was split into three separate missions with a break between each mission. The primary task of the subjects was to navigate the TigerShark aircraft to remain well-clear of other aircraft and to communicate to the confederate ATC as if they were operating normally within the NAS. Response times to DAA alerts and performance maintaining DWC were recorded during the missions. Subject pilots were also asked to complete secondary tasks while controlling the UAS and communicating with ATC, which involved responding to chat and crew alerting messages. After the completion of the research flight, the subject pilots were asked to complete a post-test questionnaire and discuss their experiences with the research team.

2.4.1 Flight-test Aircraft

The performance characteristics of the NASC TigerShark XP UAS determined its selection as the ownship for FT6 full mission. The TigerShark is a Group 3 UAS with a maximum airspeed of 80 kn and maximum operating altitude above 14,000 ft MSL, and is capable of carrying an 80-lb payload with 900 W of electrical power. For FT6, a TigerShark was outfitted with a prototype low-SWaP radar as part of the effort to characterize a non-cooperative DAA sensor in the first phase of FT6. The TigerShark was also modified with an exhaust injection smoke system to improve visual identification by manned intruder aircraft.

A NASA-owned T-34C was utilized as the live "intruder" aircraft which induced well-clear traffic conflicts during the test. The T-34C was crewed with one pilot and one observer to aid in maintaining visual contact with the TigerShark UAS during the test. The T-34C was 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 TigerShark and also provided wide area augmentation system (WAAS) quality flight data which were used as a source of "truth" for post-flight analysis.

2.4.2 Test Infrastructure

The full mission phase of FT6 required the development of a combined air and ground infrastructure to achieve the goal of testing the full UAS (including air and ground components) in an environment that is representative of the NAS. Outside of the aircraft themselves, the critical components of the test infrastructure included the NASA-developed Live Virtual Constructive - Distributed Environment (LVC-DE) which allowed multiple assets to be connected; and the research ground control station (RGCS) which hosted the subject pilots under test, the safety pilots, the test coordinator, test engineers, and researchers.

2.4.2.1 Live-Virtual-Constructive Distributed Environment

To enable a full simulation of the NAS for the FT6 full mission phase, the NASA Live-Virtual-Constructive - Distributed Environment (LVC-DE) capability was utilized to merge geographically distant assets across NASA (Ref. 6). The live components of the airspace simulation included the TigerShark UAS (ownship) and the T-34C manned aircraft (intruder) flying within the EAFB test range. An Air Route Traffic Control Center (ARTCC) sector within Northern California was simulated by transposing the coordinates of the TigerShark and T-34C aircraft from the EAFB test range. During the airspace simulation, the ownship state from the TigerShark populated the ownship position on the VSCS display while ADS-B from the T-34C populated the position of the intruder aircraft when it entered the FOR of the non-cooperative sensor emulation. Virtual and constructive elements of the airspace simulated included simulated ATC and simulated air traffic that were generated from the NASA ARC AOL. The person functioning as ATC was a trained controller with experience in the Northern California region. The ATC had access to a simulated ARTCC display and was able to communicate via voice over internet protocol (VoIP) to the subject pilot under test and the virtual pilots. The virtual pilots were trained pilots who were asked to operate a part-task simulator where their primary tasks were communicating with ATC and navigating according to airspace procedures and instructions. Both the ATC and virtual pilots were instructed to operate as they would in a flight within the NAS. Constructive traffic was simulated aircraft on pre-programmed routes and operated primarily in sectors adjacent to the sector being simulated for the flight test. The flight-state data of the virtual and constructive aircraft were broadcast into the simulation alongside the state data of the live aircraft, which were in turn displayed on the VSCS display of the subject pilot.

2.4.2.2 The Research Ground Control Station

Subject pilots utilized an RGCS workstation within the NASA Mobile Operations Facility 5 (MOF5). The MOF5 is a NASA mobile trailer that can be configured to support different missions onsite at or offsite from NASA

AFRC. For FT6, NASC used their Mobile Operations Center (MOC) for launch and recovery of the TigerShark, and as a back-up control station for the FT6 missions. Shortly after launching the TigerShark the NASC pilot in the MOC handed control over to the NASA pilot in the MOF5. One end of the MOF5 was configured as the GCS for the TigerShark, while the other end of the MOF5 was physically separated to function as the RGCS for the subject pilots. For full mission flights, the NASA pilot handed off control of the TigerShark to the subject pilot on the other end of the MOF5. The MOF5 was configured with displays using the VSCS software from the Air Force Research Laboratory (Ref. 7). All pilots in the MOF5, NASA and subject pilots, had access to the VSCS displays. The VSCS displays enabled the subject pilots to monitor DAA alerting and guidance on the tactical situation display, navigate the path according to the flight plan, and upload heading hold commands to the TigerShark. There was also a health and status display with a chat window that required pilots to complete secondary tasks. Subject pilots communicated to ATC via headset equipped with a push-to-talk switch. An image of the workstation used in FT6 full mission is contained in Figure 2.4.2.2-1.

For full mission flights, the GCS portion of the MOF5 allowed the NASA pilot to function as a safety pilot. The NASA pilot had the capability to take control from the subject pilot in the RGCS at any time. The safety pilot GCS was used prior to and after the data collection phase of the flight to transition to and from launch and recovery operations. The safety pilot GCS could have also been used to take control of the Tigershark XP in the event of a safety problem, such as if the subject pilot commanded the Tigershark XP to depart the Edwards AFB test range or caused an unscripted encounter with another aircraft.

Figure 2.4.2.2-1: The Vigilant Spirit Control Station control interface located within the Mobile Operations Facility 5 Research Ground Control Station.

2.4.3 Detect-and-Avoid System

The DAA alerting and guidance on the RGCS was generated by the DAIDALUS algorithm (Ref. 8). The DAA alerting and DWC thresholds for cooperative and non-cooperative aircraft for FT6 are defined in Table 2.4.3-1. The DAA guidance bands constantly updated to present ranges of headings that would result in a loss of DWC without further action. At the onset of an alert, pilots commanded a heading outside of the bands to remain DWC. Once traffic was predicted to penetrate the DWC volume within 60 s, the yellow "Corrective DAA" alert would caution the pilot to start coordinating an avoidance maneuver with ATC. The duration of the corrective alert, a system-generated recommended maneuver to avoid violation of the DWC volume around the ownship, was dependent upon the speed and approach angle of the intruder, with the fastest closure rate encounter allowing no caution-level alerting against non-cooperative traffic detected at the 2.5 nmi ATAR range. When traffic was within 30 s of violating DWC, the red "DAA Warning" alert informed the pilot to start maneuvering immediately. Once a DWC violation was imminent and no longer avoidable, the DAA system presented a directive recovery wedge that instructed the pilot to fly within a specific range of headings immediately for collision avoidance.

Table 2.4.3-1: Detect-and-avoid well-clear and alerting definitions for Flight Test 6 Full Mission.

	Detect and Avoid Well-Clear Definition			**Alert Time**	
	*hmd**	*h**	τ_{mod}*	Corrective	Warning
Cooperative	4000 ft	450 ft	35 s	60 s	30 s
Non-cooperative	2200 ft	450 ft	0 s		

*hmd** = horizontal miss distance
*h** = vertical height threshold
τ_{mod}* = modified tau threshold

2.4.2.3 Test Points

Full mission test points included six DAA conflicts for subject pilots to avoid, with two live encounters occurring per flight circuit. Four encounters used the non-cooperative DWC definition to test the low-SWaP radar emulation, while the remaining two were designated as cooperative traffic targets and used the cooperative DWC definition. Live, non-cooperative intruders were scripted to approach ownship from either a head-on, 45-deg, or 90-deg crossing angle at "slower" or "faster" ground speeds at either 100 or 170 kn (Figure 2.4.3.1-1). The flight circuits were presented in a counterbalanced order across subject pilots to eliminate order effects. Test observers and researchers monitored the progression of conflicts for any substantial anomalies with the scripted trajectories or DAA system performance. If necessary, operators were prepared to abort and re-fly an identical backup encounter.

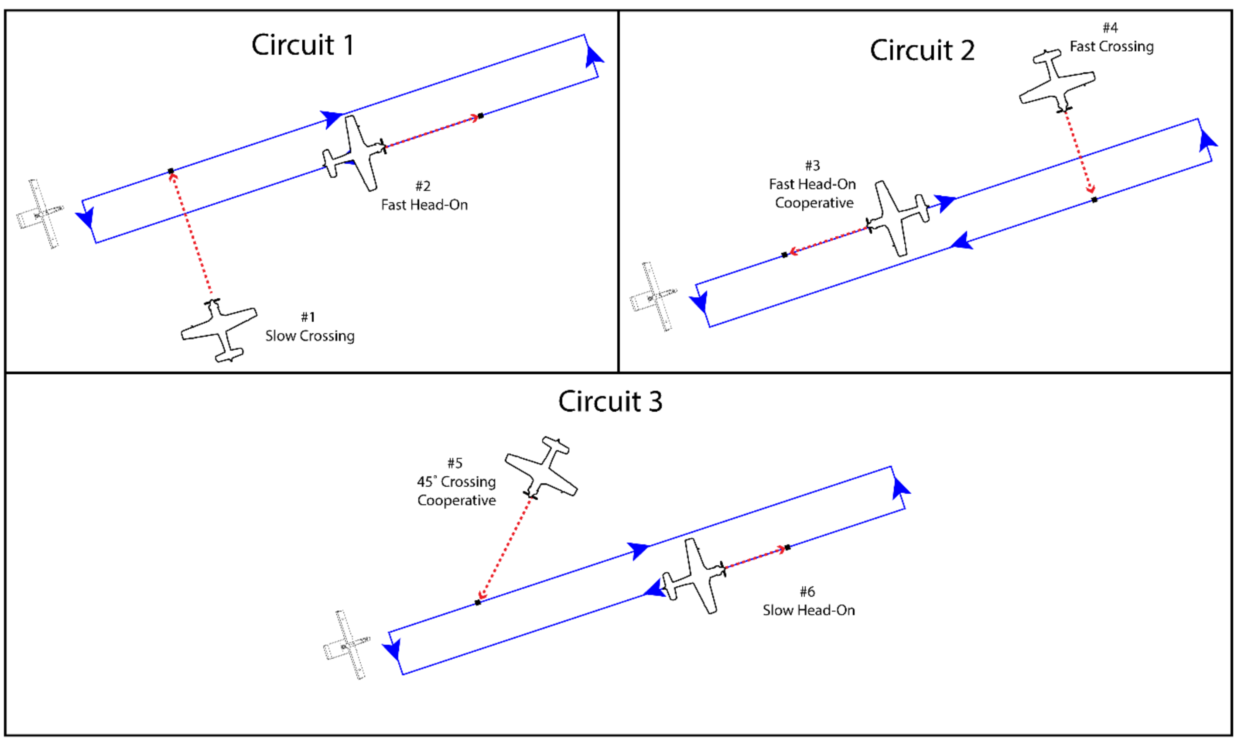

Figure 2.4.3.1-1: Encounter geometries used in Flight Test 6 Full Mission.

2.5 Results Overview

One key observation from FT6 was the unintended consequences of the +/- 110-deg azimuth limit on the emulated sensor. Only traffic that was within 110 deg of either side of the nose of the aircraft were detected on the traffic display. Due to the large turn magnitudes (128 deg on average) that were input to avoid fast-closing conflicts at close ranges, intruder aircraft exited the field of regard and disappeared from the display before the ownship was clear of conflict during 41 percent of the non-cooperative events. The turn magnitudes and field of regard dropout frequency both increased by over 15 percent in the live flight environment compared to HITL simulation results. A contributing factor may have been the less-steady aircraft states in the live environment (for example, wind-related changes in airspeed or heading) that affected the stability of the DAA guidance bands. The live environment may have also influenced more conservative inputs from pilots. This finding implies that pilots may need additional guidance from ATC to confirm whether the return path trajectory is free of conflict before executing the maneuver toward the next waypoint in these scenarios.

Although these dropout occurrences do result in more time spent off-course and less awareness of when it is safe to return to the mission route, separation performance remained sufficient across all encounter cases. Similar to HITL results, subject pilots had at least 25 s of alert look-ahead time and were able to avoid losses of DWC in all FT6 flight circuits. On average, DAA alerts were generated at 2.41 nmi and DAA maneuvers were initiated by pilots within 14 s at 1.83 nmi. Non-cooperative aircraft detected at 2.5 nmi flew within 0.77 nmi of the ownship during conflicts on average, compared to 1.42 nmi with cooperative aircraft. The minimum separation across the entire test was 0.47 nmi (2871.5 ft) during a fast-closure encounter, which was between 650-700 ft outside of the DWC threshold.

Post-test sentiment from subject pilots was highly positive with regard to the utility of the DAA system for conflict assessment and avoidance. While pilots indicated that the 2.5-nmi surveillance range modeled in the study was sufficient to assess conflicts in this test setting, where they were primed to avoid them, all but one pilot expressed the desire for a broader radar coverage of 3-4 nmi (and as far out as 8 nmi) during nominal UAS operations. It should be noted that FT6 emulated the ATAR range deemed minimally sufficient for successful conflict avoidance with a pilot in-the-loop (that is, without automation support). Maximizing the sensor range to the extent possible would allow more time for ATC coordination and situation awareness during UAS missions that require more multi-tasking. Complete FT6 full mission results can be found within Reference 9.

3.0 CONCLUSIONS

Flight Test 6 full mission successfully demonstrated the efficacy of a Group 3 unmanned aircraft system with the candidate sensing capability and non-cooperative detect-and-avoid well-clear outlined in the Minimum Operational Performance Standards for detect-and-avoid. While the majority of the results validated the results of previous laboratory studies such as in separation performance and system acceptability, key differences were observed in live flight that were not previously observed. The increased incidences of ownship maneuvers causing the intruders to fall out of the field of regard of the non-cooperative sensor and the increased magnitude of lateral maneuvers compared to the laboratory studies should have implications for both modelling and certification efforts in the future. Manufacturers should consider developing sensing systems that exceed the Minimum Operational Performance Standards to prevent unmanned aircraft system operators from entering situations in which an intruder is not being actively tracked during a detect-and-avoid encounter. It should also be noted that the Minimum Operational Performance Standards only provide requirements for the avoidance of traffic, and not for the re-joining of a course approved by Air Traffic Control. Further work could be completed to develop operational return-to-course procedures including requirements for automated execution of return to course. These topics will become increasingly relevant as remotely-piloted and autonomous beyond visual line-of-sight operations become routine.

Another outcome of Flight Test 6 full mission that is relevant to future research into remotely-piloted and Advanced Air Mobility operations is the demonstrated utility of the Live Virtual Constructive – Distributed Environment capability in airspace research. As advanced concepts such as automated flight rules and airspace management for emerging operations are incorporated into the concept of operations for new entrants, the capability to investigate the effects of new technologies in the National Airspace System will become more relevant. The ability to combine virtual and constructive elements with live aircraft that are geographically separated can help bridge the gap between laboratory studies and flight tests or demonstrations.

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