Pilot Perspective of UAS Flight-Test at the National Aeronautics and Space Administration (NASA)

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ABSTRACT

In the late 20th century, the National Aeronautics and Space Administration (NASA) was involved in the research and development of Unmanned Aircraft Systems (UASs) to support unique science missions. To meet these planned missions, NASA developed specifically tailored flight-test procedures and techniques. In this last decade, through the process of executing numerous UAS flight-test missions, NASA learned a great deal about how to plan and conduct UAS ground and airborne tests, operating diverse UASs ranging in size from large (Group 5): the NASA RQ-4 "Global Hawk"(Northrop Grumman) (Falls Church, Virginia, U.S.A.)
high-altitude, long-duration unmanned aircraft and the NASA MQ-9"Ikhana" (General Atomics Aeronautical Systems Inc. (GA-ASI) (Poway, California, U.S.A.) Unmanned Science and Research Aircraft System to medium and small (Groups 3 and 2): the NASA X-56 Multi-Utility Technology Testbed (Lockheed Martin Skunk Works) (Bethesda, Maryland, U.S.A.); the NASC RQ-23 TigerShark-XP™ (Navmar Applied Sciences Corporation (NASC) (Warminster, Pennsylvania, U.S.A.) unmanned aerial vehicle; among others. For the research case of incorporating UAS into the National Airspace System (NAS) in the United States, NASA developed scripted and unscripted encounters incorporating manned and unmanned aircraft, as well as encounters with simulated (virtual) traffic, and even researched, via simulation, the integration of autonomy for UAS see-and-avoid requirements. This paper will discuss development and implementation of flight-test approaches from the perspective of the test pilots who supported these missions and includes the lessons learned during the test process.

1.0 PROGRAM BACKGROUND

The NASA Unmanned Aircraft Systems (UAS) Integration into the National Airspace System (NAS), or UAS-NAS Project, was an effort spanning almost a decade and aimed to inform the regulatory authorities on the development of Minimum Operational Performance Standards (MOPS) to allow routine access of UAS of different sizes and capabilities into the NAS. The NASA contributions for MOPS development originally started under the Access 5 national project. Active from 2003 to 2006, Access 5 was the precursor to UAS-NAS for which planning began in 2009 prior to its initiation in 2011. Most of the flight-tests discussed in this paper were flown in support of UAS-NAS, while a portion of flight-test activities supported the NASA Armstrong Flight Research Center (AFRC) (Edwards, California, U.S.A.) Resilient Autonomy (RA) Project, which addressed approaches to enable the progressive incorporation of trusted autonomy solutions into UAS operations. All the missions discussed in this paper were flown or supported by the author.

2.0 FLIGHT-TEST ACCOMPLISHMENTS

The keystone flight-test accomplishments covered in this paper include the UAS-NAS Flight Test 4 (FT4) Project involving Detect and Avoid (DAA) flight-testing, the Chase Certificate of Waiver Authorization (COA), called No Chase COA (NCC) flight demonstration in the NAS, and NASA Flight Test 6 (FT6) involving further DAA testing on smaller UASs. This paper also highlights successful RA Project flight-testing of UAS autonomy using distributed live simulation teleconferencing resulting from the coronavirus disease 2019 (COVID-19) lock-down.

2.1 Flight-Test 4 Milestone

Conducted in 2016, FT4 was the fourth in a series of UAS-NAS efforts supporting the development of MOPS addressing DAA and air-to-air radar (ATAR) for Group 5 (>1320-lb vehicle weight) UAS. The research was conducted using the NASA Ikhana Unmanned Science and Research Aircraft System, a civilianized MQ-9 UAS. The flight-test was conducted in partnership with General Atomics Aeronautical Systems Inc. (GA-ASI) (Poway, California, U.S.A.): the manufacturer of the MQ-9 UAS. Other partners included Radio Technical Commission for Aeronautics (RTCA) (RTCA, Inc.) (Washington, District of Columbia (DC), U.S.A.) Special Committee 228 Validation and Verification sub-working group, and Honeywell (Honeywell International, Inc.) (Charlotte, North Carolina, U.S.A.).

2.1.1 System Description – The Ikhana Unmanned Aircraft System

The NASA Ikhana UAS was a NASA-owned civilianized single-engine turbo-prop MQ-9 Predator "B" UAS, which served as the "ownship" subject vehicle in flight-testing versus cooperative intruder aircraft. The Ikhana UAS was based at the NASA Armstrong Flight Research Center (AFRC), located at Edwards Air Force Base (EAFB) (Edwards, California, U.S.A.). The EAFB lies within restricted airspace that is ideal for transit directly to and from the test airspace without need of chase aircraft or Federal Aviation Administration (FAA) compliant, certified DAA systems. The general performance capabilities of the Ikhana UAS are as follows: weight: 10,500 lb, speed: 200 kn, ceiling: 40,000 ft, and designed for long-endurance flight times of 24 hours.

Capable of low- to high-altitude flight, with a capacity to carry and power multiple research payloads, NASA chose the Ikhana UAS as best-suited for this DAA research. Figure 2.1.1-1 highlights the scale of the aircraft, and Figure 2.1.1-2 shows the aircraft in the UAS-NAS configuration.

Figure 2.1.1-1: (above left) the Ikhana Unmanned Air Systems (UAS) ground testing, 2008 (NASA photo ED08-0151-02); and Figure 2.1.1-2: (above right) the Ikhana UAS during Unmanned Air Systems (UAS) National Air Space (NAS) testing, 2018 (NASA photo AFRC2018-0217-18).

The Ikhana UAS served a two-fold purpose for testing: first, as an airborne platform to test multiple DAA systems in flight while using a representative UAS command and control (C2) architecture and flight methodology; and second, as a vehicle to examine the whole system of human, vehicle, and interface, testing the utility of the prototype DAA cueing and displays in the Ground Control Station (GCS), described in the GCS system section. The aircraft system-under-test (SUT) package (Figure 2.1.1-3) included the following components:

- A GA-ASI prototype ATAR, active electronically scanned array (AESA) surveillance radar;
- An Automatic Dependent Surveillance-Broadcast (ADS-B) (FreeFlight Systems) (Irving, Texas, U.S.A.) with Mode S Extended Squitter;
- A transponder (1090ES, operating on 1090 MHz);
- A Traffic alert and Collision Avoidance System (TCAS) II (1030 MHz);
- A Sense-And-Avoid (SAA) Processor (SAAP) module – this key component received, processed, and resolved all sensor inputs and interfaced with the GCS displays for pilot response and with the autopilot software from the aircraft. The autopilot was modified to allow for automated avoidance maneuvers (turns and /or climb/descents) if enabled and the avoidance criteria was met; otherwise, the pilot reacted from visual and audio cues to manually fly the avoidance maneuvers;
- A stand-alone Tropospheric Airborne Meteorological Data Reporting Edge Probe (TAMDAR); system, which collected atmospheric measurements from an external probe; and
- A data recorder for the DAA system, which logged the airborne detections and parameters during testing.

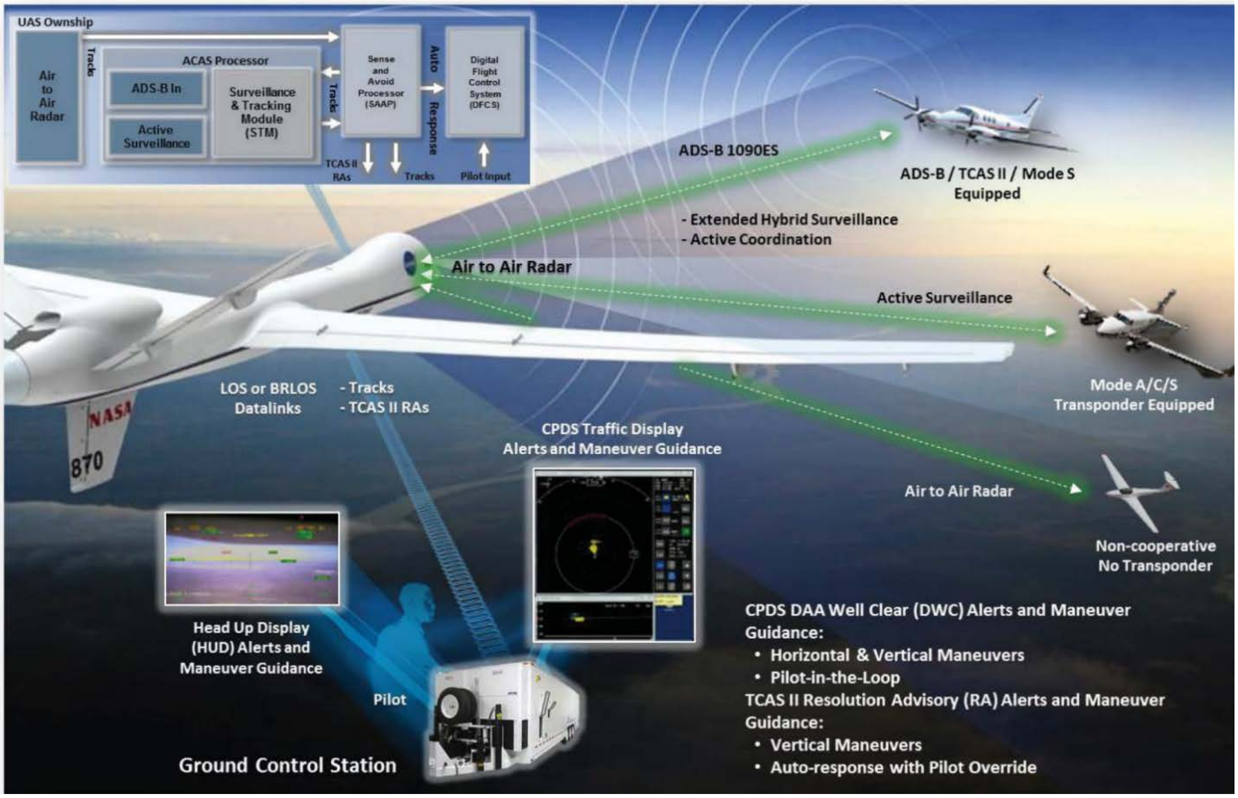

Figure 2.1.1-3: the Ikhana UAS systems-under-test diagram (2018) [1].

As shown in Figure 2.1.1-4, the aircraft was equipped with a modified nose cowling to house two AESA surveillance radar panels, each pointed 45-degrees laterally away from the nose (longitudinal axis) to give front quadrant scan coverage (Figure 2.1.1-5).

Figure 2.1.1-4: (above left) the modified nose cowl containing the active electronically scanned array (AESA) surveillance radar of the Ikhana Unmanned Aircraft System (UAS) with the Honeywell-owned Beechcraft King Air C90 (Dynamic Aviation) (Bridgewater, Virginia, U.S.A.) intruder aircraft in the background (NASA photo ED15-0201-56); and Figure 2.1.1-5: (above right) the GA-ASI AESA surveillance radar or "Due Regard Radar" (DRR) (GA-ASI photo, https://www.ga-asi.com).

Powered by a Honeywell TPE331 (Honeywell International Inc.) (Charlotte, North Carolina, U.S.A.) single-shaft turboprop engine, the Ikhana UAS retained its legacy core system functionality for UAS-NAS testing that included remote-pilot-controlled flight controls, autopilot, Embedded Global positioning system/Inertial navigation system (EGI), pitot-static system, line-of-sight C2 links (C-band), satellite C2 link (Ku-band), an airborne radio, fixed forward-looking cameras (one daytime, one infrared), and a slewable multi-spectral camera turret under the chin.

2.1.2 Ground Systems Description

The Ikhana GCS (Figures 2.1.2-1 and 2.1.2-2) and associated C2 antennas comprised the remaining elements of the complete unmanned aircraft "system." The GCS, a NASA-owned and modified early MQ-1/MQ-9 prototype mobile facility accommodated two pilot stations at one end, one technician (or third pilot/observer) station, and a control-room style table with five to six consoles, plus essential C2, ground test team communications, satellite communications (SATCOM), backup battery power, and the SUT prototype DAA pilot displays, with internet and fiber-optic connectivity to antennas and NASA networks. Antennas included two line-of-sight C2 C-band antennas (one primary near the runway, one backup - adjacent to the emergency landing lakebed site near the GCS), a SATCOM C2 Ku-band antenna, and building-mounted local Air Traffic Control (ATC) radio antennas connected to the GCS. Separate from the GCS was the main control room Mission Control Center 3 (MCC3), which housed the mission director and some test team members; and the live virtual constructive (LVC) laboratory, which hosted the engineering research teams monitoring the flights. The GCS, main control room, and LVC lab were connected via live intercom and radio consoles.

Figure 2.1.2-1: (above left) an early-model General Atomics (GA-ASI) (General Atomics Aeronautical Systems Inc.) (Poway, California, U.S.A.) mobile Ground Control Station (GCS) (NASA https://www.nasa.gov/sites/default/files/images/171917main_mobile_330.jpg)**; and Figure 2.1.2-2: (above right) the pilot-in-command console inside the National Aeronautics and Space Administration (NASA) Ikhana Ground Control Station (GCS) (NASA photo ED07-0243-18).**

The GCS served two important functions: 1) served as the cockpit; and 2) served as a research operations site. The GCS housed redundant pilot and co-pilot stations as well as a Test Conductor (TC), an Operations Engineer (OE), a GCS avionics technician, and a researcher representative, as shown in Figure 2.1.3-1 The TC maintained communications with the MCC3, GCS researcher, and the pilot. Communications with the rest of the research engineers in the LVC and the MCC3 were maintained solely by the GCS researcher.

The MCC3 housed the mission conductor/director and associate team members who viewed a top-view live airspace traffic picture and orchestrated the flight-test execution and card order, assisted in airspace deconfliction, and directed the airborne timing that was essential for each geometry encounter to achieve test objectives.

2.1.3 System Description – Intruder Support Aircraft

The NASA employed the support of various types of fixed-wing aircraft to achieve DAA objectives across a broad envelope of speeds, sizes, and maneuvering capabilities. These aircraft (Figure 2.1.3-2) included Gulfstream GIII (Gulfstream Aerospace Corporation) (Savannah, Georgia, U.S.A.); Beechcraft T-34C (Beech Aircraft Company) (Wichita, Kansas, U.S.A.); Aeromot TG-14A (Grupo Aeromot Aircraft Corporation) (Porto Alegre, Brazil); Beechcraft King Air C90, B200 and C-12 (Beech Aircraft Company) (Wichita, Kansas, U.S.A.) chase/intruder aircraft. Equipped with various combinations of TCAS, ADS-B, and Identification, friend or foe (IFF) Transponder, the intruder aircraft piloted by highly experienced pilots provided an important role as a scripted target for detecting, alerting, and avoidance maneuvering by the Ikhana UAS. Like the Ikhana UAS, the intruder aircraft flew tight-tolerance timing and positioning for each encounter, converging at a closest point of approach (CPA) to achieve a desired angle and distance for detection. The more complex encounters involved scripted mid-run maneuvers by the intruder aircraft and/or the Ikhana UAS; other encounters involved multiple intruder aircraft - sometimes a total of up to four - flying in concert to test the ability of the SUT to resolve and avoid the traffic conflict.

Figure 2.1.3-1: the NASA Ikhana Ground Control Station, engineering test team stations (NASA photo: Ken Ulbrich).

Figure 2.1.3-2: the UAS-NAS test aircraft used in Flight Test 4 (FT4) encounters: (back row, left to right) the NASA King Air B200 (Beech Aircraft Company) (Wichita, Kansas, U.S.A.); the NASA Gulfstream III (Gulfstream Aerospace Corporation) (Savannah, Georgia, U.S.A.); and Honeywell King Air C90 (Honeywell International Inc.) (Charlotte, North Carolina, U.S.A.) intruder aircraft; and (front row, left to right) the NASA TG-14A (Grupo Aeromot Aircraft Corporation) (Porto Alegre, Brazil); NASA T-34C (Beech Aircraft Company) (Wichita, Kansas, U.S.A.) intruder aircraft; and the NASA Ikhana UAS (NASA photo: AFRC2016-0138-01).

2.1.4 Flight Test 4 Flight-Test Approach

Flight Test 4 (FT4) expanded on the previous successful flight-tests concept of pre-planned intercept profile geometries (scripted encounters) between the Ikhana UAS and pre-coordinated intruder aircraft, under the oversight of a control room to guide and orchestrate the start, timing, and end of encounters according to success criteria. The goal of the vast combinations of FT4 encounter geometries was to test the DAA capability and accuracy in a wide variety of flight conflict situations.

Once agency participant roles and responsibilities were identified, flight-test concepts were established and incorporated in test planning and formulation, including the following.

- Test point geometry was tailored to ensure safe execution (how close do the aircraft need to be to each other to achieve test success, and how to avoid risk to non-participants).
    - A CPA (the green triangle in Figure 2.1.4-1) was used on every test encounter between the Ikhana UAS and the intruder(s) aircraft to provide minimum safe separation while achieving the end-state research objective.
- Early involvement of project pilots ensured feasibility and efficient sequencing of test execution.
- Airspace selection must involve consideration of distance and terrain as well as room for participant test aircraft to maneuver.
- Timing was a key factor since geometry at specific ranges was a critical test objective. Standard and minimum test separation (between aircraft) was defined for with and without visual contact.
- A build-up philosophy was employed to fly simpler, lower risk test encounters prior to more complex encounters. This approach of flying lower risk test points first helped provide an iterative process of improving execution based on initial lessons learned while increasing proficiency and efficiency prior to more complicated encounters.
    - Simple encounter types included: single-intruder encounters; non-maneuvering encounters by both Ikhana UAS and intruder aircraft; single-axis single-maneuver by one aircraft (see

Figure 2.1.4-1); greater than 500-ft altitude separation (visual not required within 1 mile).
  - o Complex encounter types included: single- to multiple-intruder aircraft; combined vertical and horizontal maneuvering or multiple and/or sequential maneuvering by one or more aircraft during the encounter; and minimum-allowed altitude separation requiring the intruder aircraft visual identification (VID) of the Ikhana UAS by one mile (medium-speed intruder).
- Next, test execution standards, tolerances, timing references, and test radio callouts were established to include test team roles during normal or emergency operations, and a proper test termination plan.
- Situational awareness tools were identified for the appropriate players to equip oversight persons, air crew, and test conductors with resources to communicate (while conforming to FAA sterile cockpit rule), see the real-time traffic picture, and/or utilize timing cues and tools as necessary for test point execution.
- Contingency operations were addressed to ensure emergencies, no visual, or lost C2 link situations following expected resolution procedures.

The structured test operations plan listed essential pre-mission areas including defining mission briefings, test phases, areas and airspace, test elements and ground control stations, mission roles and responsibilities, safety elements, training plans, and daily schedules. Two key areas - safety and training - were important for a good understanding from all players prior to test execution. Safety elements included: flight safety, mission rules and go-no-go criteria, C2 limitations, test abort procedures, post-encounter procedures, contingency operations, and visual contingencies. Contingency operations included understanding the ability of the UAS to manually abort a test encounter (rapid response, predictability, accuracy); whether any auto-pilot-coupled SUT can be immediately and safely disengaged for aborts; and finally, how the UAS would execute lost-link contingencies at any point during the test encounters.

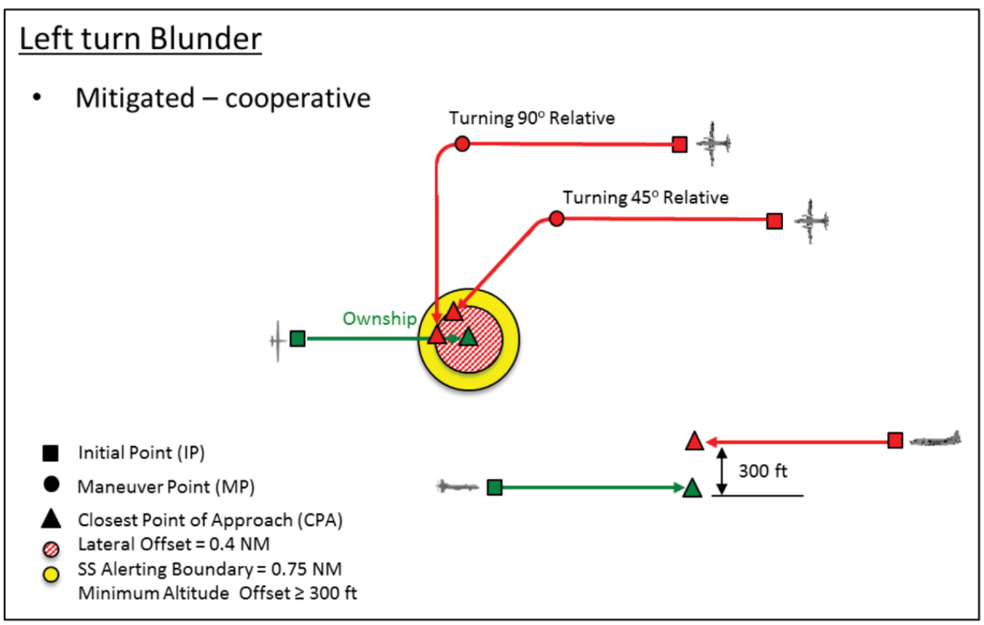

Figure 2.1.4-1: a subset of scripted encounters with various geometries with planned intruder maneuvers and closest point of approach (CPA) desired outcome relationship. Each different intruder line represents a test point that required an associated set of test cards [1].

2.1.5 Training, Familiarization, and Rehearsal

A tailored training plan focused on familiarizing air crew (both manned and unmanned) and test team members with all aspects of executing the specific test profiles, planned test objectives and airspace, down to specific test equipment displays. Pretest training ensured familiarization with the modifications and restrictions on the test aircraft and defined the scripted test encounters and profiles. Training also detailed the SUT displays, alerts, audio, and functionality. Roles and responsibilities per station or position were integrated with a radio communications "contract" and introduced in an example tabletop scripted test encounter with callsigns, notional aircraft, and sample test points. The Ikhana UAS and intruder profile overviews were described for all air crews to understand the expected safe integration of the two aircraft types (UAS and piloted/manned) in a single airspace for test execution.

2.1.6 Test Execution

The daily "rhythm" of flight-test involved a day-prior mission overview brief with the test team and Ikhana UAS and intruder pilots; day-prior coordination also involved reserving airspace and frequency spectrum usage. Flight-test day involved an early morning crew briefing followed by preflight and takeoff. Once airborne, the intruder aircraft would join with the Ikhana UAS for altimeter verification, then separate for encounter setup. The encounters typically involved the intruder aircraft and Ikhana UAS being 10- to 15-miles apart, orbiting and awaiting the next start time, both would adjust their holding patterns to arrive at the Initial Point (IP) on time (within 10 seconds), on ground-speed, on track, and on altitude. Each encounter waypoint was pre-loaded by air crew into their respective flight management, GPS, and/or tablet navigation system to fly specific ground tracks to achieve precise angles and positions at the desired DAA range.

2.1.7 Completion

FT4 planned and successfully executed these more challenging encounters (geometries and mid-encounter maneuvering); multiple intruder aircraft test execution (and aircraft equipage combinations); and overcame day-to-day added complexities due to airspace changes, weather, and intruder aircraft/pilot availability. Originally, 292-specific encounters were planned and designed to collect the data for researchers. During FT4 testing, as the research requirements matured, the original 292-planned-specific encounters were reduced to 267, and the team ultimately executed 261-unique encounters (98-percent completion) for a total of 321 encounters (including repeats). FT4 gathered excellent data for the entire SUT and met all project objectives, gathering the necessary data for researchers and stakeholders to inform the regulatory development of DAA and ATAR MOPS.

The successful outcome was largely attributed to the experience the team acquired from earlier flight-tests, including the Airborne Collision Avoidance System for UAS Airborne Collision Avoidance System-Xu (ACAS Xu) Self Separation (SS) initial flight-test conducted in partnership with the FAA in 2014 and 2015, and FT3 flown in the summer 2015. These flight-test experiences helped shape team training that proved valuable for the FT4 activity and beyond. Lessons learned (further discussed in Section 4) including the benefits of tabletop crew training before test, the value of system integration and testing, efficient and safe incorporation of manned with unmanned aircraft in scripted flight-test, and the in-depth analysis of each encounter and its test points, positively impacted further flight-testing.

2.2 No Chase COA Milestone

Conducted in 2018, NCC continued the UAS-NAS efforts supporting the development of MOPS addressing DAA and ATAR for Group 5 UASs, once again using the Ikhana UAS for data research to ultimately demonstrate flight of an FAA-approved, see-and-avoid-capable UAS in the NAS without the use of a safety chase plane.

2.2.1 Regulatory Background

No Chase COA built directly upon the results from FT4. The FT4 results facilitated ongoing development of standards (the RTCA MOPS). Radio Technical Commission for Aeronautics subsequently released MOPS documents DO-365 and DO-366. DO-365 defines standards for DAA systems used in UAS transiting through Class B, C, D, E, and G airspace and performing extended operations higher than 400-ft Above Ground Level (AGL) in Class D, E (up to Flight Level (FL) 180), and G airspace. This MOPS did not apply to small UAS (UASs) operating in low-level environments (below 400 feet) or other segmented areas, nor did it apply to operations in the Visual Flight Rules (VFR) traffic pattern of an airport or to surface operations. Radio Technical Commission for Aeronautics also revised DO-366(A) standards for ATAR for Traffic Surveillance with new radar specifications derived to meet the non-cooperative sensor requirements for DAA systems as described in RTCA DO-365B. The revised standards include support for multiple classes of aircraft and include collision avoidance functions as described in the MOPS for ACAS Xu, RTCA DO-386. These standards specify the radar system characteristics that should be useful for designers, manufacturers, installers and users of the equipment [3-4].

In turn, the RTCA MOPS (DO-365) helped develop the FAA Technical Standard Order (TSO) C211, which informs manufacturers of the minimum performance standards for DAA equipment; and (DO-366) helped develop the FAA TSO-C212, which informs manufacturers of the minimum performance standards for ATAR [5-6].

Finally, the NCC demonstration leveraged these TSOs. The NCC flight was a major milestone of the UAS-NAS Project. Discussions of a demonstration event like this one began as early as 2014, and the actual flight of the Ikhana UAS into the NAS - without a safety chase vehicle in Class A, E, and D airspace - was accomplished on 12 June 2018. The major goal of this flight was to demonstrate an alternate means of compliance to the FAA see-and-avoid regulations for a UAS using DAA technology, which typically required a human observer (ground and / or chase aircraft) to replace the lack of defined see-and-avoid capability.

2.2.2 No Chase COA Flight-Test Approach

A System Checkout (SCO) phase was performed prior to executing the NCC flight, in which the Ikhana UAS flew a slightly improved version of the FT4 DAA configuration. The Ikhana UAS demonstrated the operational performance of the updated, installed DAA system previously flown during numerous scripted encounters against intruder aircraft of various equipage and performance. The SCO flights initially involved basic systems checks and envelope expansion test points and then culminated in several flights of scripted encounters, similar to FT4, against several different intruder aircraft in order to stress the DAA system. Then the team flew the rehearsal NCC flight that followed the flight path in the NAS and was coordinated in advance with the various FAA stakeholders. The rehearsal flight allowed for observation of the DAA-enabled Ikhana UAS configuration to perform the mission with a safety chase before the solo NCC flight was performed. Once the system was tested with stressing cases that could be encountered in the NAS, a photo chase flight was performed for operational rehearsal and execution, and finally, the flight without chase was achieved.

2.2.3 No Chase COA Planning and Route of Flight

The planned demonstration route of flight was developed to ensure the Ikhana UAS operated in each type of airspace desired by MOPS development (class B, C, D, E below FL180; and G above 400-ft AGL); thus, the flight route took off from home base at the EAFB, climbed within restricted airspace to FL200, and entered the NAS under ATC, instrumented flight rules (IFR) at FL200 (class A airspace) using a build-up approach to work down in altitude over the flight profile into more congested, VFR airspace. The over 200-mile route, which avoided populated areas, transitioned from local Joshua Terminal Radar Approach Control Facility (TRACON) to Los Angeles Air Route Traffic Control Center (ARTCC), and then to Oakland ARTCC before descending into Class E, and transitioning back through Los Angeles ARTCC to Joshua TRACON and into the airport arrival pattern at a tower-controlled (class D) airport and surrounding class G airspace before re-entering restricted airspace and returning to land back at EAFB.

Once the route was determined, the test team worked with the FAA to establish a safe, robust contingency plan that involved five location-dependent emergency lost-link profiles to ensure an expeditious but predictable exit path from the NAS back into restricted airspace if a lost-link event or emergency occurred during the NCC flight.

Also, during planning and coordination with stakeholders, it was critically important to understand the system behavior in all cases of airborne traffic conflicts since the NCC flight would occur with non-cooperative bona fide traffic in the NAS. Subsequently, the team used this knowledge to develop use cases to stress the system in preparation for the NCC demonstration. The DAA MOPS defined use cases which identified the Ikhana pilot employment of the DAA and ATAR systems and their interaction with ATC to fulfil mandatory see-and-avoid requirements. The four NCC Concept of Operations (ConOps) use cases were:

- Ikhana pilot detects and calls out VFR traffic to ATC and coordinates maneuver.
- Intruder aircraft maneuvers after DAA well-clear avoidance maneuver has begun causing a change in the avoidance maneuver (Figure 2.2.3-1)
- Ikhana UAS encounters VFR traffic and maneuvers prior to ATC approval.
- Ikhana pilot maneuvers to a mandatory TCAS II Resolution Advisory.

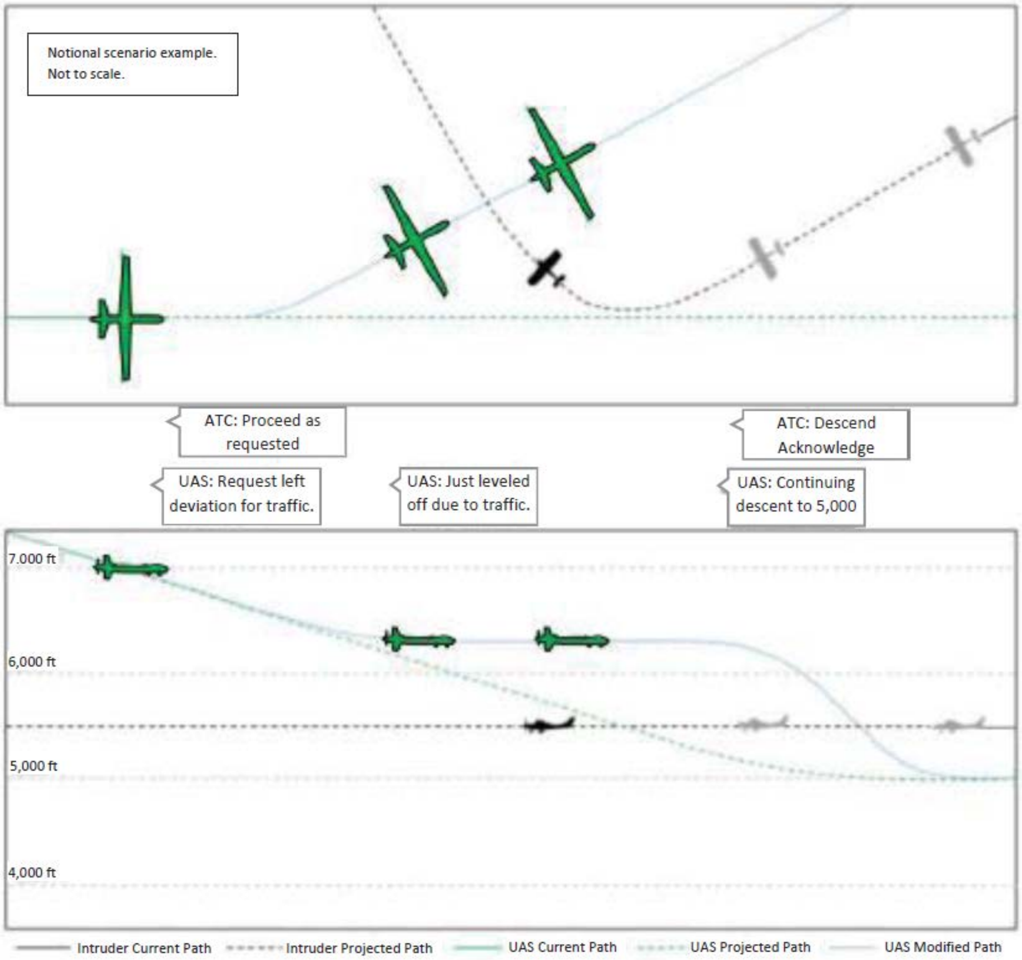

Figure 2.2.3-1: No Chase COA planning example showing secondary three-dimensional (3D) avoidance maneuver (level-off) versus unscripted traffic that turns suddenly during an initial descending turn avoidance maneuver [1].

2.2.4 Completion

Both the rehearsal (photo chase) NCC and the solo NCC final mission profiles were completed successfully without incident including several unscripted uneventful ATC and traffic interactions. Ultimately, all NCC phase 1 programmatic milestones were fully achieved. The minimum success criteria of receiving FAA approval of the COA to fly without chase was obtained in March 2018. Full success criteria were achieved once the flight without chase was completed in June 2018. This positive outcome is largely attributed to the experience acquired from the preceding series of testing: ACAS Xu SS initial flight-test flown in December 2014; FT3 flown in the summer of 2015; FT4 flown in the summer of 2016; and ACAS Xu Flight Test 2 (FT2) flown in the summer of 2017 [1].

2.3 Flight Test 6 Milestone

Phase 2 of the UAS-NAS Project culminated with Flight Test 6 (FT6) in 2019. This campaign utilized a medium-sized UAS to advance the path for Group 3 (56- to 1320-lb weight) UAS integration in the NAS.

The FT6 used the RQ-23 TigerShark XP™ UAS from Navmar Applied Sciences Corp. (NASC) (Navmar Applied Sciences Corporation) (Warminster, Pennsylvania, U.S.A.) UAS, which was a key partner in the execution of this flight-test. In addition to numerous scripted encounters similar to FT4, FT6 also conducted "full mission" flights, or longer distance flight tracks in the restricted test airspace which integrated with simulated airspace among air traffic (simulated and live) with the real RQ-23TigerShark XP™ UAS, which were flown by "subject" pilots immersed in the virtual environment.

2.3.1 FT6 System Description – Aircraft and Ground Control Station

The NASC RQ-23 TigerShark XP™ UAS was a Department of Defense (DoD) Group 3 UAS equipped with low size, weight, and power (SWaP) sensors, and was flown in the EAFB restricted airspace (similar to FT4) with similar NASA intruder support aircraft. The general specifications of the piston-driven single-engine RQ-23 TigerShark XP™ UAS (Figure 2.3.1-1) were:

- Wingspan: 21.75 ft
- Max altitude: 14,000 ft
- Speed: 80 kn
- Endurance: 10 hours

Figure 2.3.1-1: The Navmar Applied Sciences Corporation (NASC) RQ-23 TigerShark XP™ UAS in flight during Flight Test 6 (NASA photo AFRC2019-0142-10).

The test portion of each RQ-23 TigerShark XP™ flight was flown by NASA test pilots from the NASA Mobile Operations Facility (MOF) which housed two NASA pilots, a Test Conductor, several technicians and test engineers, and a separate isolated section for the subject pilot console to fly in the virtual test environment while NASA pilots provided safety oversight. Test orchestration was provided by the Mission Director in the main control room as during all previous UAS-NAS test flights and included voice communications between aircraft, air crew, test team and control rooms. Because of the smaller size of this UAS, the project during early planning required adding a smoke trail generator on the RQ-23 TigerShark XP™ UAS to compensate for expected reduced visual acquisition, since this was a required safety mitigation for encounters with reduced altitude separation (less than 500 ft) between the Ikhana UAS and intruder(s) aircraft. Ultimately, this provided only limited improvement for visual acquisition only in certain visual angles because of the faintness of the smoke trail and the strength of the other environmental visual factors in the test airspace.

2.3.2 Flight Test 6 Test Approach

The scripted encounters investigated the timing of DAA alerting thresholds using the low SWaP sensors on the RQ-23 TigerShark XP™ UAS versus one of three different live intruder aircraft flown at varying encounter geometries [2]. Given the limited detection range of available low SWaP sensors, the team implemented simulated capabilities using available aircraft positioning data to ensure necessary test detection ranges were assessed. Additionally, the "full mission" flight profiles validated human-in-the-loop simulations by collecting subject pilot performance data from a ground control station while controlling a live unmanned aircraft on a mission in both virtual and live (simulated) ATC-controlled airspace. During full mission flights, the subject pilot observed a research display that presented DAA advisories to maintain separation from a combination of live intruder aircraft and synthetically inserted virtual aircraft on a moving map display with basic autopilot commands that were uplinked to the RQ-23 TigerShark XP™ autopilot, with safety pilot override capability. Like previous UAS-NAS flights, testing was conducted within the R-2508 special use airspace located near Edwards Air Force Base (EAFB), California, U.S.A.

2.3.3 Completion

Over 240 encounters were flown during the twenty-week test series and FT6 proved to be invaluable for the purposes of planning, managing, and executing this type of integrated flight-test in both live and virtual environments. Data collected from FT6 was provided to the RTCA Special Committee 228 (SC-228) to help inform the Phase 2 MOPS.

2.4 The COVID-19 Impact on Resilient Autonomy Project Milestones

Separate from UAS-NAS, the NASA Armstrong Flight Research Center Resilient Autonomy (RA) project team worked with FAA and DoD to develop airborne autonomy technologies to reduce the number of general aviation accidents. The RA Project team tested and demonstrated the Expandable Variable Autonomy Architecture (EVAA) that incorporated NASA-developed safety features used in military aircraft today. To avoid interruption in EVAA development and testing, the RA team adapted to COVID-19 restrictions by successfully conducting online, real-time testing involving geographically separated test team members across the US, using a desktop flight simulator with project software modifications, pre-positioned at the home of the NASA test pilot and utilizing video-teleconferencing, under a fly-fix-fly test methodology.

2.4.1. Resilient Autonomy Background

During the last decade, the RA project researched the incorporation of autonomous management of multiple sensor and avoidance systems which became the EVAA system, a joint NASA, DoD, and FAA endeavor conducted by NASA as a sub-element within the Transitional Aeronautics Concept Program's (TACP) Transitional Tools and Technologies (TTT) Project. RA was part of NASA's Autonomous Systems sub-project; under the DoD, RA was a Joint Capability Technology Demonstration (JCTD) with funding coming as part of the rapid acquisition process from the Office of the Undersecretary of Defense for Research and Engineering. The FAA also funded a separate activity in collaboration with RA in which

EVAA was flight-tested on a general aviation aircraft.

RA program goals were to develop an airworthy, scalable autonomy framework capable of adapting to unanticipated situations; develop a government-owned system to adapt to any vehicle to allow link-less beyond line-of-sight (BLOS) operations; and inform the FAA certification process of aircraft with increased levels of autonomy. Rooted in the mid-80s development of the advanced fighter technology integration F-16 (AFTI/F-16) program's research of ground and air collision avoidance automatic maneuvers programmed into its full-authority autopilot, the automatic ground collision avoidance system (GCAS) and air collision avoidance systems (ACAS) were adapted into small-form hardware module for small UAS use in 2012. NASA then continued adapting and expanding this modular autonomy to include geo-fencing and forced-landing in a framework named expandable variable autonomy architecture or EVAA [7].

2.4.2 System Description

The EVAA software was containerized on a small hand-sized stand-alone computer, which managed the component safety software packages, and interfaced to the flight simulator and displays to inform the pilot of conflicts, autonomous maneuvering, and mode changes and status. The flight safety software packages contained and managed by EVAA were:

- ACAS. This system receives detected traffic conflicts from DAA sensors to compute and execute an avoidance maneuver.
- Automatic Ground Collision Avoidance (Auto-GCAS). This system, from which EVAA was derived, avoids imminent ground collision by taking control of the aircraft prior to impact at the last possible recoverable moment, locking out the controls and performing an automatic recovery maneuver and immediately returns full control to the pilot once clear of terrain. Auto-GCAS is credited with saving the lives of eleven F-16 pilots since its introduction. The RA team converted the F-16 algorithms to be suitable for the capabilities of general aviation aircraft or UASs.

To adapt to COVID-19 restrictions, the RA team adapted the EVAA to interface with an X-Plane flight simulator, providing integrated EVAA sensing, avoidance automatic maneuvering, and displays and warnings. The team sent simulator equipment to the home of the NASA pilot in which the EVAA computer, research computer, monitor, control yoke, throttle, and pedals were installed. The RA team successfully utilized teleconferencing software to live-stream and record the piloted simulator flights, and to communicate live with multiple test team members via a geographically separated "control room," with the test conductor orchestrating the live flight-testing remotely according to the flight cards sent by email.

2.4.3 Resilient Autonomy Flight-Test Approach

As a result of the COVID-19 stay-at-home restrictions, the RA project containerized the EVAA simulation in a desktop format which was deployed at the home of the project pilot. Utilizing the open architecture of the X-plane flight simulator, traditional flight inceptors, and the stand-alone EVAA computer box, the test team conducted dozens of flight-test simulator sessions over live video teleconferencing and collected data for ground and air collision avoidance test objectives, proving a unique capability for future test cases (Figure 2.4.3-1).

Figure 2.4.3-1: Screen grab from the National Aeronautics and Space Administration (NASA) video showing a controlled Expandable Variable Autonomy Architecture (EVAA) Ground Collision Avoidance (GCAS) terrain avoidance maneuver, simulated by a HQ-90 UAS, flown by a NASA pilot for the DoD live demonstration (NASA https://www.nasa.gov/sites/default/files/styles/side_image/public/thumbnails/image/resilient_autonomy_image_.png?itok=kDNm5zTL) [7].

2.4.4 Resilient Autonomy Completion

The continued EVAA testing through the COVID-19 pandemic allowed RA to successfully complete two live simulation EVAA demonstrations: one for DoD and one for Alaska bush pilots. Both demonstrations were simulator-based and tailored for each audience. A small UAS platform was simulated for the DoD demonstration, and a single-engine general aviation aircraft was simulated for the Alaska bush pilots. In both demonstrations, RA broadcasted live simulations of the EVAA system that was piloted by a NASA test pilot operating from his home. These simulations demonstrated ACAS and Auto-GCAS features in operation versus system-stressing scripted terrain and traffic scenarios as well as the EVAA flight path management function and its autonomous forced landing capability.

3.0 LESSONS LEARNED

A primary goal of this paper is to inform on the most important operator lessons learned from UAS-NAS flight-test execution at NASA Armstrong Flight Research Center from the perspective of the test pilots that conducted the encounters and provided oversight on the safe execution of test points by the subject pilots during full mission phase. These lessons learned focus mainly on planning and test execution, and address the flight-test phases of systems check-out, payload/sensor characterization flights, scripted test encounters, and full-scenario flight-testing, but conceivably apply to other types of UAS flight-testing as well as to piloted general aviation aircraft.

3.1 Project Planning Lessons

Due to the complexity and importance of safely testing a modified UAS in conjunction with manned support aircraft as well as integrating into the nation's public airspace system, a large planning effort was undertaken by the many project team members across NASA and its test partner organizations. As a result, many planning-related lessons learned were collected.

3.1.1 Early Coordination with Spectrum Management

It is important to involve local spectrum management officials early in the discussion of the flight-test plan and utilization of communications and datalinks and frequencies in flight in order to initiate national level approvals and certifications in time for testing. Despite successful COA approval for NCC, the flight into the NAS was delayed several months to address details in the spectrum approval process including use of certain operational frequencies in the NAS that were previously only approved for flight-test within restricted special-use airspace.

- Federal Agencies require certification through National Telecommunications and Information Administration (NTIA), whereas non-federal entities require Federal Communications Commission (FCC) licensing. Further, additional NTIA approvals may be required for frequencies and/or equipment when used outside approved restricted airspace.

3.1.2 Federal Aviation Administration Operational Approval

Involve Federal Aviation Administration (FAA) Spectrum Office early during formulation and during the safety risk management (SRM) process; this task was initially missed in early planning.

- FAA operational approval was independent of spectrum approval; similarly, spectrum approval was independent of COA approval.

3.1.3 Federal Aviation Administration Early Involvement in Mission Design

Involve FAA early on in the formulation process of the mission profile in the NAS to consider, recommend, and ultimately approve the route and profile of test flights in the NAS. Involving FAA later in the approval process without accounting for time needed to locate and inform the right FAA approvers resulted in several months of delays.

3.1.4 Early Schedule Margin

Consider flying early envelope expansion flights as stand-alone flights, separate from follow-on systems check flights to ensure proper basic flight-testing is accomplished without undue outside pressure to finish quickly. Additionally, plan to include several pilot-proficiency flights early to ensure readiness for the complex nature of any flight-test encounters.

3.1.5 Chase Aircraft

If support aircraft have chase roles during a flight (photography, close formation, instrument verification, et cetera), the project must first identify the UAS cruise airspeed and limits to understand which aircraft can feasibly execute chase duties. This step is especially applicable to smaller UASs such as with the RQ-23 TigerShark XP™ UAS; besides the TG-14A motor glider, all other aircraft had to S-turn behind the RQ-23

TigerShark XP™ UAS to maintain chase position without approaching stall.

3.1.6 Limiting Many Waypoints

For flight-tests using many waypoints, attempt to reuse waypoints across many test profiles to keep the number of waypoints to a minimum and to allow for efficient input of coordinates into manned and unmanned flight management or autopilot systems.

3.1.7. Daily Test Card Usability

Build daily flight-test cards to specifically address the essential elements of information for the test team that include an overview card ("dance card") that lists the expected order and number-code deck of cards for that specific day with essential one-line profile information (e.g., altitude; system on/off; et cetera). Information should be efficiently organized and simply worded to facilitate easy reference during busy execution of flight-test; otherwise, pilots will have difficulty understanding the order and finding the correct card if the pilots are furnished with the entire set of project flight cards versus supplied cards for specific days. Ensure to involve project air crew early on in the card review process, well before the day of flight.

3.1.8 Extending the Flight-Test Phase

Increase the number of flights accordingly if the number of test points increases as a result of expanded research desires and new discoveries, since flight endurance is limited per aircraft, and there is a limit to compressing the time between test points after which test effectiveness and timing is difficult and instances of aborts and resets increase. This step first required carefully establishing the original planned series of test flights based on multiple key factors: the number of required test points, events, and encounters with added margin for failed test encounters (resets, aborts, et cetera), weather days, and loss of airspace days.

3.2 Training and Rehearsal Lessons

As UAS-NAS testing phases were completed, one common lesson learned was the high value of incorporating and providing thorough training and realistic rehearsal for the flight test team, well before the start of test execution. Overall, this helped assure a basic level of understanding of the new prototype SUT as well as having an initial expectation of flight test pacing, flow and challenges. This helped aircrew and test members adjust test profiles and provide mission brief emphasis on areas to help ensure test safety, efficiency and success.

3.2.1 Intentional Training and Rehearsal

Determine, develop, and provide realistic and relevant air crew training, familiarization, and rehearsals focused on the SUT and the flight-test execution that resulted in:

- Noticeable advantages in test air crew effectiveness, efficiency, and awareness during test execution, which was observed when air crew first participated in thorough training and rehearsals (aside from the baseline demonstration of the researcher and initial training of DAA displays (with simulation and videos).
- The project team creating team training and table-top familiarization training on the general test flow

and radio calls. Likewise, the project pilot-created differences training for the Ikhana air crew including how to interact with and use the system switches, displays, and audio during testing. Air crew training should highlight important, unfamiliar SUT characteristics that might be confusing during the busyness of testing such as: auto-scaling of DAA scope, magnetic versus true heading, sequence of avoidance warning levels as displayed, and what the correct responses should be to various cues.

- Training that should include radio terminology that is correct for the test configuration and is in accordance to MOPS or FAA-supporting standards organization.
- Knowing that airborne time-on-target execution is a difficult task and warrants special emphasis in crew training.

3.2.2 Practice Complicated Tasks

Time should be dedicated in simulator, tabletop, or proficiency flight events allowing pilots to plan and practice (rehearse) complex maneuvering of the UAS (and/or intruder aircraft) to achieve repeatable, accurate results: especially for combined vertical and horizontal (3D) maneuvers, or any maneuvering that is not a usual practice. The NCC rehearsal flight with photo chase in the NAS - prior to the solo demonstration - benefited the entire team during practice flights and monitoring of the SUT along the flight profile in the NAS, allowing solo execution to occur more smoothly.

3.2.3 Build-up Approach, Simple to Complex

Use a build-up approach for test air crew to gain familiarity and proficiency in test execution by ordering simple test encounters first. In addition to the required ground familiarization training and rehearsals, incorporate a schedule for accomplishing flight observations of the pilot and co-pilot during test; have test air crew “acclimate” to the pacing, radio calls, displays, and SUT in the co-pilot crew position for a period of test flight before flying as pilot in command.

3.3 Flight Planning Lessons

Several lessons learned were collected that were unique to pilot activities and directly related to improving the efficient and safe execution flight test. The test aircrew not only worked with test team members to ensure the most efficient order of test points was used when possible, but also discussed and debriefed how to better ensure a consistent high level of pilot performance and ensure the best possible safety mitigations planned for upcoming flights.

3.3.1 Execution Details on Flight Cards

If researchers desire the Ikhana UAS to maneuver within certain constraints at a particular condition during an encounter, this flight execution should be detailed in the test cards, for example: “When the traffic symbol turns yellow, make one continuous turn to the original guidance heading and maintain until end of run. Only turn toward the south.” Just as important as setup conditions, the details on how to execute and successfully complete the test point should be briefed and/or included on the test cards.

3.3.2 Maximize Pilot Performance

Ensure adequate manning of flights with complex pilot tasks requiring high mental workload to allow for crew swaps or rest periods (such as a brief airborne loiter periods) to best capture pilot peak performance (approximately 2 hours or less of continuous active flight-testing). For flights later in a series of uninterrupted days of intense flight-testing, consider adjusting or shortening pilot shifts to maintain pilot peak performance.

3.3.3 Optimal Flight-Test Pacing

Orchestrate timing of each flight encounter to allow normal (standard rate turn) maneuvering and holding. Though tempting to compress the timing between test points, this practice has proved to create more mistakes and delays; therefore, avoid tight timing margins which encourage aggressive aircraft repositioning between encounters. Moderate test pacing increases the likelihood of the test aircraft arriving at the start point on time and stabilized on conditions with adequate pilot situational awareness of the execution instructions.

3.3.4 Efficient Altitude Profile

Plan a single day test series (dance card) to efficiently transition through altitudes and avoid unnecessary altitude changes which wastes time and fuel.

3.3.5 Visual Acquisition During Encounters

When visual acquisition of the UAS by intruder aircraft is a key safety mitigation tool for deconfliction between test aircraft, the timing and/or positional assumptions must account for the relative closure speed between the aircraft. During SCO, the Gulfstream G-III airplane was planned as a “medium-speed” intruder aircraft, using a 1-mile visual acquisition minimum for abort criteria but should have been planned as a 2-mile minimum as the aircraft flew at higher speeds rendering the 1-mile limit ineffective for guaranteeing time for abort response, maneuvering, and safe separation between aircraft.

3.3.6 Backup Cards

Plan the flight encounter profiles with alternative options to account for the possibility of airspace limits, changes, or interruptions which include:

- Early planning to increase probability of airspace availability and decrease interruption, identify the best and most consistently available airspace, and identify what time or day(s) provide uninterrupted test time. Planning involves early communication with owners of the airspace to understand availability and limitations, and for them to understand the extent of the planned test campaign, airspace needs, timeframe, numbers of aircraft, types of maneuvers, et cetera.
- Briefing more cards than possible to complete each day to ensure valuable test time utilization. Thus, if there is extra time for additional test, the test team can execute briefed test items. Ad-hoc, unbriefed flight-testing should never be accomplished.
- Adding extra encounters in each card deck for the day, ensures alternative encounters can still be accomplished if the airspace changes. Consider having backup encounters with backup altitudes with geometries that fit in a single or alternate airspace if applicable, since encounters spanning multiple airspaces run the risk of being cancelled if only one airspace becomes unavailable.

3.3.7 Schedule Enough Air Crews

Build the air crew schedule to include cancellations especially when utilizing guest help with competing responsibilities. Project should define the minimum essential crew required to accomplish a nominal test flight and adjust according to length and/or complexity of the flight.

3.4 General Execution Lessons

The pilots collected lessons learned from the actual execution of UAS flight testing, covering a broad spectrum of test phases. These flight test phases included systems check-out, envelope expansion, test rehearsals, and scripted encounter flights with intruder support aircraft. These lessons learned not only helped increase safety mitigations, but also improved techniques for greater accuracy of test point accomplishment as well as efficient accomplishment of more test points successfully in a period of flight time.

3.4.1 Pivot to Virtual Testing

In the extreme event of major restrictions to testing such as what occurred with COVID-19 pandemic, adapting test schedules and test methods may help maintain research progress. Pivoting to a geographically-distributed test team concept, particularly for live testing over teleconferencing tools, which can allow for continued limited testing and simulation that can be valuable to achieve project goals [7].

3.4.2 Mitigate High Task Loads

Use creative tools to minimize pilot task loading such as: In the GCS or cockpit, highlight areas of important focus to rapidly cue the eyes of the pilot during testing (via temporary markers, stickers, tape, et cetera.); consider what pilot switches, menus, buttons can be safely readied for execution (e.g., a complex 3D maneuver) to facilitate a “one button” manual-command execution to maximize timing accuracy when feasible; and consider a structured, prebriefed division of pilot and co-pilot duties (applicable to UAS and/or intruder crew). For example:

- Pilot Flying: fly (ground track, ground speed, altitude), determine timing and adjustments.
- Pilot Not Flying: radio calls, setup waypoints / flight management system, call and maintain visual, monitor timing, and call for speed/turn adjustments.

3.4.3 Proper Radio Terminology

Especially when testing in support of MOPS development, new radio terms or phrases related to prototype SUTs may already be prescribed by MOPS; be aware of and use the correct terminology. Proper radio terminology was apparent when corrected by ATC in debrief after the NCC rehearsal flight where the DAA SUT detected an airliner that ATC then called out. The correct radio terminology in the MOPS for a UAS flying with a DAA system with an active detection is “traffic detected.”

3.4.4 Plan for Lost-Link

Brief and plan for contingencies during testing such as unplanned lost-link events, to include having thorough knowledge of UAS behavior in different lost-link scenarios. A degraded C2 link event occurred during an SCO flight, and the intruder aircraft became a safety chase while the UAS crew used CRM skills, systems knowledge, and checklist discipline to resolve the issue and land safely.

3.4.5 Visual Acquisition of Smaller UAS

During encounters, visual acquisition of smaller UASs such as the RQ-23 TigerShark XP™ UAV involved later, closer-range acquisition, even when a visual enhancing smoke trail was utilized, which did not increase visual ranges in most cases because of the limited utility of a faint smoke trail versus competing environmental factors.

3.4.6 Environmental Effects on Visual Acquisition

The ability of intruder pilots to visually acquire a UAS varies greatly, based on many factors: color and glossiness of UAS skin; sun angle; background texture, clutter, color and contrast; clouds, haze, and smoke. A reflection (glint) of the sun on the UAS renders the longest visual distances but is usually momentary. Additionally, intruder eyesight, effective long-distance scan pattern, as well as helmet visors, sunglasses, and aircraft windshield or canopy glass optical quality all affect visual acquisition range; therefore, it remains important to always be ready to abort the encounter if safety conditions are not met. Train air crew to visually scan near the horizon when altitude separation at long range is at or less than 500 ft and to aim the visual scan in the correct elevation for increased likelihood of visual acquisition.

3.4.7. Rejoin with Altitude Separation

Maintain altitude separation (i.e., 500-ft below) when joining with the Ikhana UAS until visual and closure speed is manageable. When manned aircraft joined with the Ikhana UAS, typically ATC or the test conductor provided a position “point out,” followed by the pilots visually scanning for the UAS while range decreased. In some cases, with early morning sun angles, visual acquisition was at much closer range, making the altitude separation essential for safety.

3.5 Timing Execution Lessons

Central to the UAS-NAS flight testing approach, scripted encounters were based on two or more aircraft arriving at a closest point of approach (minimum range) in a safe, controlled, precise manner. The ownship and intruder(s) needed to be on condition (course, heading, ground speed, altitude) within tight tolerances, and most importantly needed to arrive at their respective end-point on time within just a few seconds. The tight tolerance ensure not only desired test point data collection for the performance of the DAA system, but also ensured safe miss distance between aircraft to avoid near-collisions. To do so, timing techniques evolved among the test aircrew, and lessons learned were captured.

3.5.1 Optimize Displays for Test Accuracy

Understand and best utilize installed navigation system displays with pre-loaded waypoints, graphics, and 3D guidance cueing to facilitate accurate test execution, on time, on speed, on altitude and on course to include follow-on accurate maneuvering. Basic tools for timing and positional test accuracy include:

- Watch, digital clock, or aircraft clock, set to briefed time-hack, with seconds displayed. Use GPS estimated time of arrival (ETA) and/or estimated time en route (ETE) displays with seconds if possible.
- Modern “glass” cockpit navigation map display is desired; precision navigation system is highly desired.
- Portable tablet with suitable navigation software, for example: Foreflight (The Boeing Company) (Chicago, Illinois, U.S.A.) software is a very useful backup tool because of occasional position lag, battery life or heat issues; thus, portable tablets should not be depended upon as the primary navigation source.
    - Use vector stick tool, set to 60 seconds for rough timing adjustments.
- The ability to view live ADS-B tracks on the moving map display increases situational awareness. Use either installed system or portable ADS-B device (e.g., Stratus- or Sentry-type unit).
- All test encounter (start and end points) waypoints pre-loaded and saved. It is recommended to save

individual "flight plans" for each test encounter according to the test naming/numbering convention for easy call-up in flight. Understand how to sequence waypoints to overfly versus lead-turn, and avoid premature waypoint sequencing according to desired test execution.

3.5.2 Impact of Winds on Timing

Strong winds in the test airspace may adversely affect the ability of a smaller slower UAS to effectively adjust ground track and speed to fix timing errors; the UAS minimum and maximum airspeed limits may prevent the remote pilot from achieving the desired test ground speed with a strong headwind or tailwind. It is important to understand how to use aircraft displays and navigation system to adjust for winds to ensure accurate timing. Turning maneuvers in strong winds requiring constant ground speed will require exceptional pilot workload to adjust airspeed and turn radius accordingly.

3.5.3 Loiter Execution

Loiter in a racetrack pattern in relation to the start point, with downwind legs offset from the inbound start point leg by one standard-rate-turn radius (180-degree turn), adjusting spacing for crosswinds as required. Stabilize early on, the next test card parameters such as altitude and ground speed.

3.5.4 Fixing Timing Errors

Fix timing errors using the racetrack pattern as follows:

- Next encounter start point time is given while on downwind (i.e., 09:50:00).
- Intruder aircraft passes downwind abeam the start point (09:46:20).
- Subtract abeam time from start time (09:50 – 09:46:20 = 3 minutes 40 seconds).
- Subtract one minute for 180-degree standard rate turn = 2 minutes 40 seconds.
- Continue the downwind leg past the abeam point for the following amount:
  - Half of the computed time = 1 minute 20 seconds.
- Then 180-turn inbound and continue to make small adjustments as required:
  - Speed adjustments can fix small errors up to about 10 seconds.
  - Maneuvers such as S-turns can fix larger timing errors on the inbound leg; otherwise abort on off conditions at the start point according to the abort criteria.
- Mission Conductor should allow three minutes minimum for less maneuverable intruder aircraft to abort, or reset and be in position for the next start time.

4.0 CONCLUSION

The National Aeronautics and Space Administration (NASA) Unmanned Aircraft Systems (UAS) flight-testing built upon efficient and effective flight-test approaches to achieve test milestones that furthered Detect and Avoid (DAA) Minimum Operational Performance Standards (MOPS) development. The collaborative efforts between NASA, industry partners, Department of Defense (DoD), and the Federal Aviation Administration (FAA) made it possible to execute flights in the National Air Space (NAS). Through careful project planning, building on lessons learned, and in some cases, adaptability to adversities like the COVID-19 pandemic, project milestones were achieved using standards from MOPS, which were not previously executed operationally. Best practices and lessons learned during the NASA UAS flight-testing, especially thorough early planning, training and rehearsal, and the build-up approach to testing, significantly reduced the time to complete these project activities. With this type of testing, the hope is to facilitate increased routine access of the UAS into the NAS and enable UAS operators to file-and-fly easily, safely, and unencumbered by Chase Certificate of Waiver Authorization (COA) requirements in the NAS as any traditional piloted/manned aircraft.

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