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Integration of Automated Systems Test Campaign NC-IAS

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Executive Summary

The National Aeronautics and Space Administration (NASA) 2022 Strategic Plan included the goal to catalyze economic growth and drive innovation in the aviation industry, and to address challenges in air transportation and airspace management within the National Airspace System (NAS). The Aeronautics Research Mission Directorate (ARMD) specifically was tasked with leading aviation innovation to enable safe and sustainable air transportation through revolutionary vehicle advances and efficient flight operations. As a part of meeting these objectives and advancing air mobility concepts, NASA initiated the National Campaign (NC) in the Advanced Air Mobility (AAM) Project within the Airspace Operations and Safety Program (AOSP). The NC was designed to support operational demonstrations with industry as well as needed research and development to support NASA-led research flight demonstrations.

Within the NC, the Integration of Automated Systems (IAS), an NC activity, tested and evaluated flight deck automation and airspace operations management functions needed to enable Urban Air Mobility (UAM) operations. These tests were accomplished through a partnership with Sikorsky Aircraft (specifically, Sikorsky Innovations, Stratford, Connecticut), a Lockheed Martin company, and DARPA (the Defense Advanced Research Projects Agency (DARPA), Arlington County, Virginia) by leveraging two automation-enabled helicopters equipped with unique capabilities that enabled NASA to develop and test two-ship conflict encounters to demonstrate flight path management and hazard avoidance technologies. The enabler in this testing was the NASA-developed “middleware” (MW) software (also known as Expandable Variable Autonomy Architecture (EVAA)), which, among other things, allowed multiple algorithms to be incorporated into one software build that was hosted on the dissimilar-type Sikorsky helicopters.

The IAS test campaign period of performance was from March 2022 to October 2023 and was structured as a phased (or spiral) approach that ultimately led to the first-ever demonstration of two-ship UAM/AAM operations designed to safely choreograph specific conflict encounters and mission scenarios to test the research algorithms for strategic and tactical aircraft deconfliction. Lessons learned are included in the body of the report. Data collected will be used to inform the Federal Aviation Administration (FAA) and industry standards groups on the increasingly automated systems needed for future AAM operations. The test encounters developed for these flight tests were proven to be highly predictable, repeatable, and were safely exercised for flight path planning and Detect and Avoid (DAA) algorithms. These same test encounters should be leveraged by future flight-test campaigns to verify that operational safety is not compromised as the AAM architecture matures. Next steps include repeating similar encounters using unmanned aircraft carrying DAA sensors in the National Airspace.

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1 BACKGROUND

The NASA 2022 Strategic Plan included the goal to catalyze economic growth and drive innovation to address national challenges. The Aeronautics Research Mission Directorate (ARMD) specifically was tasked with leading aviation innovation to enable safe and sustainable air transportation through revolutionary vehicle advances and efficient flight operations. This directive was further broken into strategic thrusts which included the following: "safe, quiet, and affordable vertical-lift air vehicles" and "assured autonomy for aviation transformation."

As a part of meeting these objectives and advancing air mobility concepts, NASA initiated the National Campaign (NC) in the Advanced Air Mobility (AAM) Project within the Airspace Operations and Safety Program (AOSP). The NC was designed to support operational demonstrations with industry as well as the research and development needed to support NASA-led research flight demonstrations.

Within the NC, the Integration of Automated Systems (IAS) Subproject was tasked to test and evaluate flight deck automation and airspace operations management functions needed to enable future Urban Air Mobility (UAM) operations. Data collected will inform FAA and industry standards groups on the increasingly automated systems needed to enable AAM operations.

The greater IAS team was comprised of Center personnel from the NASA Ames Research Center (ARC), Moffett Field, California; Langley Research Center (LaRC), Hampton, Virginia; and Armstrong Flight Research Center (AFRC), Edwards, California.

In early 2022, the Sikorsky Innovation Division was selected by NASA to enter into a multi-year partnership agreement with NASA and DARPA to research, develop, and flight-test automation technologies for AAM operations to transform transportation, cargo delivery, and a variety of public services. Specifically, two of the Sikorsky Innovation Division aircraft, the Sikorsky Autonomous Research Aircraft (SARA S-76B) helicopter and the Optionally Piloted Vehicle (OPV) S-70 helicopter were the research test beds utilized in the IAS Project to represent AAM vehicles. The IAS flights were conducted under public-use operations/rules with NASA, providing final airworthiness approval in conjunction with DARPA processes and flown in the airspace surrounding the Sikorsky facilities located at Stratford and Bridgeport, Connecticut, including over the Long Island Sound.

2 OVERVIEW

The core IAS test objective was to enable and conduct evaluations of two air-traffic conflict-resolution algorithms being evaluated under the NASA Automated Flight and Contingency Management (AFCM) Subproject: The Airborne Collision Avoidance System-Xr (ACAS-Xr) for rotorcraft (algorithm used by Hazard Perception and Avoidance (HPA) team under AFCM) and the Autonomous Operations Planner (AOP) (algorithm developed by the Flight Path Management (FPM) team under AFCM).

Secondary IAS test objectives were to exercise two other urban air mobility / advanced air mobility (UAM/AAM) autonomous flight operation algorithms: 1) Improved Ground Collision Avoidance System (iGCAS); and 2) 4D auto-approach and auto-land algorithms, the auto-approach algorithm was developed by NASA, and the other auto-landing algorithm was developed by Sikorsky. Tertiary objectives were to improve the human-machine interface (HMI) and to integrate all of the tested technology interfaces into the same tablet.

Lastly, a software environment in which to host all the above-mentioned software was also evaluated: a NASA-developed version of a Multi-Monitor Run-Time Assurance (MM-RTA) software architecture (per American Society for Testing and Materials (ASTM) F-3269 guidelines (ref. 1) referred to as the IAS middleware (MW): a continuation from the NASA AFRC Expandable Variable-Autonomy Architecture (EVAA) developed and tested in 2018 to 2021. The MM-RTA (i.e., MW) architecture provides a robust methodology for enabling unmanned and autonomous systems. The EVAA framework coordinates various functionalities with risk-based alerting, safely bounding untrusted behavior. The framework is structured to readily enable the addition and removal of monitors, sensors, and aircraft models with minimum validation and verification requirements. The IAS MW ran core modules and also utilized externally developed software plugins (i.e., external to the MW software team) such as ACAS-Xr, AOP, et cetera, conceptually similar to software applications (apps). The plugins were custom components of each research project team (FPM, HPA, etc.) and IAS Flight Test Services (IFTS). The benefit of using the MW for integration in this project was that it enabled ease of research software integration into the test platforms because the AFCM algorithms (HPA and FPM) only needed to be integrated with the MW instead of the Sikorsky research system, regardless of any updates to the aircraft host research platforms, because the aircraft and avionics are abstracted by the MW. Additionally, MW by its very design enables future research growth such as integration of multi-sensor subsystems/algorithms. For the research described in this report, only one algorithm was active at a time as a buildup to future research.

Integration of Automated Systems (IAS) project-level specific objectives:

- Spiral 1:
  - Verify that the IAS middleware is receiving and interpreting all data required to satisfy the interface requirements for HPA and FPM.
  - Quantify the ability of the SARA aircraft to fly 4D trajectories that are representative of HPA and FPM commands in the presence of varying wind conditions.
  - Identify if any inconsistencies exist between the IAS middleware and the HPA and FPM interfaces.
- Spiral 2:
  - Investigate AFCM system requirements in a UAM Maturity Level (UML)-4 relevant environment.
  - Evaluate other developing AAM technologies for IAS integration and identify future automation needs.

Additional objectives that evolved included the following:

- Evaluate the tactical performances of the ACAS-Xr and AOP strategic performance in deconflicting dual or multi-aircraft operations. The ACAS-Xr and AOP algorithm data analysis, performance, and results are presented in their own dedicated reports (Appendix L, (refs. 6-10) (ref. 6 and ref.10 to be published).
- Evaluate the HPA and FPM team-developed research displays and aural messages driven by ACAS-Xr and AOP, respectively (ref. 11) (to be published).
- Evaluate the ability of the IAS MW, in combination with ground test control personnel and aircrew, to efficiently set up and execute the tests (ref. 14) (to be published).
- Demonstrate developmental candidate UAM/AAM Instrument Flight Procedure (IFP) approaches (ref. 12) (to be published). The goal of this work is to progress toward development of design criteria Terminal Instrument Procedures (TERPS) for UAM/AAM

electric Vertical Takeoff and Landing (eVTOL) Instrument Flight Rules (IFR)-like procedures of the FAA 8260 series orders.

- Demonstrate the operational utility of integrating a Ground Collision Avoidance System (GCAS) within a UAM/AAM representative vehicle (e.g., the Sikorsky eVTOL surrogates, the SARA, and OPV) that operates in relatively close proximity to the ground while enroute or in terminal airspace.

Appendix B provides a description of the system engineering approach and process as well as the Model-Based System Engineering (MBSE) tool used to develop the IAS test system requirements from the project goals and objectives. Appendix B also provides the associated requirements verification & validation (V&V) matrix showing traceability and V&V status.

2.1 The IAS Primary Research Software Objectives – HPA and FPM

The IAS test effort enabled HPA to test ACAS-Xr with real sensor inputs in a live cockpit setting (ref. 6) (to be published). The test effort expanded upon the overall goal of the HPA for the IAS test effort to collect, analyze, and provide data to standards bodies and the ACAS series (-Xa, -Xu, -Xr) development team. The resulting collected data would then be used to evaluate/verify the HPA simulations. In addition, the HPA findings are shared with Radio Technical Commission for Aeronautics (RTCA) Special Committee SC-147 and SC-228. While the ACAS-Xr team focuses on fast-time simulation to generate safety and operational suitability metrics, the NASA HPA team is testing ACAS-Xr in real time with pilots-in-the-loop. The HPA is focused on pilot impressions of ACAS-Xr viability and usability across a variety of conditions (ref. 11) (to be published). For example, HPA research questions included the following:

- Does Xr generate acceptable/viable guidance in all phases of flight (cruise/forward flight, hover/low speed, terminal area, low altitude)?
- How do pilots compare/contrast the Collision Avoidance System configuration to the Detect and Avoid (DAA) configuration?
- What are pilot response times to different alert types DAA alerts; horizontal Resolution Advisories (RAs); vertical RAs; blended RAs?
- Were pilots able to maintain well clear / avoid Near Mid-Air Collision (NMACs) against our various encounters in different phases of flight?
- In what circumstances did pilots not comply with an RA and why?

Like HPA, FPM had specific goals for the IAS test effort, including advancing the readiness of an FPM evaluation toolset, supporting refinement of the evaluation toolset, and discovering unknowns about FPM performance and behavior (refs. 7-10) (ref. 10 to be published). The FPM broad IAS-1 objectives included verifying AOP functionality and performance, establishing technical readiness of the evaluation toolset, and investigating system requirements in a UAM Maturity Level (UML)-4 relevant environment (refs. 7-9). Furthermore, the FPM assessed functions of the integrated test system, which included the following: the test aircraft (SARA and OPV helicopters, datalink, ground station, data streams, background traffic); verified end-to-end system function and tested procedures; and performed scripted-baseline FPM function verification. In contrast to HPA, however, where human factors were the core test interest, FPM human factors testing was wholly out of scope for the IAS tests. The current FPM implementation and test concept is human-in-the-loop, but this concept may not be the long-term concept for how AOP or other strategic dynamic flight path optimization tools will be used. The modified version of the AOP under test is simply a reference prototype FPM system (ref. 7). The purpose of the FPM IAS flight test was to evaluate FPM as a representative technology as well as identify barriers, emergent behaviors, and challenges with flight path management as a function to inform the higher-level FPM CONOPS.

The specific goals of the FPM automation system (refs. 7-9) were to construct and maintain a flight path with five principal qualities: feasibility, deconfliction, harmonization, flexibility, and optimality.

1) A feasible path is one that conforms to the aircraft performance and range capabilities; complies with the airspace structure, rules, and constraints; avoids the terrain and charted obstacles; and meets the arrival constraints.
2) A deconflicted path is one that avoids unsafe proximity to known aircraft, dynamic obstacles, inclement weather, and other emergent airspace hazards.
3) A harmonized path is one that follows cooperative rules and procedures to ensure that the use of the airspace is coordinated with other airspace users.
4) A flexible path is one that provides adequate maneuverability to ensure future flight path changes, if needed, are available and feasible.
5) An optimal path is one that best achieves the operator's business objectives for the specific flight.

2.2 Roles and Responsibilities

The core IAS test team was comprised of NASA IAS, NASA AFCM, and Sikorsky personnel. The DARPA was a partner in the effort, providing resources and project-level assistance to advance autonomy in AAM and unmanned operations, helping to reduce the overall costs of the NASA the process. The IAS team was responsible for development of the middleware (MW) and integration onto the Sikorsky aircraft, including Input/Output (I/O) data couplers within the MW to interface with the research algorithms. The IAS team hosted simulation capabilities at AFRC for the MW as well as the integration of the MW with the research algorithms for development and V&V activities. Additionally, the IAS team was responsible for all systems engineering, software compliance, overall test planning, safety planning, and obtaining airworthiness approval from AFRC. Part of this effort included real-time conformance monitoring for both safety and mission success, leading to valuable situational awareness of how the tests were progressing and provided immediate feedback to the research teams.

The AFCM team was responsible for the two main research algorithms tested during IAS-1: 1) AOP (from FPM research team and their strategic airspace management FPM concept); and 2) ACAS-Xr (from HPA research team, algorithm from John Hopkins University and Massachusetts Institute of Technology (MIT)). This responsibility included the software development, simulations of the individual research algorithms, development of test requirements to IAS so that the applicable data was gathered during flight-testing, and analysis of flight data for inclusion in their own report/papers (Appendix L, (refs. 6-10) (ref. 10 to be published)). This report covers brief high-level results (e.g., Section 5.4 and Section 6.7) but mainly focuses on the IAS and MW specifics.

Sikorsky was responsible for providing aircraft operations, aircraft maintenance, and test operations/facilities/equipment in support of the flight-testing as well as simulation software for the lab at AFRC in order to develop software and conduct V&V ahead of flights. They provided the networking, datalink infrastructure for the testing, as well as the Ground Control Station (GCS): a large mobile trailer/RV out of which testing was conducted. Additionally, they integrated NASA-provided and/or requested hardware onto their aircraft for certain test requirements, such as the computers hosting the test software, Automatic Dependent Surveillance-Broadcast (ADS-B) capabilities, and all the power and antenna requirements associated with the additional hardware.

3 VEHICLE AND SYSTEMS DESCRIPTIONS

The IAS test program utilized two surrogate eVTOL representative aircraft, both with the capability to host NASA research algorithms in a manner that balanced agile software development with low technical and flight safety risk. The NASA partnered with Sikorsky Innovations (the Advanced Concepts group within Sikorsky), located in Stratford, Connecticut, and leveraged both of their two research aircraft: the Sikorsky Autonomy Research Aircraft (SARA) S-76B and the Optionally Piloted Vehicle (OPV) S-70 Black Hawk™ helicopter as IAS research testbeds (fig. 1). Integrated evaluations and demonstrations of candidate technologies were accomplished utilizing the two surrogate aircraft testbeds and their associated automation research software. Both helicopter test beds incorporate the Sikorsky software packages MATRIX™ and the DARPA-Sikorsky Aircrew Labor In-cockpit Automation System (ALIAS) systems. The IAS team identified and provided key technologies needed to evolve UAM/AAM into progressively more complex, automated operations utilizing these two testbeds and their associated ALIAS/MATRIX™ system, all the while ensuring airworthiness processes and reviews were appropriately met. Interfacing with the MATRIX™ system was achieved through a Sikorsky-developed piece of software, called the Autonomy Mission Manager (AMM), which served as the interface point for external commands to be sent to the Vehicle Management Computer (VMC) and for state data to be made available.

Figure 1. (Left) Sikorsky S-76B (SARA); and (right) S-70 (OPV) Black Hawk™ helicopter.

Detailed vehicle descriptions can be found in Appendix C.

3.1 Middleware Description

To accomplish the HPA and FPM, iGCAS, and auto-approach testing onboard the SARA required an interface between the HPA, FPM, and iGCAS research software and the Sikorsky automation research system. This interface software, termed the “middleware” (MW) was based on the Expandable Variable-Autonomy Architecture (EVAA) suite that was developed previously under the Resilient Autonomy Project at NASA AFRC (fig. 2 shows a functional diagram of the

EVAA/MW system implemented for IAS). The capabilities of the MW progressed and were successfully tested in all the IAS test spirals (1A/B and 2A/B/C). The IAS middleware provided the following:

- Conversion of HPA/FPM trajectory commands into representative 4D trajectory commands (latitude, longitude, altitude, and time) compatible with the AMM/MATRIX™.
- Interfaces (termed I/O "couplers") to receive data from environmental sensors (ADS-B), and aircraft systems that provide aircraft state/sensor data (airspeed, altitude, Euler angles and rates, etc.).
- Interfaces with external, NASA-developed research software (blue-circled items in fig. 2):
    - ACAS-Xr algorithm.
    - Autonomous Operations Planner (AOP) algorithm.
    - iGCAS algorithm (also utilizes map/map manager).
    - Vertiport research auto-approach trajectories.
- Precise synchronization of the timing and trajectories between the SARA ownship and the OPV intruder during the air-to-air encounter scenarios (ref. 14) (to be published).
- Via a NASA ground interface called the Middleware Engineer (MWE) display, a software "switch" determined whether to utilize ADS-B-In data from the OPV to provide its position data to SARA and, therefore, to HPA and FPM, or to utilize navigation data from the OPV Embedded GPS/INS (EGI) that is telemetered to the GCS and relayed up to the SARA in flight.
- The IFTS module provides test-unique support by means of test-team developed ground control station displays, which interfaces with the NASA research tablets (hosting NASA IAS displays), and a research software mode control.
- Records NASA data.

The EVAA/IAS middleware is a multi-monitor runtime assurance (MM-RTA) system (ref. 1) that provides enormous flexibility for ensuring vehicle safety in the event of unplanned occurrences or needed deviations from the mission plan to ensure safety. It provides all the data interfaces with the Sikorsky AMM system through the couplers shown in fig. 2 and fig. 3.

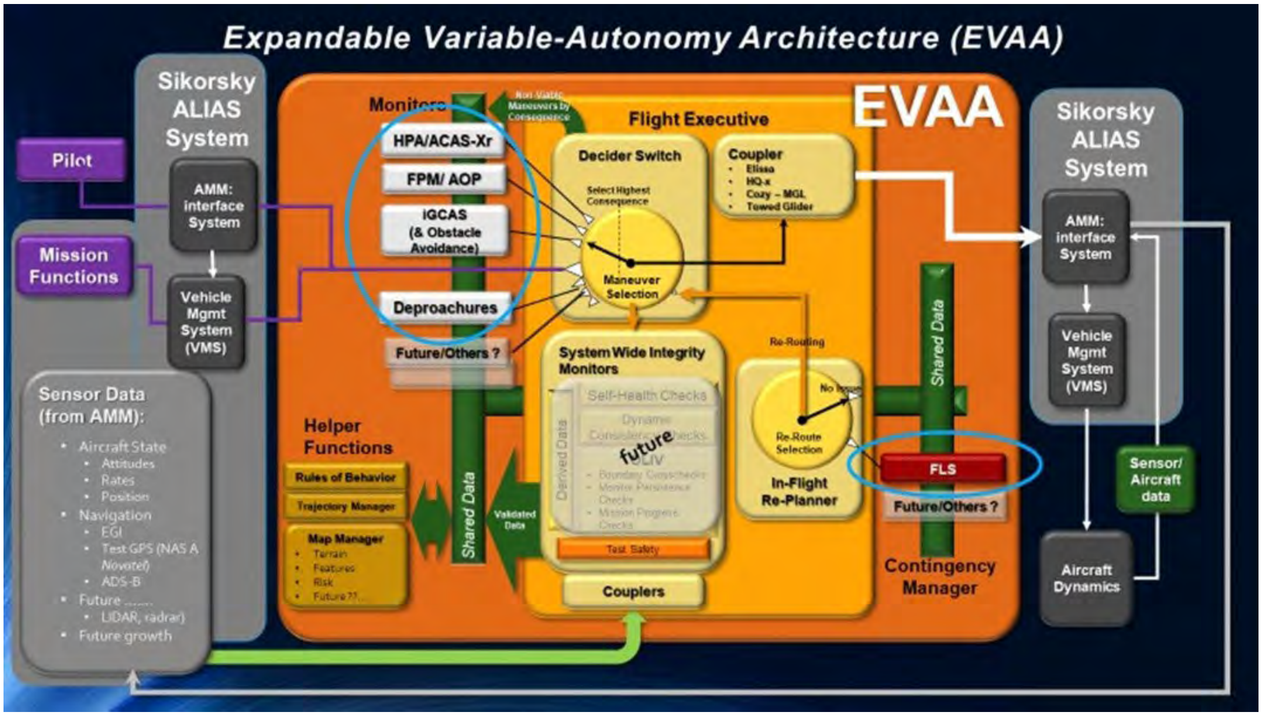


Figure 2. IAS middleware/EVAA system architecture.

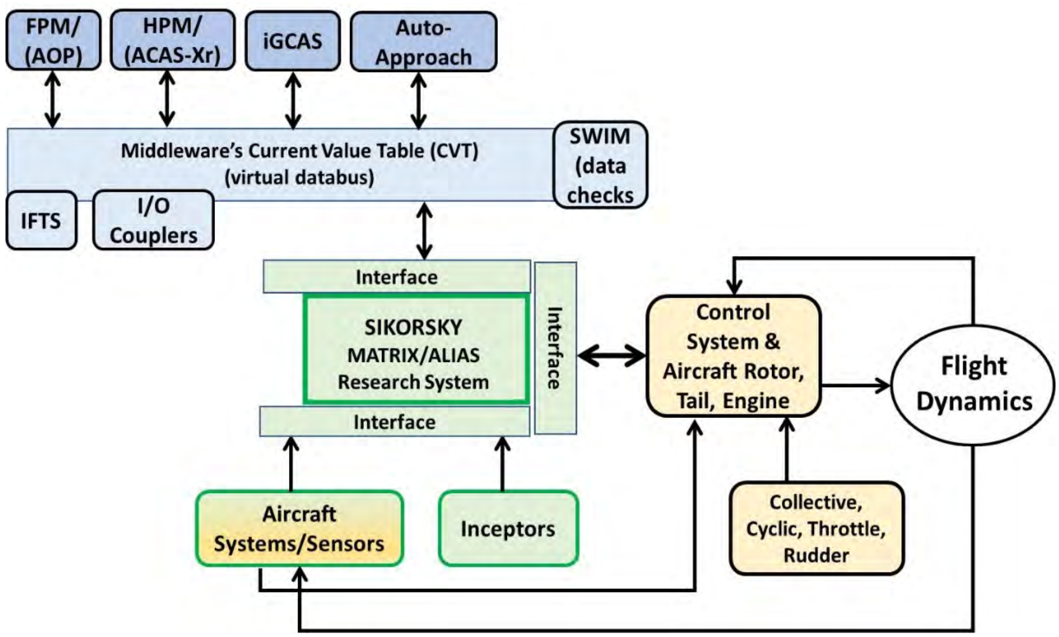


Figure 3. Sikorsky-NASA MW interfaces.

3.2 The HPA Description

Hazard Perception and Avoidance (HPA) utilizes the FAA/MIT/Johns Hopkins University-developed ACAS-Xr algorithm package (but not the HPA-developed research displays; these displays were developed by the HPA team based off of previous DAA work) as the central algorithm to perform tactical conflict detection and resolution. The ACAS-Xr provides guidance against two different hazard criteria: 1) DAA well clear (per the RTCA DAA UAS MOPS [DO-365B]), which extends to ~90 seconds from Closest Point of Approach (CPA), and 2) Near Mid-Air Collision (NMAC), which is a 500-foot horizontal separation and a 100-foot vertical separation. The ACAS-X series (Xa, Xu, Xr) are the next generation replacements for TCAS II, dependent upon aircraft type, and capable of detecting/avoiding cooperative (i.e., two-way communication between ACAS/DAA systems) and noncooperative air traffic. For IAS testing, the SARA helicopter hosted the HPA/ACAS-Xr software and as such was termed the "ownship" aircraft, whereas the OPV helicopter did not host HPA software and served as the "intruder" aircraft for all air-to-air testing.

The ACAS-Xr algorithm receives external air traffic/intruder information from the intruder aircraft (for IAS testing, ADS-B was used as the input data source providing aircraft position/state data) and generates tracks of the intruder(s) and the ownship to determine whether a DAA well clear or NMAC violation is predicted to occur within the appropriate look-ahead time. The ACAS-Xr algorithm then provides, depending upon the collision/violation urgency, various avoidance maneuvers (horizontal, vertical, or blended: a mix of both horizontal and vertical) and notifications (in the form of visual/displays and auditory messages) to remedy the situation. The types of advisories/avoidance provided to the pilot are a function of which ACAS-Xr configuration is active, the Collision Avoidance System (CAS) configuration or the DAA configuration. In the CAS configuration, Resolution Advisories (RAs) and Traffic Advisories (TAs) are provided. The RAs are provided for situations deemed by the ACAS algorithm as more urgent in nature than TAs that are provided as situational awareness information to the pilot. In the DAA configuration, DAA alerting, and guidance replaces the Traffic Advisory (TA) alert type. Unlike TAs, which are only used for Situational Awareness (SA), the DAA information is intended to be used by the pilot to determine when and how to maneuver against traffic predicted to violate DAA well clear.

There were four different of ACAS-Xr configurations and flags managed by the MW software during the IAS-HPA tests:

1) Collision Avoidance System (CAS) configuration – provides short-term, warning-level RAs and TAs to avoid NMACs.
2) Detect And Avoid (DAA) configuration – provides caution-level, DAA alerting and guidance to maintain DAA well clear, in addition to RAs to avoid NMACs.
3) *Terminal* area intruder flag (T) – available only in the DAA configuration, this flag was used to designate the intruder as flying within terminal airspace and correspondingly reduced the size of the DAA well-clear hazard region and suppressed all alerting and guidance, except for Vertical RAs.
4) *Structured* airspace intruder flag (S) – available only in the DAA configuration, this flag was used to designate the intruder as flying within structured (i.e., high-density) airspace and correspondingly reduced the size of the DAA well clear hazard region and suppressed all DAA alerting and guidance but allowed horizontal and vertical RAs.

In all the above configurations, the HPA test algorithms could be set (specified on the test cards) to execute the ACAS-Xr commanded RAs either automatically through the MW (utilizing a nominal 500-foot per minute climb/descent rate; and a 3-degree per second standard yaw rate), or by relying upon the NASA research pilot to fly (via the SARA inceptors) the ACAS-Xr-recommended RA provided on the HPA research display. All maneuvers were made against the caution-level, and DAA guidance was made manually via SARA inceptors. Appendix I has a description of the HPA research display, including the digital buttons available on the display to interface with the MW/ACAS-Xr algorithm controls. As mentioned previously, ACAS-Xr provided associated avoidance maneuvers when their specific collision/well-clear criteria were violated. Table 1 (light blue area for HPA/ACAS-Xr) provides the HPA criteria used to decide near-miss/well-clear violations for IAS testing.

Table 1. ACAS-Xr and AOP avoidance criteria.

Algorithm	Mode	Horizontal Zone	Vertical Zone	Avoidance Type(s) Maneuver
ACAS-Xr	Collision Avoidance (CA)	±500 ft	±100 ft	Resolution Advisory (RA) Traffic Alerting (TA)
	Detect & Avoid (DAA)/Well Clear	±4000 ft	±450 ft	Resolution Advisory (RA) Detect & Avoid (DAA)
	Terminal airspace	±1500 ft	±450 ft	Resolution Advisory (RA) (vertical only)
	Structured airspace	±1500 ft	±450 ft	Resolution Advisory (RA)
AOP	• Conflict detection: 3 minutes • Conflict resolution: 6 minutes • Resolution freeze horizon: 40 sec. • OP resolution refresh cycle: 20 sec. The various trigger critera/ parameters set by FPM team	±1500 ft (Zone dist. set by FPM team)	±450 ft	Conflict Resolution (CR) (alternate route(s) options that will satisfy mode criteria)

As will be described in subsequent test methodology sections of this report, a total of 33 various HPA encounters were conducted during the project Capstone (Spiral 2C) tests at different geometries (head-on, acute and obtuse angles, coaltitude, climbing/descending, ground speeds etc.) in order to stimulate ACAS-Xr under a variety of conditions.

3.3 The FPM Description

Flight Path Management (FPM) utilizes the NASA Automated Flight and Contingency (AFCM) subproject-provided research software to perform dynamic (e.g., in flight, in real time) aircraft strategic route planning. A reference prototype FPM automation system was developed at NASA LaRC to explore and refine the FPM concept. This reference prototype, a modified version of the NASA Autonomous Operations Planner (AOP), was tested in FPM simulation activities (batch and human-in-the-loop) at NASA Langley in a representative UML-4 operational environment before being utilized for IAS flight-testing. The FPM automation system manages the route trajectory of the ownship and makes "conflict resolution" (CR) recommendations, or options, available to the pilot on the FPM research display (NASA tablet) in the horizontal, vertical, or blended directions to resolve the AOP-predicted route conflictions. In determining the various CR options, the AOP considers multiple parameters (see Section 2.1), including the required time of arrival of the ownship to its landing or upon entry to the vertiport. For IAS tests, the FPM/AOP system did not maneuver the aircraft until the pilot had selected one of the AOP-provided options on the FPM research display. Unlike HPA testing, the NASA research pilot did not have the option to hand-fly the CR using the SARA inceptors but instead allowed the MW to automatically maneuver the aircraft after the research pilot selected a CR option on the NASA tablet.

Additionally, unlike HPA/ACAS, the trajectory data protocols used to exchange routing information among air traffic is not standardized; therefore, for IAS testing, the FPM research team's established data protocols were implemented.

For IAS testing, as with HPA testing, the SARA helicopter hosted the FPM/AOP software and as such was termed the "ownship" aircraft, and the OPV helicopter did not host FPM/AOP software and served as the "intruder" aircraft for all air-to-air testing. The FPM testing/AOP environment, however, included between 250 to 330 virtual air-traffic aircraft that were observed by the AOP algorithm in the SARA as legitimate air traffic to be accounted for in conflict resolutions with the intruder/OPV. These 250 to 330 virtual air-traffic aircraft were part of the FPM airspace simulation research environment that was moved from the Dallas Fort Worth, Texas area to the area surrounding the Bridgeport, Connecticut test area. The virtual Dallas Fort Worth environment and the virtual traffic were provided to AOP from databases on-board SARA.

Since the nature of the IAS FPM/AOP testing was much more in the research realm with essentially no aviation community-established/FAA criteria, the breadth of testing and associated desired encounters were broader than for HPA/ACAS testing. For instance, FPM testing was divided into eight types/groups of encounters as opposed to the four configurations/modes in HPA/ACAS. There were more differences in AOP control parameter variations (for instance, how far ahead in time the AOP looked forward in routing/timing) among these eight groups in order to provide a wide scope of research data, each under varied conflict geometries. Furthermore, for FPM, unlike HPA which utilized ADS-B data, the data source for the intruder/OPV state data was the OPV navigation system data provided to the FPM software on the SARA, which was relayed through the GCS. Candidate separation standards for UML-4 were incorporated into the FPM/AOP design. Look-ahead and alerting time horizons for UML-4 were modified based on engineering judgement and preliminary batch testing. The resulting baseline look-ahead horizons, which could change per FPM group modifications to the AOP, were as follows:

- Conflict detection: 3 minutes.
- Conflict resolution: 6 minutes.
- Resolution freeze horizon: 40 seconds.
- AOP resolution refresh cycle: 20 seconds.

The light green shaded area, shown previously in table 1, provides the criteria used to decide the AOP/FPM near-miss/well-clear violations for IAS testing.

A total of 34 various FPM/AOP encounters were conducted (from 51 test cards) during the project Capstone (Spiral 2C) tests at differing geometries (head-on, acute and obtuse angles, coaltitude, climbing/descending, etc.) in order to stimulate the AOP under a variety of conditions.

3.4 Auto-Land/Auto-Approach Description

The NC candidate UAM/AAM procedure design test objectives were assessed during IAS-1 Spiral 2C testing (ref. 12) (to be published). The primary focus was on flight path conformance, passenger comfort, time required, and landing accuracy. The building and "coding" of Instrument Flight Procedures (IFPs) were implemented in the design of MW-controlled auto-approaches. Only the straight-in approach landing followed by an auto-landing portion of a future, complete IFR flight phase was performed in IAS (in Spiral 2C). The NASA-designed UAM representative approaches included 5-, 8-, and 12-degree approaches and a linear deceleration rate. These approaches had been coordinated with the FAA to some extent and with the Bridgeport/Sikorsky Memorial Airport (KBDR) airfield and Sikorsky, but they were not certified approaches. Figure 4 shows representative diagrams for notional, complete UAM/AAM vertiport holding pattern "wheel" and side views of a notional approach; however, for these Spiral 2C tests only the straight-in portion (to include landing) from the inner/release section of the wheel was executed (i.e., not the approach to the wheel, nor the wheel itself were flown).

The representative approach routes were parameterized using 4D trajectories within the MW to demonstrate the feasibility of the auto-approaches/auto-landings on an actual VTOL aircraft (note: these were conducted on the OPV due to better performance margins but could have also been conducted safely on the SARA) and planned as if a UAM vertiport was located at KBDR. To conduct these tests, a selected location at KBDR was designated as a NASA IAS target vertiport location and the straight-in, linear descent rate approach was auto-flown via the MW or the Sikorsky auto-land system (fig. 5). Following each MW-controlled approach termination to an ~30- to 50-foot hover above the designated vertiport on the approach plate, the aircraft was commanded via the Sikorsky baseline system to perform a fully automated landing to the vertiport. Performance criteria such as altitude loss, lateral, and vertical deviations from the planned/commanded path will be evaluated for approaches and potentially for departures. Pilot questionnaires were collected to capture comments regarding the approaches. Additional details can be found in the auto-land paper referenced in Appendix L.

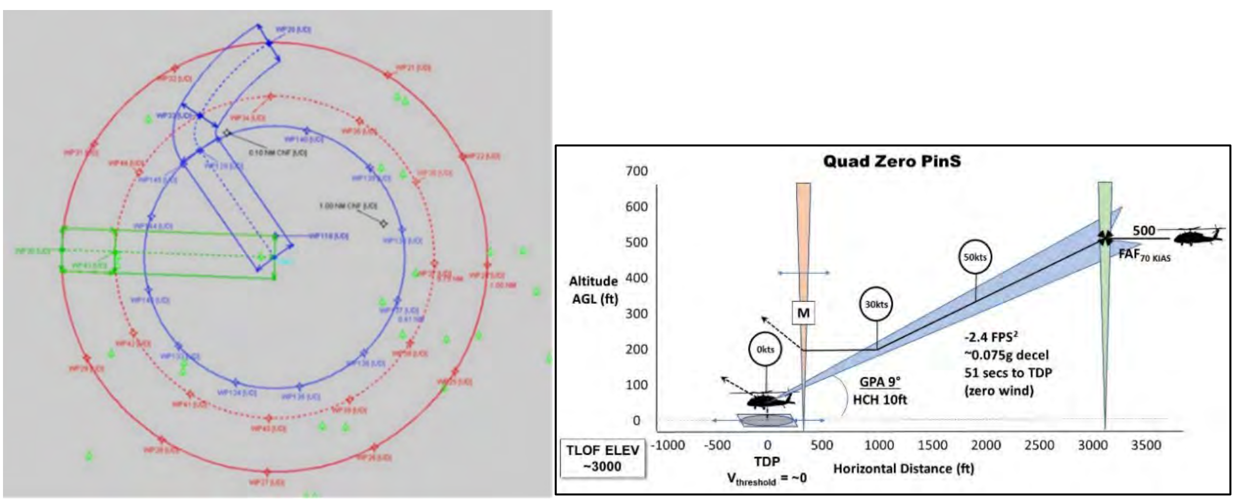


Figure 4. (Left) Notional UAM/AAM holding "Wheel"; and (right) approach side-view.

Figure 5. The KBDR approach line to KBDR.

3.5 The iGCAS Description

A demonstration of the NASA EVAA/MW architecture to integrate a variety of flight safety monitors and provide 4D trajectory control of the ground/obstacle avoidance maneuver was accomplished by integrating iGCAS with the IAS middleware. The iGCAS has a solid implementation pedigree through fielding an earlier version (GCAS on U.S. Air Force F-16 and F-35 aircraft). At a top level, iGCAS utilizes a high-resolution digital terrain (including water) elevation map stored in memory (a 1/9th-arcsec (~10 feet) raster array) to compare the set of iGCAS-predicted trajectories (straight climb/descent, left turn climb/descent, right turn climb/descent, and level altitude left/right turn). When the last available iGCAS avoidance option is deemed to intersect with the terrain/obstacle, the corresponding avoidance maneuver is triggered. For the IAS Project, one iGCAS test was conducted by SARA against the water of the Long Island Sound following a shallow 7-degrees-down flight path angle towards the water (1,100 feet per minute descent rate) at 90 KGS. A second iGCAS test was also conducted against a 3,000-foot-tall virtual wall to demonstrate iGCAS avoidance of obstacles.

4 TEST DESCRIPTIONS

To build up technical capability safely and efficiently while striving to minimize safety risk, a spiral (or phased) “fly-fix-fly” development approach was utilized for the IAS campaign. Two development spirals were implemented in the IAS campaign following a pair of Sikorsky-conducted “pathfinder” flights of SARA to demonstrate its capabilities firsthand to NASA in March of 2022. All the spiral testing was conducted by a joint/partnership team between NASA and Sikorsky. Each spiral built upon its predecessor spiral testing and, as a result, grew in complexity and resulting system capabilities. Lessons learned and system operations experience from each spiral were fed into the next spiral testing, thereby minimizing exposure to “unknown” unknowns and flight safety risk. Throughout the IAS test campaign, from March of 2022 through October of 2023, either the SARA helicopter, the OPV helicopter, or both were utilized depending upon the specific spiral. A total of 71.7 hours were flown between the two aircraft during 23 different missions (some with just one vehicle and others with both vehicles flying). A detailed breakout of the sorties can be found in Appendix D.

4.1 Test Location and Operations

4.1.1 Overview

All IAS flight-testing was conducted jointly by NASA and Sikorsky originating and concluding from the Sikorsky facilities located at the Sikorsky Memorial airport in Bridgeport, Connecticut, with the exception of the Pathfinder flights, which were conducted at the Sikorsky private heliport located near the manufacturing plant in Stratford, Connecticut, about 5 to 6 miles north of Bridgeport, on the shores of the Housatonic River (fig. 6 and fig. 7). The SARA and OPV are based at the Bridgeport/Igor Sikorsky Memorial Airport (KBDR) that contain two runways (each 4,700 feet by 100 feet), an Instrument Landing System (ILS), localizer (LOC); and area/required navigation (RNAV) approach capabilities along with Standard Instrument Departure (SID) Routes and Standard Terminal Arrival Routes (STAR). As stated earlier, all spiral flight tests originated and terminated at KBDR where the Sikorsky primary mobile ground control station (GCS) was located; however, some early auto-landings were conducted at the Sikorsky Private Heliport (KJSD), Stratford, Connecticut.

Figure 6. Bridgeport/Sikorsky Memorial Airport (KBDR).

Figure 7. Sikorsky Private Heliport (KJSD).

All IAS flights were conducted in the National Airspace (NAS) either above the land within an ~20-nautical mile arc north of KBDR (in the cases of Pathfinder, Spirals 1A and B, and Spiral 2A), whereas Spirals 2B and C were flown over the Long Island Sound within a 24-nautical mile by 10-nautical mile “box” to ensure adequate data/telemetry communication and away from Class D controlled airspaces as much as possible. Figure 8 and fig. 9 show images of the airspace surrounding KBDR/KJSD. All IAS spiral flights were conducted at <6,000 feet Mean Sea Level (MSL), but >2,500 feet when feasible to avoid Air Traffic Control (ATC) Class D airspace altitude restrictions and commercial airliners as much as possible. During Spiral 2C tests, the FPM runs, and the HPA low-speed hovering tests were conducted at <2,000 feet to best represent expected UAM/AAM operational altitudes.

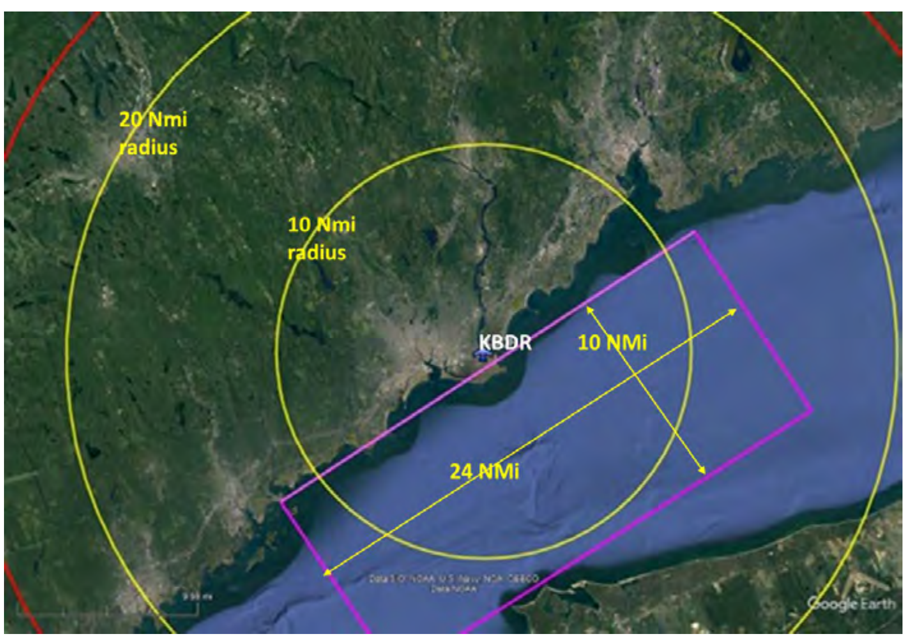


Figure 8. The IAS flight-test areas.

Figure 9. Aeronautical chart - Stratford, Connecticut area.

The IAS Project utilized the Sikorsky large-mobile GCS trailer for all spiral flights together with the displays and mission computers located in an adjoining conference room during Spirals 2B and C to host subject matter experts and additional display monitoring (fig. 10). A directional data antenna on the large GCS trailer was utilized for single-ship operations, and another directional data antenna, atop a tall lift, was devoted to the second aircraft up/downlinks required during dual-aircraft operations in Spirals 2B and C. The data streams from the OPV and the SARA aircraft were available within the GCS, and when needed during Spiral 2B/C tests, a subset of data was sent to the hangar overflow/conference room via Ethernet. More detailed system diagrams for data flow and communications for each spiral are provided within each of the specific test descriptions of Appendix E. In addition, the mission rules used to safely execute IAS tests are provided in Appendix F.

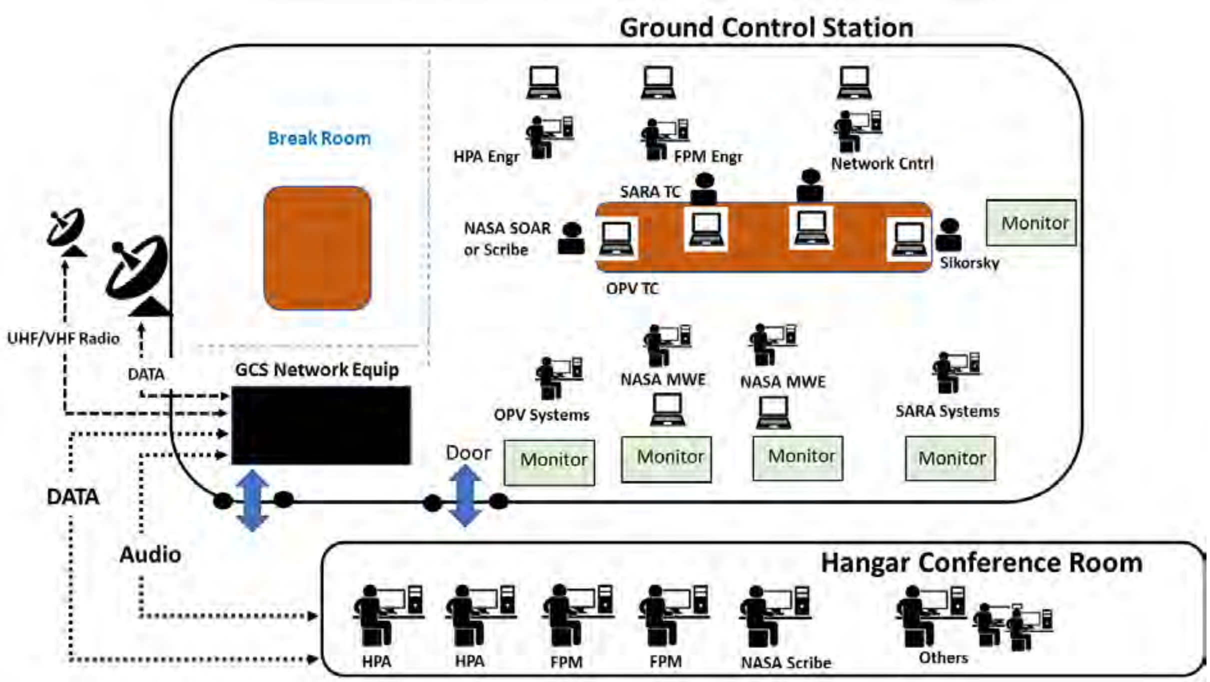


Figure 10. Sikorsky ground control station (GCS) diagram.

4.1.2 Ground Tests and Simulation Capabilities

The IAS test program utilized three locations to develop and integrate the IAS middleware and its associated IAS/NASA GCS test displays (not including the HPA/FPM software development), conduct simulations, and conduct ground tests. The NASA MW integration effort was twofold: first, integrating the MW with the Sikorsky MATRIX™/ALIAS system; and second, integrating the individual NASA research algorithms (HPA, FPM, iGCAS, and auto-approaches) within the MW. The primary MW development/system integration/simulation test location was at NASA AFRC. The Sikorsky facility at the KBDR airport is where software final V&V, aircraft ground tests, and simulations occurred. The third location was at NASA Langley Research Center (LaRC) and was utilized during Spiral 2 to assist in display development and FPM integration. The detailed NASA FPM and HPA research system software development and their associated simulations were conducted at either NASA LaRC or NASA Ames Research Center (ARC).

All the above-mentioned IAS test/locations did not include the FPM/HPA software development, nor the tests and manned/unmanned simulations conducted by the HPA/FPM development teams ARC/LaRC, respectively. The HPA/FPM development efforts did not include their integration with the MW. Instead, the HPA/FPM development occurred independently, within research-style environments and included extremely detailed test simulations (manned and unmanned batch simulations).

For the NASA IAS, software development/integration effort simulators were utilized at every stage of development to ensure that the software being developed was tested as it would be flown. Two types of simulation environments were utilized for development and integration: one lower-fidelity kinematic-based simulation, and the other, a higher-fidelity aero-based simulation, both provided by Sikorsky. Both simulation environments fully simulated the AMM I/O interface to the MATRIX™ system of the aircraft. The low-fidelity desktop simulation was termed the Software Development Kit (SDK). The second type of IAS software development/integration station was termed a *Gen*eral *Hel*icopter (GenHel) simulation. The GenHel was a more capable, Sikorsky-proprietary, higher-fidelity simulation environment that was based on a Sikorsky-developed aeromodel of the SARA S-76B. The GenHel-based simulator, purchased by NASA and located at AFRC, could have accepted input from pilots through the inceptors used in SARA; however, these were not procured in time for the IAS activities.

For final system checkout, the SARA aircraft could be put into a hardware-in-the-loop simulation mode. The checkout utilized the NASA MW hardware/software together with the Sikorsky MATRIX™/ALIAS research system on both the SARA and OPV aircraft together with a large high-definition screen placed in front of the SARA helicopter to provide visual picture of the flight environment. This Sikorsky on-aircraft simulation interfaced with the Sikorsky GCS to replicate flight in a high-fidelity manner to the engineers and the aircrew in the helicopters. Figure 11 shows an on-aircraft ground test being conducted (note the large screen in front of the SARA).

Figure 11. On-aircraft ground test.

Ground Tests: Prior to each spiral flight-test effort, table 2 and a graphic representation for Spiral 2C in fig. 2, respectively show a series of ground tests that were performed in order. These ground tests consisted of the following:

Table 2. Ground testing sequence.

Test	Description	Location	Platform
Integration tests	unpiloted, integration tests (check MW integration of HPA/FPM & displays (tablet and GCS)	AFRC	SDK / Genhel (only spiral 2C)
V&V Procedures development	unpiloted, develop and practice V&V tests	AFRC	SDK / Genhel (only spiral 2C)
Combined Systems Checks	On-aircraft integration checks (includes integration w/Sikorsky data network)	Sikorsky, KBDR	On aircraft + GCS
V&V Tests	Formal SQA witnessed V&V	Sikorsky, KBDR	On aircraft + GCS

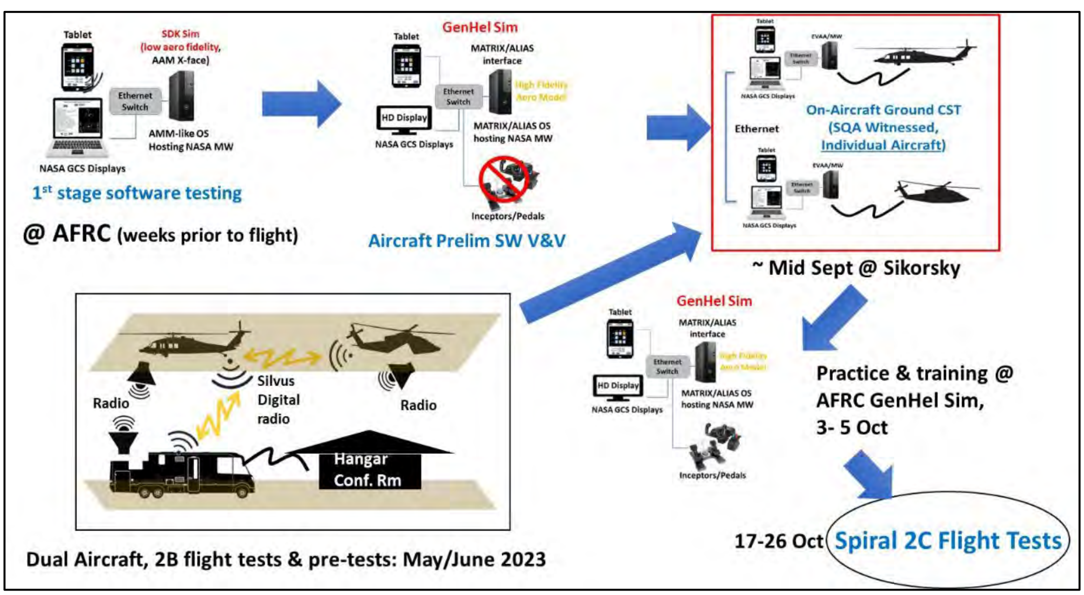


Figure 12. Ground test series, Spiral 2C flight tests.

5 THE IAS LEVEL RESULTS

Overall, the IAS testing was very successful. Spiral 2B was the first time two aircraft were flown in scripted encounters that resulted in the geometry necessary to produce conflicts for either HPA or FPM test points. With a few exceptions, all the test points flown matched what was seen during in-depth AFCM simulations, helping to satisfy one of the objectives of the project: to provide data for validation of the AFCM simulations. Detailed HPA and FPM results are covered in separate reports (refs. 6-10) written by those test teams, whereas results of individual spiral tests are presented in Appendix E.

The MW was key in enabling these encounters (except for low-speed/near-hover HPA encounters) since precise velocity vectors needed to be achieved at a very specific latitude/longitude/altitude as well as at very specific times. Hand-flying to that precision was not practical for all runs other than near hover, nor would it have been repeatable and efficient enough to produce the number of encounters successfully flown during the spirals. Auto-generated tightly timed routes for HPA and FPM encounters was a novel and exceptionally useful tool to guarantee efficient test operations (e.g., fewer aborts/resets for timing errors) and a low degree of timing and position error at the start of runs (ref. 14) (to be published). Auto-flying the encounters, via MW, freed the aircrew to easily concentrate on their specific tasks (safety and HPA/FPM research) instead of dividing their concentration to flying the aircraft and meeting strict timing requirements, thereby ensuring more productive research. This tool has use across many types of flight-testing that involves time on target, especially for multiple aircraft. Appendix E shows a detailed description of the test methodology for Spirals 2B/C. For simplicity as well as to minimize Automation-Induced Oscillations (AIO), which is addressed in Appendix J and (ref. 13) (to be published), at low airspeed conditions (Appendix H for the test matrices), the HPA low-speed test runs (setups and avoidances) were hand flown by the OPV and SARA aircrew (fig. E 15, Appendix E).

Future research could include the following:

- Add additional safety monitoring algorithms (besides ACAS-X and AOP), such as contingency-landing location selection, all operating simultaneously in concert with EVAA/MW that provide gatekeeping and I/O responsibility for the hosted algorithms.
- Add various types of sensors and enabling the MW to use its Best Source Selection (BSS) capability to show how various algorithms and sensors could be used in concert. The MW BSS capability is used to determine which of multiple sensors is providing the "best" (criteria established/set by the user) data at any given instant and provided to system behavioral research algorithms/safety monitors via the MW Current Value Table (CVT) virtual data bus. This method is an alternative to a traditional sensor-fusion approach that typically requires extensive testing to "tune" the fusion algorithm in order to reliably resolve the target/intruder.
- Expand upon the MW abstracted hardware I/O/sensor capability to assess the validity/health of all sensed states being utilized by the system as well as expand upon the aircraft reaction to system failures. This expansion could be done by employing more innovative data health checks, such as heterogeneous sensor comparisons and other methods, in addition to the more common sensor-redundancy checks. Leveraging the MM-RTA/MW design approach, when system failures are detected, the resulting reaction could be controlled via strategic contingency algorithms implemented by the MM-RTA/MW.

5.1 Contributions of MW MM-RTA Architecture

The MW (more generally, MM-RTA architectures) brought multiple benefits to the IAS Project. By its very architectural design, the MW-RTA separated the need to directly integrate the research software I/O with the Sikorsky AMM/MATRIX™ system and was able to do so by using its "coupler" modules together with its CVT virtual data bus to provide the I/O interfaces for the research algorithms. Additionally, the MW provided the ability to host all the research algorithms in one NASA software build and run them all during any given test mission without having to reboot the test software nor land and reload software. Another MW benefit was provided by its use in controlling multiple aircraft trajectories simultaneously to the timing and position levels required by the research software (<3 seconds at points along the trajectory paths). Lastly, the MW provides for future growth through its ability to enable integration of the research algorithm together via its very design, without having to recode the research algorithms themselves.

Details of, and additional MW contributions, are outlined in the following subsections.

5.1.1 The MW Integration with the Sikorsky MATRIX™/ALIAS Environment

The MATRIX™/ALIAS system design provides Level A/safety critical protection, which allows non-DO-178C DAL Level A research software (i.e., not developed as safety critical software) to interface with the aircraft control system (ref. 5). This robust design provided an enormous advantage for the IAS Project in allowing level-D developed NASA aircraft automation research software, displays, and pilot interfaces to be hosted and flight tested in a manner supporting spiral development. Had there not been an already certified MATRIX™/ALIAS environment with which to protect the aircraft from the multiple NASA research software pieces (EVAA/middleware, AOP, ACAS-Xr, and iGCAS), schedule would have been undoubtably prolonged. This is the case because the various NASA research algorithms were not required to be developed to safety-critical levels (due to MATRIX™ protections), so the project did not have to rigorously develop and test to more challenging software development process requirements (including Level A). Instead, the mature and well understood MATRIX™/ALIAS system enabled NASA to rapidly make changes and updates to the research software that controlled the aircraft automated trajectory. Furthermore, the Sikorsky Model Development Safety Process (MDSC) committee and associated Sikorsky research operations and maintenance processes, which readily accommodate the MATRIX™/ALIAS system, provided an additional layer of safety assurance for NASA when testing new autonomous research software and pilot displays/interfaces.

5.1.2 Use of the MW to Auto-fly Test Runs and Perform System Integration

Use of the MW to control the setup timing and encounter routes was a novel concept and proved to be helpful in increasing test efficiency (minimizing repeats due to manually flown setup timing errors). The FPM encounters (and to a lesser extent, HPA encounters) required controlling the timing of both aircraft to <3 seconds at the route/trajectory intersecting point/closest point of approach (CPA) in order to simultaneously ensure safety and satisfy triggering AOP or ACAS-Xr avoidance maneuver requirements under the called-for geometries. A key benefit of using the MW to control the encounters was the repeatability of the encounters. When each of the test runs was flown, there was very high confidence that the as-flown maneuver would closely match the same run executed in simulations and software V&V, as well as provide high confidence that the maneuver would satisfy the tight geometry constraints imposed by the FPM and HPA teams of a 0.1-nautical mile separation or a 0.2-nautical mile separation, respectively. This method provided high fidelity between the encounter geometries executed in simulations with those executed in flight. Extensive testing was required in Spiral 2B and in the GenHel simulator to collect data and establish the setup orbit locations relative to the encounter start points to ensure the MW algorithm would not fault while trying to resolve unsolvable route-timing constraints. Even then, however, occasional problems were encountered during flight that were primarily caused by wind effects on route timing and speed control.

Finally, another benefit of using the MW to control the encounters was the improved safety. The middleware-controlled routes were tested in simulation, and the close aircraft separations (0.1 and 0.2 nautical miles, a <3-second timing at the point of closest approach and along routes) were verified ahead of flight tests. Although, to ensure layered safety, the project did implement a mission rule that mandated visual contact with the other aircraft by at least one of the pilots when inside a 0.75-nautical mile separation. Refer to Appendix E for Spiral 2B Test Methodology, which includes a more detailed discussion of the IAS middleware operation, and Appendix F for the mission rules.

Using the MW to execute the auto-approach routes was also necessary because the central intent of the auto-approaches was to demonstrate the coupling of Instrument Flight Procedures (IFPs) with 4D trajectory commands – something MW was designed to do and implemented on the IAS Project.

See Section 6 for additional comments and lessons learned pertaining to IAS results.

5.1.3 Winds Aloft Considerations

One important aspect of the MW was the inflight computation of winds aloft. Winds aloft during air-to-air (ATA) encounters testing is an important parameter consideration for not only encounter setup and execution but also for important considerations regarding the research algorithms. Three aspects of winds must be considered in planning, executing, and analyzing UAM/AAM route planning and air-to-air encounter tests:

1) What is the effect of winds on the postflight statistical analysis of data associated with ATA encounters, data such as miss distance? The winds aloft change the flight paths between an aircraft executing a maneuver in an aircraft frame of reference (e.g., constant bank angle turn or maintain constant *heading*) versus the same aircraft executing an earth-referenced maneuver (e.g., constant radius turn or maintain *track*).
2) An important factor associated with winds aloft is accounting for them in planning the precise timing and geometry of encounters.
3) An important winds aloft consideration to determine their effect upon the ability of the aircraft to fly within a specified 3D trajectory error-band (termed, *Trajectory Planning Uncertainty Bounds (TPUBs)*. In Spirals 1A/1B flight-testing the accuracy of the SARA Embedded GPS / Inertial (EGI) system combined with its ability to maintain a flight path was well within the Trajectory-Prediction Uncertainty Bounds (TPUBS) required while in MW computed >30-knot winds were demonstrated.

5.2 The HPA and FPM Integration with Middleware

As was mentioned in the opening paragraph of Section 5, the research algorithms, including HPA and FPM, communicated their I/O through the MW and not directly by using the aircraft systems. These I/O communications included receiving aircraft position data and outputting aircraft trajectory commands for encounter routes in order to generate conflicts and the actual avoidance maneuvers (i.e., RAs, TAs, DAA alerts in the case of HPA/ACAS-XR, and conflict resolutions in the case of FPM/AOP). For the MW to execute the routes and avoidance maneuvers required, the HPA and FPM teams needed to provide the IAS software team with their preplanned routes, avoidance commands, and associated research displays and audio alerts. As part of HPA and FPM planning effort, the IAS software development team coordinated with the HPA and FPM teams to agree on the limits for maneuver dynamics, which both would utilize; a 3-degree per second turn rate and a ±500-foot per minute climb/dive rate was agreed upon. They also coordinated with the IAS operations engineers (who in turn coordinated with Sikorsky) to agree on a "box" within which all encounters would take place (see fig. 8).

The FPM (and the auto-approach/-landing trajectories) setup routes and the resulting CRs were provided to the IAS team in the form of an Efficient Universal Trajectory Language (EUTL) file format. The FPM EUTL trajectories for each of the 51 maneuvers provided test cards (each card was a given encounter geometry between the ownship and the intruder or required the ownship to comply with a change to its assigned time of arrival) and required multiple individually unique files because each encounter (setup and CR) was required to account for varied wind direction and speed. This accounting for wind variability led to hundreds of FPM EUTL files being prerun by the FPM team in batch-mode simulations before being provided to the IAS software team for coding/incorporation into the mission software load. The AOP algorithm provided the CR options to the aircrew, and once selected, the resulting maneuver trajectory path was computed by the AOP and was provided to the MW for execution. The HPA team also utilized the EUTL format for test points that were not flown at low speed (i.e., 25 KGS) but did not need to generate multiple wind-dependent files because their routes were based on ground speed/paths. Once the ACAS-Xr algorithm commanded an RA, it was either executed manually or the MW computed the resulting earth/ground reference-based RA trajectory in real time from the current position of the aircraft (location at which the RA was triggered). The MW updated its trajectory in accordance with any updates to the RA until the ownship was clear of the conflict, at which point the aircraft went wings level. The MW was not in the loop for low-speed test points, meaning the setup profiles and the RAs were all executed manually. The MW was also out of the loop when pilots were responding to DAA alerts because those maneuvers were not designed to be automated.

5.3 Automation-Induced Oscillation (AIO) Overview

During the first test Spiral 1A, and in all subsequent IAS spirals, the aircraft encountered a phenomenon, termed Automation-Induced Oscillation (AIO) by the test team, which was a bounded ~0.2-hertz limit cycle oscillation sometimes of moderate magnitude (ref. 13) (to be published). The AIO was observable in the Sikorsky GenHel simulator and in the on-aircraft simulation. If the aircraft was not turning, the AIO was limited to the pitch axis (an ~ ±5- to 6-degree pitch angle); however, if the aircraft had just completed a turn or was actively in a turn, then the oscillation could also occur in the roll-yaw axes. A Proportional-Integral-Derivative (PID) controller was added to the MW in Spiral 2A to mitigate the AIO effect on test conduct. More detail and data plots are provided in Appendix J, but an overview explanation is as follows: the AIO was the result of the MW needing to tightly control ground speed in the presence of winds in order to meet tight trajectory timing constraints on the helicopter(s) (note: the AIO occurred on both the SARA and the OPV). Since speed control on a helicopter is achieved through pitch control, resulting oscillations occurred as the dynamics of the controllers played out in flight. The multi-axis coupling on helicopters, combined with the need to stay within narrow trajectory paths (desired to be <±50 feet horizontal; and ±30 feet vertical) including during turns, led to this phenomenon being experienced in the roll-yaw axis during/following turns. In all but a few instances, the AIO did not reach a magnitude to be deemed objectionable by the aircrew and MW/Automation was paddled off, but nonetheless, the AIO phenomenon was closely monitored in real time by MCS personnel and "knock-it-off" (KIO) criteria captured in the mission rules.

5.4 HUMAN-MACHINE INTERFACE (HMI) / HUMAN FACTORS RESULTS

The main objective of the IAS team was to integrate and test the research software; however, there were valued HMI-related research questions that were pursued in parallel (ref. 11) (to be published). Specifically, the team wanted to understand whether the setup, coordination, and handover processes (transition to the research algorithm) added excessive workload to the pilots, and whether the interfaces provided sufficient situational awareness for everyone in their respective roles, but particularly the pilots. Quantitative (biometric measurements) and qualitative (a modified Bedford Workload Scale that prompted written feedback and verbal walk-throughs) feedback from the pilots were used as the initial data for this effort.

5.4.1 Post-encounter Pilot Feedback

The post-encounter questionnaire (fig. 13) was automatically presented in flight to the research pilot, located in the right seat of the SARA, at the conclusion of each test card during Spiral 2C tests. The questionnaire process was intended to take less than a minute to assess workload, ride quality, and resolution acceptability while preserving test efficiency. In-flight questionnaires improved upon the postflight workload assessments in Spiral 1, which required pilots to generalize their ratings across an entire flight sortie without context on any individual event. Post-encounter ratings were collected after each encounter using the HPA or FPM research display (25 of 33 successful HPA encounters and 34 of 51 successful FPM encounters). Missing data points were due to software limitations (i.e., the MW being out-of-the-loop for low-speed encounters) as well as time constraints that prevented all encounters from being flown. This section on human factors (HF) will focus on ratings related to test efficiency and IAS IFTS displays designed by the IAS software development team. For more information regarding findings on pilot acceptability of the alerting and guidance presentation on the research display user interfaces (i.e., AOP and ACAS-Xr), refer to a future dedicated report from the HPA and FPM teams (Appendix L).

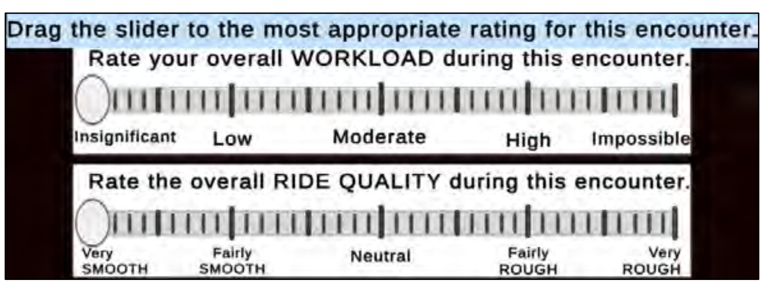


Figure 13. The IAS Post-encounter questionnaire - pilot workload and ride quality assessments.

Pilot workload was typically rated as low to moderate overall, with all encounters receiving ratings within a range of three to seven on the questionnaire (*M* (Mean)=4.5). Pilot workload was never low enough to be considered "insignificant" based on the revised Bedford scale but also never progressed to a level high enough to be considered intolerable for the task. The average workload rating suggests that many scripted encounters required a maintainable level of effort that diminished the spare capacity of the pilots for additional tasks to some degree. The relatively small sample size and unequal distribution of encounter types in the present study does not allow enough power to infer statistical significance of the differences between test conditions. Although workload never reached either extreme on the spectrum, there were minor trends observed within the scripted encounter types that influenced the average ratings.

During HPA runs, workload was lowest when RAs were automatically executed, but the highest workload rating within this subset of encounters came for those HPA maneuvers requested to be manually engaged by the pilot (per their test matrix) after the RA presentation. This rating outcome is understandable since it requires an extra step to execute and was an infrequent occurrence in the test plan. The variance in workload ratings was highest in conditions where pilots had to manually execute a resolution maneuver. The workload floor was highest in the conditions with the nearest miss distances. The horizontal separation threshold in the terminal/structured Well-clear zone is less than half the size of the nominal DAA well clear (DWC) threshold (see table 1), which resulted in initial alert ranges at closer points of approach. Terminal/structured scenarios also included cases where the ownship was in an active climb/descent at the onset of the first conflict alert. Manual CAS conditions require pilots to wait for RAs and execute after violating DWC altogether; thus, these were the only HPA conditions that never received a “low” rating below 4 (fig. 14).

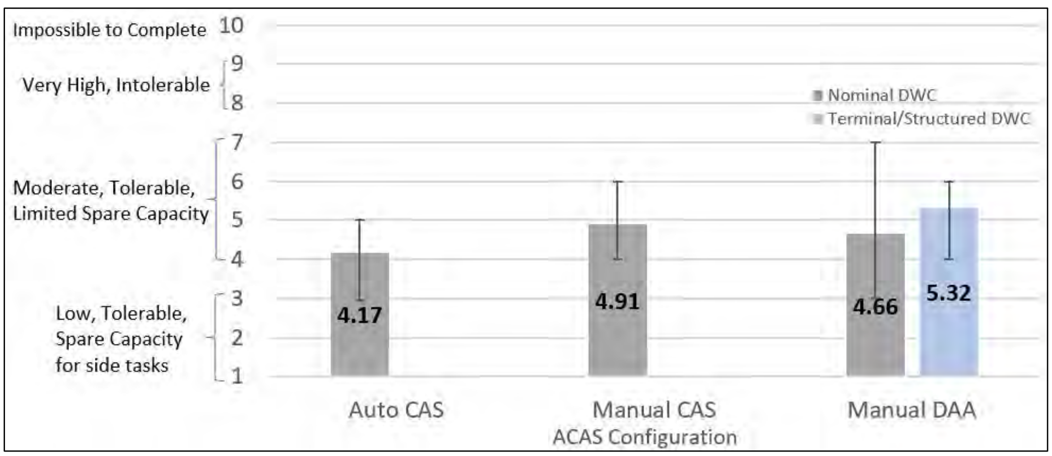


Figure 14. Average, minimum, and maximum workload ratings following HPA encounters.

Although the range of responses (3 to7) remained the same for FPM runs, the management-by-consent nature of the AOP User Interface (UI) that auto-loaded resolutions for pilots to execute with a press of a button resulted in slightly lower workload ratings on average. Workload ratings increasingly trended toward moderate when pilots were given a shorter time limit to select and execute a resolution maneuver. Workload was highest (Mean, *M*=6) during the “Short Time Parameter” condition (*M*=6.5) that required execution within 15 seconds, compared to the “nominal” (*M*=4.42) and “Long” (*M*=3.97) conditions that required execution within 20 and 40 seconds, respectively (fig. 15).

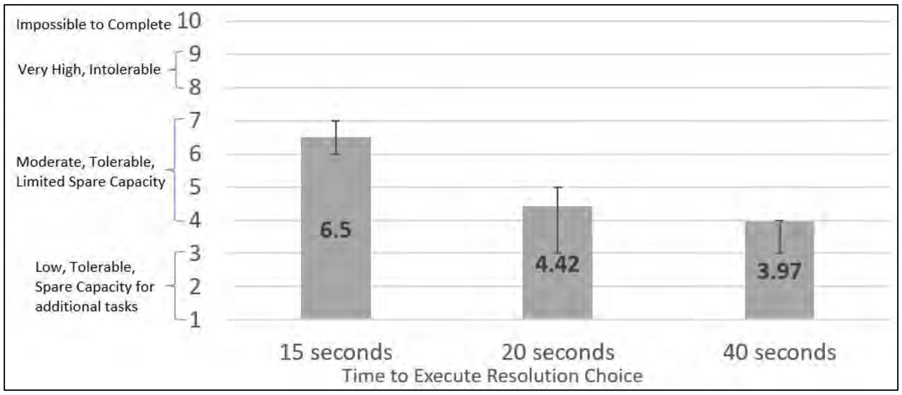


Figure 15. Average, minimum, and maximum workload ratings following FPM encounters.

Across all encounters, ride quality was rated as neutral on average on a ten-point scale (M=4.57; Range=2 to 8). The vast majority (93 percent) of encounters were rated as either smooth or neutral on the roughness scale (1 being very smooth to 10 being very rough). Only four total encounters received a roughness rating of 7 or above, with the roughest rating (8) occurring after an FPM card that contained multi-dimensional conflict resolutions (multiple CRs in different axes: speed, lateral, vertical). Preliminary analyses indicate that ride quality trends by automation level were unremarkable, and average roughness ratings were not greatly impacted by scripted pilot actions (or lack thereof) with either system under test. Roughness ratings dipped slightly for encounters rated by pilots as low workload (M=3.56) compared to moderate workload (M=4.8). Although these subsets of encounters by workload had the largest differences in roughness ratings, this contrast does not necessarily imply that the subjective workload was directly influenced by ride quality. Future research studies with more time flexibility for questionnaires would benefit from a multi-dimensional workload scale (such as the NASA Task Load Index that was replaced in Spiral 2 to preserve test efficiency) to distinguish the weight of physical versus cognitive demand within pilot-subjective workload scores when assessing correlations with ride quality. Note that these ride quality ratings only apply to the experiences of the SARA research pilots during the test phases where pilots were receiving conflict resolutions from the research algorithms under test; these ratings were not directly assessed for the IFTS setup that involved continuous route conformance adjustments or by the OPV pilot who experienced pitch oscillations throughout the campaign; thus, the post-encounter questionnaire ratings do not reflect any instance(s) where the Automation-Induced Oscillations (AIOs) made the ride quality unacceptably rough in other phases of the flight such as setup or auto-land scenarios. These AIO challenges were documented in further detail in Section 5.3 and Appendix J and will also be addressed in a separate American Institute of Aeronautics and Astronautics (AIAA) publication in 2024 (Appendix L, References).

5.4.2 Post-test (Spiral 2C) campaign pilot feedback

The NASA research pilots filled out post-test questionnaires at the conclusion of the test campaign. Informal interviews were also conducted to provide additional context to the responses. The HF subject of this report focuses on the feedback from the IAS portion of the post-test questionnaire, which addressed research tablet acceptability, training sufficiency, information sufficiency, ease of use, test efficiency, and situation/mode awareness while interacting with IAS IFTS displays during the setup phases. There was also room for open-ended comments to contextualize their ratings and note areas for improvement or most desirable features.

Mixed feedback regarding the acceptability of the NASA research tablet Getac F110 (Getac, Irvine, California) used on both aircraft led to undesirable average ratings on size/weight (12.4 inches by 8 inches by 1 inch, 3.35 pounds) responsiveness, brightness, and surface quality (fig. 16). Pilots indicated that the input sensitivity was too inconsistent, stating it was “way too sensitive for vibrations, maneuvering, knee-positioned use in helicopters; flight suit sleeve caused inadvertent button presses.” In Spiral 1, pilots noted that the tablet occasionally required multiple attempts to successfully press a button, so button sizes were increased for Spiral 2 tests to address this problem. Feedback, however, suggests that the constrained cockpit environment and position of the tablet presented challenges that would be alleviated if the test vehicle layout could have accommodated the NASA research tablet to be mounted in the cockpit, but this configuration was not feasible in either SARA or the OPV helicopter. Brightness was also a problem as pilots noted the display was hard to read in sunlight. This problem was mentioned in Spiral 1 pilot feedback, which led to disabling the auto-brightness feature in favor of full brightness. The feedback, however, remained unchanged in Spiral 2, but sunnier weather conditions in the final flight-test campaign may have been a contributing factor. Glare in direct sunlight also influenced the surface quality ratings. Future research should ensure that research displays are tested by users in representative test conditions such as varying degrees of sunlight.

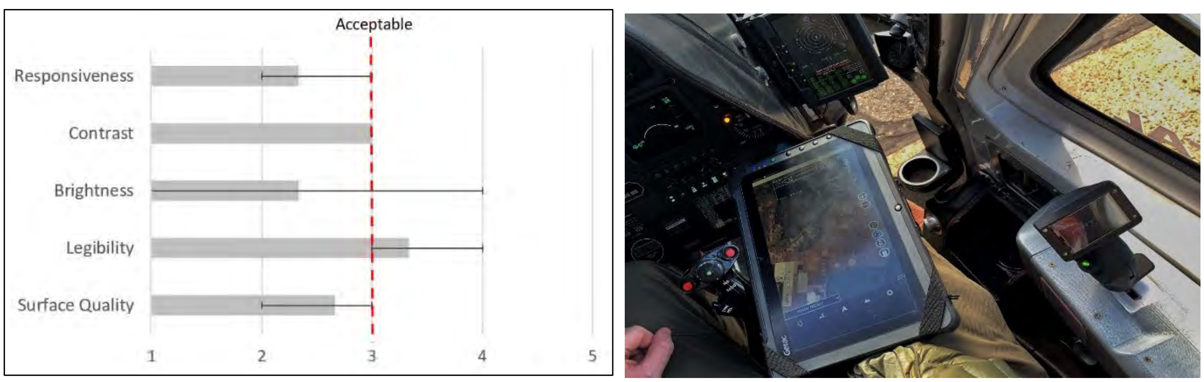


Figure 16. (Left) Average, minimum, and maximum acceptability ratings for Getac F110 tablet; and (Right) tablet photo.

It should be noted that the research tablet was rated more favorably by the OPV pilot, which suggests that the opinions about the additional research UIs used by SARA pilots was at least partially influencing responses. This idea is confirmed by one of the open-ended comments about legibility that criticized the text size of research software display elements that were not present on the MW-IFTS setup display (used in OPV and SARA). Nonetheless, these ratings present many lessons learned about the intrusiveness of a knee-positioned ruggedized tablet of this size in a live flight environment – there were lessons that were also learned in Spiral 1, but alternative solutions could not be implemented due to various limitations (see Section 6.7). The Getac tablet was used because it had the necessary interfaces to the onboard battery packs that supplied enough power for the required duration. While other tablets were smaller profile and had fewer objectionable attributes, given the need for multiple hours of power, the Getac was the only tablet that could meet the needs within the scheduled timeline of the project. With additional time and resources, this solution could be addressed. Nevertheless, it is encouraging that the shortcomings of the tablet did not increase pilot workload to an excessive maintenance level of effort when using the systems under test.

The MW IFTS display was rated as usable overall with no questions regarding ease of use but received a negative rating concerning situational awareness. Among the most essential display elements were the ownship and intruder route trajectories, wind information, ADS-B traffic situation, and lilliput commanded versus actual flight parameters. Missing features that were desired included a cue for data health status changes, an integrated map layer on the tablet interface, and more information about orbit locations such as a visual indicator of the minimum standoff range needed to properly execute the orbit. Test efficiency was rated favorably with one minor caveat about the communications procedures. One pilot noted that the aircrew can feel out-of-the-loop when ground control goes radio silent for too long during mid-sortie troubleshooting. Responses were mixed regarding potential comfort with performing the flight-test operations in a real-world environment. One pilot cited network delays and the bulky intrusiveness of the research tablet as hurdles to real-world applicability, while another pilot noted that more research is needed to assess how the automated systems perform against multiple live aircraft (instead of just one intruder) before being completely comfortable executing these scenarios in airspace with higher traffic density.

5.4.3 Biometrics and the Path Forward

While questionnaires and interviews are valuable methods for understanding individual thoughts and viewpoints retrospectively, the biometric devices the IAS team employed enabled quantification of physiological aspects that are typically subconscious. Biometrics also provide additional context in which aspects of the test phase influenced cognitive load; the output revealed real-time physical responses throughout the entire flight in addition to the pre-scripted probe. Figure 17 shows the biometric devices utilized in the IAS Spiral 2B and C tests.

Figure 17. Human factors/biometrics test equipment utilized in the IAS Project.

Through these devices, the team captured eye-tracking data, providing insights into where the attention of the pilot was focused, the duration of their fixations, and changes in pupil dilation. Additionally, a mobile functional near-infrared spectroscopy (fNIRS) was utilized to gain information about brain activity. Furthermore, data on heart rate, breathing patterns, and skin temperature were collected. Specifically, pilots wore Tobii Pro 3 wireless eye trackers (Danderyd Municipality, Sweden); PortaLite MKII fNIRS (Einsteinweg, The Netherlands); and the Zephyr Performance Bioharness (Medtronic Zephyr, Boulder, Colorado, USA) for each of these metrics, respectively. This comprehensive data set, particularly when analyzed in combination, provides a real-time depiction of the individual's underlying state. For instance, indicators such as dilated pupils, increased brain activity, elevated heart rate, respiration, and temperature can reveal when a pilot is experiencing excessive workload or heightened stress levels.

One challenge the team faced was the integration of the biometric equipment with the pilots' required attire, particularly the helmets they wore. Ensuring seamless compatibility between the equipment and the pilot's gear was not a straightforward task. The team had to strike a balance between the benefits of acquiring valuable data and the potential discomfort or distractions it may cause the pilot. Any indication of pilot discomfort or added distractions warranted immediate adaptation or, if necessary, the removal of the equipment altogether. The team, therefore, was occasionally unable to collect certain biometric measurements to preserve test efficiency. Biometrics equipment was rated as a minor nuisance by pilots on the post-test questionnaire. The fNIRS sensor on the forehead infrequently slipped and slightly obscured vision for one pilot, and the eye-tracking glasses needed to be readjusted routinely to alleviate pressure on the temples of another pilot. Nevertheless, pilots were still able to complete primary flight tasks with the equipment and never chose to opt out of their use during the flight-test campaign. Future research would benefit from employing these devices during medium-to-high fidelity simulation tests to establish a baseline in a less intrusive environment.

The wealth of data collected from these biometric sensors will play a role in informing recommendations regarding adjustments to interfaces and underlying software. For instance, if the analysis reveals that the pilot is not directing their attention toward specific information on the interface, it prompts an investigation into aspects such as visibility, placement, or even the utility of that information. Heart and brain-monitoring data will also provide more insight into physiological and psychological stressors; however, it is important to note that the primary focus for this specific line of research of the flight tests revolved around validating the functionality and effectiveness of the equipment in an actual flight setting. The purpose of the FPM Engineering User Interface was to provide the research pilots with enough SA to evaluate the quality of the resolution advisories received and the time frames under which they were asked to make trajectory change decisions. The AOP and ACAS-Xr will be covered in future reports by the FPM and HPA teams. A detailed analysis of the biometric data set will be provided in a future, separate publication about the IAS human factors results to be released in 2024 (Appendix L).

5.5 TEST EXECUTION SAFETY LAYERING

The most critical aspect of air-to-air encounter testing was to ensure flight safety; this aspect was achieved by taking a holistic view of flight safety. One consideration was to ensure a robust approach to real-time data monitoring that utilized multiple data sources to cross-check parameters and data monitored by multiple members of the test team (aircrew, test conductor, discipline engineers, etc.). The IAS Project implemented layers of data monitoring (fig. 18 and fig. 19). For instance, aircraft position data came from multiple sources (aircraft Embedded GPS-aided INS (EGI) navigation system, ADS-B In/Out, and the Sikorsky ground-radar facility called Eagle radar) and was monitored by various people:

- The safety pilot on SARA and OPV utilized ADS-B data presented on their ForeFlight (Houston, Texas, USA) integrated flight app / iPad, received by carry-on Stratus (Appareo Systems, LLC, Fargo, North Dakota, USA) equipment to monitor separation with the other test aircraft as well as nonplayer air traffic.

- The SARA and OPV NASA research pilots each monitored their aircraft's separation using their NASA tablet display that presented both positions of the aircraft and the intended routes of the MW utilizing navigation data for both aircraft.
- All aircrew (the Sikorsky safety pilot was primary) also ensured safety by establishing a mission rule that at least one aircrew member from the two test aircrafts were to maintain visual contact with the other aircraft when inside 0.75 nautical mile with preplanned KIO criteria presented on each card (specific criteria was reviewed with the aircraft prior to each run).
- The control room monitored aircraft position data obtained from EGI navigation data of both aircraft (without going through any NASA software, since this was the system-under-test) and presented current SARA-OPV range and altitude separation on a large-screen display. The same display also presented nonplayer tail number or identification number and altitude stripped from ADS-B, thereby providing good situational awareness. This Sikorsky data-driven display was considered the primary safety display during the encounters because the data path was through DO-178C Design Assurance Level A (DAL-A) safety critical software/hardware and not through NASA software.
- The MW engineer and TC had maps, an MW planned route, and current position information of both test aircraft presented on their displays.
- The Sikorsky Eagle radar facility (non-ATC function and also a nice-to-have function) assisted in providing situational awareness through traffic callouts to the SARA and OPV aircrew obtained via ground radar/transponder squawks.

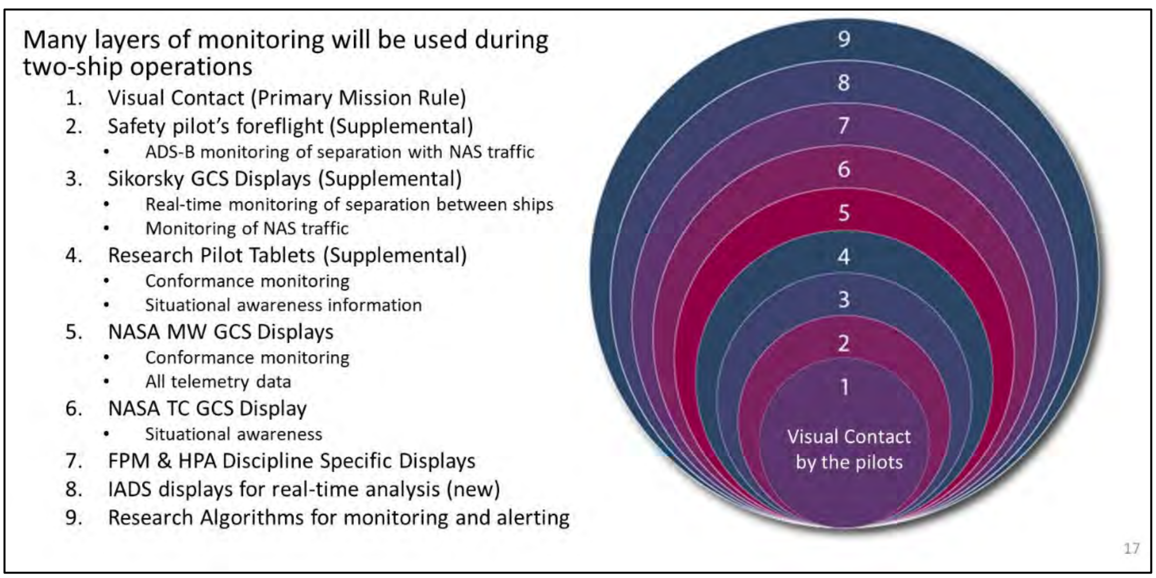


Figure 18. The IAS Project layering of data monitoring.

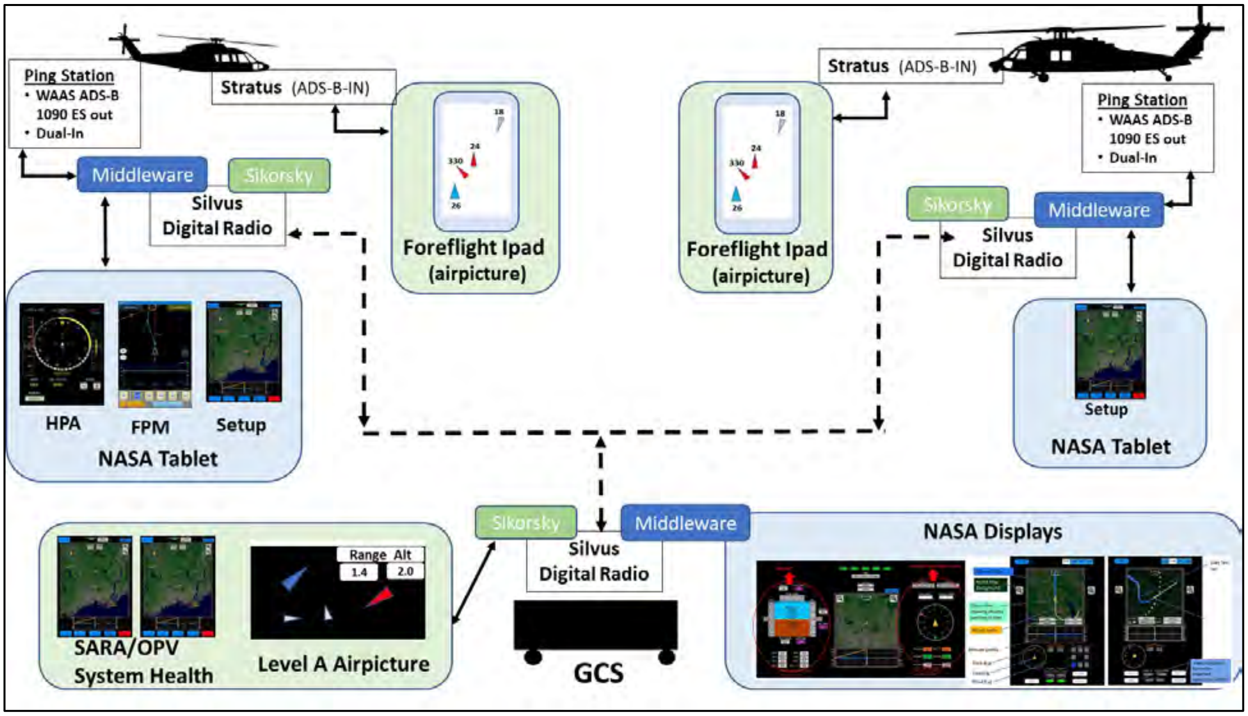


Figure 19. Displays utilized in layered data monitoring.

6 LESSONS LEARNED

6.1 LESSON 1: CONSIDERATION SHOULD BE GIVEN TO TRADE-OFFS BETWEEN TIME- AND VELOCITY-BASED TRAJECTORIES

The IAS Project research mainly relied on time-based 4-dimensional trajectories (4DTs) to execute air-to-air encounters, which would enable not only positional conformance for FPM trajectory performance uncertainty bounds (TPUBs) but also time conformance. While conformance was achieved through the middleware, there were multiple lessons learned about the trade-offs of using over-constrained time-based trajectories. Ride quality is the biggest trade-off. With very tight time tolerances, the middleware (MW) had to constantly adjust speed in order to satisfy tight time constraints, sometimes causing large swings in speed commands due to effects of winds (especially when flying with a direct tailwind or headwind) - see (ref. 13) (to be published). A proportional-integral-derivative (PID) velocity controller was used to achieve the time conformance that was "tuned" prior to flight (during V&V or CST testing) to try to smooth out ride quality, especially leading up to the hand-off to the research algorithm. It would have taken multiple flight hours to optimize the controller in all phases of the trajectory as well as in a wide range of wind conditions. Since that was not the primary purpose of this research, the team did not dedicate missions/tests to tuning the PID controller and instead used targets of opportunity during various V&V phases to get to a solution that was smooth enough so as not to detract from the research objectives. If time-based 4DTs are used operationally for AAM, more time must be spent tuning them to the specific vehicle dynamics across ranges of wind conditions and geometries. Additionally, consideration should be given to using a hybrid solution of time-based as well as velocity-based 4DTs, determined by the phase of flight and necessity of tight time conformance or not.

6.2 LESSON 2: The MW-CONTROLLED TEST SETUPS SHOULD BE IMPROVED

If possible, allow execution from any location/speed without the requirement to first enter an orbit (i.e., fix the problem where aircraft had to essentially constrain their “pre-orbit orbit” locations to allow the actual orbits to function properly). The viability of this step depends upon multiple factors, including aircraft speed control, ride quality, and system dynamics, which all contribute to whether a pre-positioned orbit is required to achieve the needed route timing across multiple aircraft at their respective start locations. In the case of SARA and OPV helicopters, their speed control is not tightly coupled with throttle (instead, speed is controlled by pitch angle and lags, which leads to AIO problems when trying to tightly control route timing). The project spent fuel and flight time transitioning to, holding in, and troubleshooting failed entries for some of the orbits/routes. See Ref 16 for further discussion of the IAS project test setup methodology.

6.3 LESSON 3: FULLY UNDERSTAND SENSOR DATA LIMITATIONS

Another lesson learned was related to sensor selection and data integrity verification. Due to its availability, ADS-B was the planned source of the intruder state data for both HPA and FPM; although, FPM indicated their research was sensor-agnostic, and IAS ended up using aircraft EGI data to provide position/velocity information. The IAS team chose a uAvionix (uAvionix, Corporation, Bigfork, Montana and Leesburg, Virginia) pingStation as the airborne ADS-B-In system on SARA. The pingStation is marketed as a ground surface receiver for situational awareness only, but it was pursued for ease of integration rather than a higher-cost or certified (and likely less open/accessible) ADS-B-In solution. The pingStation was never verified to meet any of the detailed ADS-BIn Technical Standard Order (TSO) requirements for sensitivity, latency, discrimination, capacity, or track prioritization for example, but the pingStation provided data interfaces in formats JavaScript Object Notation (JSON) that could be easily ingested by the IAS MW. During the first two-ship operations in Spiral 2B, occasional severe lags and dropouts in received ADS-B signals (anywhere from 10 to 45 seconds) were noted. The lags were primarily due to an ICD (Interface Control Document) implementation problem on the IAS side, which was later corrected. But those extreme cases of latency and dropouts illustrated the criticality of sensor data sources and the need to account for and verify sensor uncertainty. When trying to conform to tight time trajectories, receiving position data with that much latency negatively impacted the encounter orchestration of the MW as well as the conflict detection and resolution of the AOP. The team worked around this problem by using the actual telemetry of the intruder as an alternative, but telemetry may not be available operationally. Future AAM operations, therefore, should ensure that appropriate sensors and receivers are used for conflict detection and avoidance, with sensor fusion or stacking from multiple sources where possible. Care should be taken to ensure correct sensor integration and data integrity. If ADS-B is used, the software should be designed to be tolerant if ADS-B message fields are missing or invalid; for example, the software should not misleadingly designate an intruder altitude as 0 feet if altitude data is invalid or dropped out. Latency and sources of time error should be budgeted and verified.

6.4 LESSON 4: TAKE ADVANTAGE OF USING CERTIFIED, SAFETY-CRITICAL WRAPPER SYSTEM TO ENABLE (ANDPROTECT) RAPID PROTOTYPED SOFTWARE

Part of the reason for selecting the Sikorsky aircraft for this research was due to its "fault-tolerant," safety wrapper MATRIX™/ALIAS design, meaning no matter what the NASA *research* software commanded, if it reached a design limit of the Sikorsky technology MATRIX™ Autonomous Mission Manager, the aircraft reverted back to the Class A flight control software through both physical and software partitions. This feature allowed the team to more quickly design and test the MW software as well as the research algorithms because the safety risk of executing the research software was greatly reduced due to the fault-tolerant, safety protection design inherent in MATRIX™/ALIAS. This feature, however, is a very different architecture than NASA software development processes were designed for, so exploiting the full capability of the fault-tolerant architecture and allowing increased agility in the NASA software development process was not always exercised. Future projects that utilize a similar fault-tolerant architecture should negotiate and document a streamlined approach to software development and documentation such that changes can be made more quickly and efficiently since the main risk is a technical risk - having an inefficient sortie if the software is not working properly, and changes need to be uploaded while the aircraft are flying, or the sortie needs to be ended early. In addition to determining a more agile software configuration process, agreeing on and documenting a way to make changes to configuration files, that is even more agile than true software coding changes, will further enable an agile system to include addressing other lessons learned, such as being able to tune the PID controller (which is a configuration file) in flight. In addition to differentiating between configuration files and flight software, additional discussion should clarify the definition of configuration files. This project operated under the strict interpretation that route files (i.e., the waypoints and parameters that build a trajectory, or in other words, a mission/flight/route plan) were considered configuration files and accordingly locked down to the overarching stringent flight software configuration control requirements. This interpretation did not appear consistent with standard aircraft operations and the flexibility of Visual Flight Rules (VFR), IFR and unmanned aerial vehicle (UAV) that operators have to freely build routes, select waypoints, and change mission plans. See Appendix K for a description of the IAS Project Software Management Approach.

6.5 LESSON 5: DATA NETWORK DESIGN CONSIDERATIONS NEED TO BE SELECTED DELIBERATELY

Networking was sometimes a big challenge in this project, especially in earlier spiral events. Ensuring internet protocol addressing is known, documented, and has been confirmed to go a long way in mitigating some of these problems. Additionally, being judicious about using Transmission Control Protocol messages - only when necessary - helps to limit bandwidth saturation. In an attempt to not oversaturate the datalink, however, the opposite can happen where important or time-critical messages that may have been delivered via User Datagram Protocol (UDP) to save the datalink actually caused malfunctions or inefficiencies in the software because they truly needed to be TCP messages (i.e., guaranteed delivery). Considering which messages are most critical early in the software design can help to mitigate some of these challenges that hamper efficiency during flight test. Additionally, balancing situational awareness on the ground (through a pilot tablet Virtual Network Computing (VNC) repeater, for example) with datalink saturation is another important consideration. Having the ability to check the status of the saturation in real time, which was possible with the Sikorsky datalink setup in the GCS, helps to drive decisions such as shutting down some of the additional repeater displays during flight test.

6.6 LESSON 6: ADVANTAGE OF SOFTWARE-CONTROLLED TRAJECTORIES FOR MULTI-SHIP ENCOUNTER TESTING

Also, see Section 5.1.2 and (ref. 14) (to be published). One of the biggest challenges of this research was choreographing two vehicles to be at a specified location at a specified velocity vector at an accurate time, also known as time=0 (“T-0”). The MW was key in choreographing this challenge so that actual conflicts would arise as expected and the research algorithms would trigger as expected, enabling the ability to make a comparison to simulation data. Had the test runs been manually flown in high/variable wind conditions, and the trajectories been aircraft referenced (e.g., bank angle, turn rate) instead of 4D/ground referenced, time conformance could have been very challenging. Additionally, winds consideration became a problem during the IAS Project when translating simulations of AOP encounters to inflight encounters required special considerations for winds, adding nontrivial workload to planning. A second advantage of using MW software to control the encounters was that all of the test runs were flown in simulation (manned or unmanned) precisely as they were in flight, thereby providing excellent fidelity between training and data obtained from simulation versus the same data that was obtained from the flight test. Lastly, the use of software-controlled encounters would be even more useful for any future air-to-air testing in which coordinating encounters involving three or more aircraft is required due to the added timing complexity.

6.7 LESSON 7: IN-COCKPIT TABLET CONSIDERATIONS

Early on in the project, pilots indicated that the Getac tablet size, weight, and unpredictable touchscreen sensitivity were all objectionable and that they preferred a different tablet as a result (ref. 11) (to be published). Though the team was able to procure additional types of tablets to address this problem, they were never exercised because of the limitations of the power and connectivity interfaces that were inherently available. Namely, since both aircraft did not have the ability to provide internet connectivity via ethernet as well as WiFi, other tablets were not equipped to accept both power and connectivity simultaneously. While this problem could have been overcome by installing additional capabilities in the aircraft, the project did not have the dedicated time or resources; therefore, the Getac was accepted as the easiest path forward. For operational considerations, however, if a pilot tablet is necessary, the Getac would likely not be the optimal choice given some of the objectionable attributes.

6.8 LESSON 8: ALTITUDE REFERENCE DATUMS AND EGI ERRORS NEED TO BE ACCOUNTED FOR IN AUTO APPROACH/LANDING TESTING

In the first attempt of the auto-approach/auto-land testing using the MW, the target altitude to level off was 30 feet. While the correct altitude reference datum World Geodetic System (WGS-84) was used in the assumed geometry of the level off, the error in how the aircraft used the EGI system was not accounted for (GPS altitude is not the same as WGS datum altitude); and therefore, the aircraft was presumed higher than it was and did not level off at the expected altitude (ref. 12) (to be published). This problem was easily corrected with a software fix that targeted 100 feet to give an additional buffer. This problem, however, was highlighted for its importance in understanding that there are different vertical reference datums that can come into play when leveraging navigational systems and databases as well as errors in installed systems where both must be factored in when designing a maneuver such as this one. With the inherent safety layers that were described earlier, mainly the Sikorsky flight control system design, which allows the pilot to quickly revert to manual controls using the Class A flight control laws, this error was easily corrected during the maneuver and then later corrected in the software.

6.9 LESSON 9: MODEL-BASED SYSTEM ENGINEERING (MBSE) CONSIDERATIONS

The Model-Based System Engineering (MBSE) is based upon the concept of employing graphical models to capture, identify, define, analyze, and communicate requirements, design details, system architectures, use cases, behaviors and functions, activity and interface diagrams, as well as a host of system-related information for complex systems.

The utilization of the MagicDraw (an (MBSE) application) by the IAS team to create and capture the IAS requirements and develop activity diagrams for flight-testing proved to be very useful in quickly getting the greater team in sync. MagicDraw facilitated the development of network and activity diagrams to show the sequential interactions between subsystems as well as for development of states/modes and human-machine interface HMI diagrams. The flight scenarios and HMI diagrams proved to be enormously useful as several test tablet design errors were caught early on to allow sufficient time for corrections to be made. If these corrections were not caught early on, they may not have been discovered until prior to flight-test execution, which may have impacted the schedule.

The MBSE was used to create models that identified and captured interfaces to/between subsystems and their interactions, which assisted integration efforts by ensuring consistency and compatibility for intended operations. Network, sequence, and activity diagrams were created to improve design team collaboration, communication, and synchronization. The MBSE modeling allowed for more efficient requirements, analysis, and optimization to ensure they were concise, accurate, and complete and made traceability practically seamless from children requirements back up to parents and then to objectives for verification and validation. All of the above demonstrated the MBSE-MagicDraw combination to be a powerful tool for design, development, integration, and testing of system requirements. The application provided a useful framework for capturing, analyzing, and communicating the system-related details and information that helped to optimize the system designs and associated requirements. The MBSE “simplifies complexity”!

Appendix A: ACRONYM LIST

4DT	Four-Dimensional Trajectory
AAM	Advanced Air Mobility
ACAS	Aircraft/Airborne Collision Avoidance System
ACAS-Xa	Airborne Collision Avoidance System – for standard aircraft
ACAS-Xr	Airborne Collision Avoidance System – for rotorcraft
ACAS-Xu	Airborne Collision Avoidance System – for unmanned aircraft
ADS-B	Automatic Dependent Surveillance-Broadcast
AFCM	Automated Flight and Contingency Management
AFOP	Armstrong Flight Operations Procedure
AFRC	Armstrong Flight Research Center
AGL	Above Ground Level
AIO	Automation-Induced Oscillations
ALIAS	Aircrew Labor In-cockpit Automation System
AMM	Autonomous Mission Manager
ARMD	Aeronautics Research Mission Directorate
ASTM	American Society for Testing and Materials
AOP	Autonomous Operations Planner (FPM developed algorithm)
AOSP	Airspace Operations and Safety Program
API	Application Programming Interface
ARC	Ames Research Center
ATA	Air-To-Air
ATC	Air Traffic Control
CAS	Commercial Aircraft Services
CFR	Code of Federal Regulations
CPA	Closest Point of Approach
CR	Conflict Resolution (FPM/AOP)
CVT	Current Value Table
DAA	Detect and Avoid
DWC	Detect-and-Avoid Well Clear
DARPA	Defense Advanced Research Projects Agency
dGPS	Differential Global Positioning System
DR	Discrepancy Report
EGI	Embedded GPS-INS
ES	Extend Squitter (ADS-B 1090-Megahertz ES)
ETA	Estimated Time of Arrival
EUTL	Efficient Universal Trajectory Language
EVAA	Expandable Variable Autonomy Architecture
eVTOL	electric Vertical Takeoff and Landing
FAA	Federal Aviation Administration
fNIRS	functional Near-Infrared Spectroscopy
FPM	Flight Path Management (subset of AFCM)
GCAS	Ground Collision Avoidance System
GCS	Ground Control Station
GenHel	General Helicopter
GPS	Global Positioning System

GW	Gross Weight
HCB	Horizontal Clearance Buffer
HF	Human Factors
HITL	Hardware-In-The-Loop Lab
HMI	Human Machine Interface
HPA	Hazard Perception and Avoidance (AFCM software)
HPC	High-Performance Computer
HW	Hardware
I&T	Integration and Test
IAS	Integration of Automated Systems
ICAO	International Civil Aviation Organization
ICD	Interface Control Document
IFP	Instrument Flight Plan
IFR	Instrument Flight Rules
IFTS	IAS Flight Test Services
iGCAS	Improved Ground Collision Avoidance System
INS	Inertial Navigation System
I/O	Input/Output
KCAS	Knots, Calibrated Airspeed
KIAS	Knots Indicated Airspeed
KIO	Knock It Off
KGS	Knots Ground Speed
KTS	Knots, True Airspeed
LaRC	Langley Research Center
LNAV	Lateral Navigation
LOC	Localizer
LoS	Loss of Separation
M	Mean (average)
MBSE	Model-Based System Engineering
MC	Mission Controller
MCR	Mission Capability Review
MD	Mission Director
MDSC	Model Development Safety Committee
MML	Master Measurand List
MM-RTA	Multi-Monitor Run Time Assurance
MSL	Mean Sea Level
MW	Middleware
MWE	Middleware Engineer
MX	Maintenance
NAS	National Airspace
NC	National Campaign
NMAC	Near Mid-Air Collision
NPR	NASA Procedural Requirements
OPV	Optionally Piloted Vehicle
OS	Operating System
PIC	Pilot-in-Command

PID	Proportional-Integral-Derivative
PSIU	Primary SARA Integration Unit
RA	Resolution Advisory (HPA/ACAS-Xr)
RF	Radial Fix
RP	Research Pilot
RNAV	Area/Required Navigation
RNP	Required Navigation Performance
RTA	Required Time of Arrival
RTCA	Radio Technical Commission for Aeronautics
SA	Situational Awareness
SARA	Sikorsky Autonomous Research Aircraft
SBC	Single Board Computer
SDK	Software Development Kit (Sikorsky description of SARA interfacing)
SIL	Software-In-the-Loop
SOR	Senior Operations Representative
SP	Safety Pilot
STAR	Standard Terminal Arrival Routes
TA	Traffic Advisory (HPA/ACAS-Xr)
TC	Test Conductor
TCP	Transmission Control Protocol
TD	Test Director
TERPS	Terminal Instrument Procedures
TF	Track to Fix
THA	Test Hazard Analysis
TPUB	Trajectory-Prediction Uncertainty Bounds
TPWG	Test Plan Working Group
UAM	Urban Air Mobility
UAS	Unmanned Aerial System
UAT	Universal Access Transceiver (ADS-B 978 Megahertz)
UML	UAM Maturity Level
UTM	Unmanned Air Systems Traffic Management
V&V	Verification & Validation
VCB	Vertical Clearance Buffer
VFR	Visual Flight Rules
VMC	Vehicle Management Computer
VMC	Visual Meteorological Conditions
VTOL	Vertical Takeoff and Landing
VVM	Verification &Validation Matrix
WAAS	Wide Area Augmentation System
WC	Well Clear
X-face	Interface

Appendix B: SYSTEMS ENGINEERING APPROACH

Following best practices, the systems engineering approach began with project scoping, which led to developing and firming up the goals and objectives for the IAS Subproject in which the objectives were then scrutinized and clarified with criteria for minimum and maximum success. For metrics, Measures of Performance (MOPs) were identified as the technical performance measurement attributes to be implemented by associating them with the relevant requirements. Operational concepts, use cases, behaviors, and intentions were all discussed, evaluated, reviewed and scrutinized by the IAS team to start the requirements development process (starting on the upper-left side of the system engineering "V" process) along with the creation of an Operations View for the subproject to use in reviews.

A series of Requirements Working Group (RWG) meetings were convened to begin the process to create and develop the necessary requirements for mission success. The first order of business was to identify the Unique Identification (UID) nomenclature to use for IAS. Next, the transformations and decompositions of the project goals and objectives led to the initial set of requirements for Spiral 1, which was expanded upon for Spiral 2 utilizing a "tier" approach instead of "levels" to avoid confusion with project schedules where "levels" were used. In conjunction with requirements, development, and documentation, the test plans for each spiral were created by weekly Test Plan Working Group (TPWG) meetings. Personnel from all aspects of the project (test operations, AFCM team members, safety, systems, program management, etc.) participated in the weekly TPWGs (test scenarios are described in Appendix E, mission rules are provided in Appendix F, and the test matrices are provided in Appendix H). Also, per the NASA systems engineering process, the system hazards and mitigations were developed through periodic System Safety Working Group (SSWG) meetings, again, as with the TPWGs and RWGs, personnel from all aspects of the project participated. The resulting system hazards and mitigations are provided in Appendix G.

To assist with the software and tablet development, diagrams were created for states/modes and activities to show the sequential interactions anticipated for AOP and ACAS-Xr engagement during various flight phases such as cruising to an assigned orbit location, releasing to fly towards T-0, then flying the mission run to execute the technology under test until there was the call for KIO, next mission run, or return-to-base (RTB). The states/modes diagram-development exercise was extremely fruitful and was beyond expectations as multiple significant errors were caught early, allowing plenty of time for tablet HMI corrections to be made. Otherwise, these errors most likely would not have been discovered until the execution of V&V or simulations just prior to flight-testing, leading to schedule setbacks.

MagicDraw was used to host the requirements for IAS as well as all the diagrams and other relevant information, such as a document tree, system block, and interface diagrams for example. These requirements were exported to an Excel file to create a Verification and Validation Matrix (VVM) to capture the V&V status for all the requirements and ensure traceability, as shown in table B 1. The VVM, shown in table B1, contains all IAS requirements from Tier-0 through Tier-2 such as verification methods, procedures, measures of effectiveness (MOE), and other relevant information to ensure that the verification activities for the requirement was executed, completed, and all data was duly recorded for evaluation. An HMI diagram was also developed in MagicDraw along with states/modes diagrams for the test tablets that allowed the entire team to collaborate to quickly reach a common understanding of the test process, identified procedural errors, and remediate tablet design deficiencies early on.

The IAS requirements were also exported from MagicDraw and populated into the Objectives and Requirements Document (ORD) for approval and would be placed under configuration control as well as for collaborating with AFRC leadership, research projects, and other relevant partners. In addition to informing the Flight-test Plan, the IAS ORD requirements were subsequently further decomposed into more detailed software and hardware (HW) requirements contained in the Interface Control documents, researcher documents, and other subsystems documents.

Table B 1. Verification & Validation Matrix (VVM).

Spiral-2C Update 05 December 2023	*IAS-1: SPIRAL 2 REQUIREMENTS VERIFICATION & VALIDATION MATRIX (VVM)*								
NAME	**TEXT**	**TIER**	**MOE**	**VER METHOD**	**TEST PHASE**	**V&V PROCEDURE**	**STATUS**	**VER RESULT**	**NOTES**
16 TEST [IAS1S2-0001]	NC IAS shall test AFCM technologies to support validation in a relevant environment with added operational and simulation elements. [IAS1S2-0001]	0		Inspection			Completed	PASS	
16.1 AFCM Software	IAS shall support the integration of HPA and FPM software for flight-testing. [IAS1S2-1001]	1	1	Inspection			Completed	PASS	
16.1.1 FPM	IAS shall integrate and host AOP software onboard the ownship. [IAS1S2-2001]	2	1	Test	Flight Test	AAM-NC-093-001.3 IAS Flight-Test Systems (IFTS) V&V Procedures Section 14.1, Step 1	Completed	PASS	
16.1.2 HPA	IAS shall integrate and host ACAS-Xr onboard the ownship. [IAS1S2-2002]	2	1	Test	Flight Test	AAM-NC-093-001.3 IAS Flight-Test Systems (IFTS) V&V Procedures Section 18.1, Step 1	Completed	PASS	
16.1.3 HPA Aural Alerts	IAS shall integrate audio capability onboard the ownship for the research pilot to hear the HPA aural alerting. [IAS1S2-2025]	2	1	Test	Flight Test	AAM-NC-093-001.3 IAS Flight-Test Systems (IFTS) V&V Procedures Section 18.1, Step 4	Completed	PASS	
16.1.4 Engagement Coordination	IAS shall ensure that the aircraft are coordinated for test execution such that the AFCM software is tested as intended. [IAS1S2-2003]	2	2	Analysis	Ground Test	AAM-NC-093-001.3 IAS Flight-Test Systems (IFTS) V&V Procedures Section 14.1, Step 8	Completed	PASS	
16.1.5 Command Latency	IAS shall ensure that the aircraft under test initiates tracking of new 4DT trajectories within 5 seconds of trajectory generation. [IAS1S2-2026]	2	2	Analysis	Postflight	AAM-NC-093-001.3 IAS Flight-Test Systems (IFTS) V&V Procedures Section 14.1, Step 7	Completed	PASS	
16.2 AFCM Hardware	IAS shall integrate a computer onboard to host the AFCM software. [IAS1S2-1009]	1	1	Inspection			Completed	PASS	
16.2.1 AFCM HW Mounting	IAS shall ensure that the AFCM HW is mounted in accordance with the design requirements of the test aircraft. [IAS1S2-2020]	2	1	Inspection	Ground Test	AAM-NC-093-001.3 IAS Flight-Test Systems (IFTS) V&V Procedures Section 25.2 and IAS1S2-2020 AFCM HW	Completed	PASS	

						Mounting (16.2.1) V&V Inspection Report			
16.2.2 AFCM HW Power	IAS shall ensure that adequate electrical power is made available onboard the test aircraft for the NASA-provided AFCM HW. [IAS1S2-2021]	2	1	Inspection	Ground Test	AAM-NC-093-001.3 IAS Flight-Test Systems (IFTS) V&V Procedures Sections 12, 13.3 and 25.2	Completed	PASS	
16.2.3 ADS-B-Out	IAS shall confirm that the installed ADS-B-Out system on the aircraft under test meets the requirements of 14 CFR § 91.227 for: (a) NACP ≥ 8, (b) NIC ≥ 7, (c) NACV ≥ 1 (d) SIL ≥3, (e) SDA ≥ 2. [IAS1S2-2027]	2	1	Analysis	Flight Test	IAS ADS-B analysis PAPR reports (5 July 2023)	Completed	PASS	
16.2.5 ADS-B-In	IAS shall ensure that the installed ADS-B-In system on the aircraft under test receives traffic information by an appropriately equipped aircraft on either radio frequency link: 1090 megahertz ES or 978 megahertz UAT. [IAS1S2-2029]	2	1	Analysis	Flight Test	IAS ADS-B analysis PAPR reports (5 July 2023)	Completed	PASS	
16.3 Network Interfaces	IAS shall provide a datalink network interface for the ownship and intruder aircraft. [IAS1S2-1002]	1	4	Inspection			Completed	PASS	
16.3.1 4DT to GCS	IAS shall provide the capability to transmit 4DT Intent Data from the intruder aircraft down to the GCS. [IAS1S2-2004]	2	1	Test	Flight Test	AAM-NC-093-001.3 IAS Flight-Test Systems (IFTS) V&V Procedures Section 14.1, Step 8	Completed	PASS	
16.3.2 GCS MW	IAS shall ensure that the software in the GCS is able to receive 4DT Intent Data from the intruder and re-transmit it to the ownship. [IAS1S2-2005]	2	1	Test	Flight Test	AAM-NC-093-001.3 IAS Flight-Test Systems (IFTS) V&V Procedures Section 14.1, Step 8	Completed	PASS	
16.3.3 4DT to ownship	IAS shall assess the ownship for the capability to receive 4DT Intent Data transmitted from the GCS. [IAS1S2-2006]	2	1	Test	Flight Test	AAM-NC-093-001.3 IAS Flight-Test Systems (IFTS) V&V Procedures Section 14.1, Step 8	Completed	PASS	
16.3.4 Datalinks	IAS shall ensure that the datalinks have sufficient link margin and throughput at range to support flight test operations. [IAS1S2-2007]	2	4	Demonstration	Flight Test	AAM-NC-093-001.3 IAS Flight-Test Systems (IFTS) V&V Procedures Section21	Completed	PASS	
16.3.5 dGPS Interoperability	IAS shall ensure that the Network supports the dGPS communications between the aircraft and GCS. [IAS1S2-2008]	2	4	Demonstration	Flight Test	IAS provided dGPS systems were subsequently not used and did not impact the results	See Notes	See Notes	EGI data was used instead
16.4 TSPI	IAS shall provide the capability to collect TSPI Truth Data. [IAS1S2-1003]	1	2	Inspection			Completed	PASS	

16.4.1 dGPS	IAS shall provide differential GPS (dGPS) systems to be as a truth reference system onboard the "aircraft under test" for position accuracy. [IAS1S2-2009]	2	2	Analysis	Flight Test	IAS provided dGPS systems were subsequently not used and did not impact the results	See Notes	See Notes	EGI data was used instead
16.4.2 dGPS Mounting	IAS shall ensure that the dGPS system is mounted in locations in accordance with the design requirements of the test aircraft for optimized performance. [IAS1S2-2010]	2	2	Inspection	Ground Test	AAM-NC-093-001.3 IAS Flight-Test Systems (IFTS) V&V Procedures Section 25.2 and IAS1S2-2010 dGPS Mounting (16.4.2) V&V Inspection Report	Completed	PASS	
16.4.3 dGPS Power	IAS shall ensure that 28-VDC / 2.5-Amps power is made available onboard the test aircraft for the NASA-provided dGPS system. [IAS1S2-2011]	2	2	Inspection	Ground Test	AAM-NC-093-001.3 IAS Flight-Test Systems (IFTS) V&V Procedures Section 25.2 and IAS1S2-2011 dGPS Power (16.4.3) V&V Inspection Report	Completed	PASS	
16.5 Simulated Backgroun d Traffic	IAS shall run FPM-provided UML-4 simulated background traffic with individual 4DT trajectories. [IAS1S2-1004]	1	1	Inspection			Completed	PASS	
16.5.1 Backgroun d Traffic Playback	IAS shall transmit the FPM-provided virtual background traffic 4DTs to the AOP onboard the Ownship. [IAS1S2-2012]	2	1	Test	Flight Test	AAM-NC-093-001.3 IAS Flight-Test Systems (IFTS) V&V Procedures Section 14.1, Step 8	Completed	PASS	
16.6 intruder middlewar e	IAS shall ensure that the intruder aircraft network provides access along with the capability to host the MW software onboard. IAS1S2-1010]	1	1	Inspection			Completed	PASS	
16.6.1 AFCM Commands	IAS MW shall allow the research pilot to send AFCM commands to the intruder aircraft AMM. [IAS1S2-2024]	2	1	Test	Flight Test	AAM-NC-093-001.3 IAS Flight-Test Systems (IFTS) V&V Procedures Section 14.1, Step 6	Completed	PASS	
17 EVALUATE [IAS1S2-0002]	NC IAS shall evaluate other developing AAM technologies for IAS integration and to address future automation needs. [IAS1S2-0002]	0		Inspection			Completed	PASS	
17.1 IGCAS	IAS shall evaluate the IGCAS feature to assess for suitability for future AAM operations. [IAS1S2-1006]	1	4	Inspection			Completed	PASS	
17.1.1 IGCAS Integration	IAS shall integrate the IGCAS software into the ownship. [IAS1S2-2014]	2	4	Test	Flight Test	AAM-NC-093-001.3 IAS Flight-Test Systems (IFTS) V&V Procedures Section 20.1, Step 5	Completed	PASS	

17.2 Auto-landing Maneuvers	IAS shall evaluate auto-landing maneuvers to assess for suitability for future AAM operations. [IAS1S2-1011]	1	4	Inspection			Completed	PASS	
17.2.1 Auto-landing Procedure Design	IAS shall develop procedures for auto-landing and integrate associated software into the test tablets and test aircraft. [IAS1S2-2030]	2	4	Test	Flight Test	AAM-NC-093-001.3 IAS Flight-Test Systems (IFTS) V&V Procedures Section 19, Step 2	Completed	PASS	
18 IDENTIFY [IAS1S2-0003]	NC IAS shall identify suitable display requirements to fly integrated operations. [IAS1S2-0003]	0		Inspection			Completed	PASS	
18.1 Displays	IAS shall develop an airborne test display for human-machine-interface (HMI) with the research systems. [IAS1S2-1008]	1	3	Inspection			Completed	PASS	
18.1.1 Pilot Workload	IAS shall perform pilot workload assessments to inform future design requirements. [IAS1S2-2018]	2	3	Analysis	Postflight	Pilot workload questionnaires responses were collected immediately after each encounter, and the generation of noncorrupt output files were successfully completed.	Completed	PASS	
18.1.2 Pilot Display Stop/Reset	IAS shall have a dedicated HMI capability to allow for stopping or resetting a test mission profile being flown. [IAS1S2-2019]	2	3	Test	Ground Test	AAM-NC-093-001.3 IAS Flight-Test Systems (IFTS) V&V Procedures Section 18 and Section 19	Completed	PASS	

Appendix C: VEHICLE DESCRIPTIONS

The S-76 SARA Description

The IAS flight tests utilized the Sikorsky research-modified S-76B aircraft (see fig. 1) hosting the Sikorsky MATRIX™ research system. The SARA aircraft currently has a civil FAA-issued Experimental Airworthiness Certificate and a public use certificate via a DARPA-issued flight clearance; however, NASA AFRC was responsible for the flight-test safety review during IAS operations. The S-76B is a medium-size commercial helicopter with a 4-blade span of 44 feet; an operating weight of 8,750 pounds, and a maximum weight of 11,700 pounds. The aircraft is powered by two Pratt & Whitney (East Hartford, Connecticut) PT6B-36 engines, resulting in a cruise speed of 140 knots and an ~2-hour endurance. The electrical distribution system provides 28 volts direct current (VDC) (1 kW available); 115 volts alternating current (VAC) / 500-W electrical power to the MATRIX™ research system.

The SARA aircraft cockpit provides side-by-side seating for a crew of two with traditional dual helicopter controls. In addition, the research pilot (right seat) is outfitted with dual inceptors for highly augmented SARA operations. The two inceptors provide altitude, acceleration/deceleration, and yaw control to the SARA automation system. During NASA research flights, the left seat (as pilot-in-command) was responsible for aircraft safety and reversion of control back to traditional S-76B control (via a button on the traditional cyclic pitch control or "cyclic") in the event of a problem. The NASA research or test pilot (in the right seat) was responsible for executing the IAS testing, including using a NASA-provided research tablet, hosting NASA-developed mission support software that interfaced with SARA via WiFi or ethernet. The S-76B traditional cyclic and collective control systems are hydraulically boosted. Traditional flight controls are servo-assisted, utilizing a Stability Augmentation System to augment aircraft control (not fly-by-wire). The Sikorsky automation may be disconnected on the SARA using a variety of methods in order to ensure flight safety: 1) manipulation of either pilot or right-seat collective; 2) via a trigger switch on the SARA inceptor; 3) via the SARA cockpit control panel; or 4) automatically via the systems protection software (during a limit exceedance or detected equipment failure).

Of importance for the NASA research system data analysis is the aircraft position and velocity data. The accuracy of the SARA systems to provide the current position of the aircraft and then achieve the MW-commanded trajectory path is dependent upon the aircraft navigation system. The SARA navigational performance of the helicopter, while proprietary, exceeded what was required for this testing.

The S-70 Optionally Piloted Vehicle (OPV) Black Hawk™ Helicopter Description

In addition to the SARA aircraft, Sikorsky Innovations also operates a research-modified version of a commercial S-70 version of a military Black Hawk™ helicopter, termed the Optionally Piloted Vehicle (OPV). The research-specific systems on the OPV that enable highly autonomous operations and 4D trajectory flight are very similar to those on the SARA, with the exception that the OPV/S-70 baseline helicopter utilizes a fly-by-wire control system instead of a classic fly-by-cable control system that are utilized on the SARA. The OPV aircraft implements the DARPA-Sikorsky Aircrew Labor In-cockpit Automation System (ALIAS) that provides the ability of the aircraft to operate unmanned; however, NASA did not utilize this capability for the IAS test project. In addition, there are no inceptors on the OPV but instead, the standard S-70 controls may serve as automation inceptors when engaged in the associated autonomy modes. As with the SARA, the OPV helicopter may be commanded via 4D routing software hosted on tablets carried aboard the aircraft.

The S-70 Black Hawk™ helicopter is a medium-sized commercial version of an HH-60 military helicopter with a 4-blade span of 65 feet; and a maximum weight of 22,000 pounds. The helicopter has a cruise speed of 160 knots and an ~3-hour endurance.

The Sikorsky automation may be disconnected on the OPV in a variety of methods in order to ensure flight safety: 1) Remotely with the "Standby" button on the pilot and copilot cyclic grips; 2) via the aircraft modes page on the Multi-Function Cockpit Displays (MFCU); 3) manually by selection of direct mode, manual slew of the stabilator controls; 4) by using the near-ground pilot abort function; or 5) automatically via detected system failures that can interfere with proper operation of the OPV autonomous mode.

MATRIX™/ALIAS Description

Both helicopters are outfitted with the Sikorsky MATRIX™ system. The MATRIX™ system, together with critical aircraft system interfaces (with an Embedded GPS-INS (EGI)-navigation system, flight controls, electrical power, etc.) enables highly augmented aircraft operations (using research pilot (right seat) inceptors and a tablet) representative of future UAM/AAM vehicles. The MATRIX™ system has the following characteristics:

- Designed to DO-178C DAL A. (ref. 5).
- Class A software.
- Configuration management for flight critical software is reviewed by an independent software quality group.
- The safety pilot (left seat) or the research pilot (right seat) can easily disconnect the research automation to resume manual flight.
- Open architecture, full-authority capability utilizes 4D curvilinear trajectories to manipulate flight path without relying on outer-loop autopilot commands.
- Linux-based system can host NASA algorithms directly. Note: the NASA IAS software team is responsible for NASA software integration with minor assistance from Sikorsky-related SARA I/O coordination.

As stated previously in the S-70/OPV description, the OPV is outfitted with the ALIAS automation system and a Sikorsky retrofitted fly-by-wire control system to interface with MATRIX™/ALIAS.

The selection of Sikorsky MATRIX™/ALIAS research system was made with the goal of providing a low safety risk, near turn-key operation of the NASA research software. Together with the MM-RTA interface design of the MW that readily provides the system interfaces to the lower-level NASA research software (AVAS-Xr, AOP, GCAS, etc.), the flight-safety-critical Level A/1 MATRIX™/ALIAS environment provided an isolated, software/hardware wrapper environment in which to operate the Level D/4 NASA research algorithms. This resulting combination of the Sikorsky and FAA-approved wrapper environment together with the NASA MW architecture gave great flexibility and development flexibility to the NASA research software development teams (ACAS-Xr, AOP, iGCAS, etc.).

Appendix D: IAS TEST SORTIES SUMMARY

Table D 1. The IAS test program mission summary.

Mission/ Flight #	Mission Type	Date	SARA Pilot	SARA Safety Pilot	OPV NASA pilot(s)	OPV Safety Pilot	NASA TC	Sik TC	SARA Flight time	OPV Flight time	NASA Cumulative time (Not including Pathfinder)	Brief Description of Mission
1	Pathfinder	22-Mar-22	Ringo				-	?	0.9		0.9	Familiarization Flight
2	Pathfinder	22-Mar-22	Zahn				-	?	0.6		1.5	Familiarization Flight
1	Spiral 1A	30-Aug-22	Howe	Ward	not flown	not flown	Scofield	Mondell	1.5	-	1.5	SARA only HPA and FPM routes in winds
2	Spiral 1A	30-Aug-22	Zahn	Ward	not flown	not flown	Scofield	Varillo	1.8	-	3.3	SARA only HPA and FPM routes in winds
3	Spiral 1A	31-Aug-22	Zahn	Ward	not flown	not flown	Scofield	Varillo	1.7	-	5.0	SARA only HPA and FPM routes in winds and auto-landings
4	Spiral 1A	31-Aug-22	Howe	Ward	not flown	not flown	Scofield	Varillo	1.7	-	6.7	SARA only HPA and FPM routes in winds and auto-landings
5	Spiral 1B	10-Nov-22	Ringelberg	Ward	not flown	not flown	Scofield	Varillo	1.4	-	8.1	Spiral 1A DR fixes (HPA & FPM), but bowtie did not work. No Autoloand
6	Spiral 1B	10-Nov-22	Ringelberg	Ward	not flown	not flown	Scofield	Varillo	1.4	-	9.5	Spiral 1A DR fixes (HPA & FPM), but bowtie did not work. Auto-landing
7	Spiral 2A	15-Feb-23	not flown	not flown	Ringo (back seat)	Williamson	Scofield	Varillo	0.0	1.8	11.3	OPV : MW and HPA tests (Bow-ties)
8	Spiral 2B	8-Jun-23	Howe	Williamson	Zahn + Ringo (back)	Davis	Guion	Mondell + Varillo	0.2	0.4	11.9	**Mission aborted** due to poor visibility (Canadian fires)
9	Spiral 2B	27-Jun-23	Howe	Williamson	Simeth+Ringo (back)	Davis	Scofield	Mondell + Varillo	1.8	2.0	15.7	Conducted 1st dual ops. FPM only, encountered problems with data links
10	Spiral 2B	27-Jun-23	Howe	Williamson	Simeth+Ringo (back)	Davis	Scofield	Mondell + Varillo	1.6	1.7	19.0	Conducted 1st dual ops. FPM only, encountered problems with data links
11	Spiral 2C	17-Oct-23	Ringelberg	Davis	Zahn + Howe (back)	Fell	Guion	Mondell + Varillo	1.4	1.4	21.8	Attempted HPA-CAS, but problems forced to fly HPA low-speed runs instead
12	Spiral 2C	18-Oct-23	Howe	Rucci	Zahn + Ringo (back)	Fell	Guion	Mondell + Varillo	2.2	2.4	26.4	Conducted 6 group 1&2 FPM runs + OPV 5° auto-approach
13	Spiral 2C	18-Oct-23	Ringelberg	Rucci	Zahn + Howe (back)	Fell	Guion	Mondell + Varillo	2.2	3.2	31.8	Conducted 8 HPA-CAS runs & iGCAS1 (against water)
14	Spiral 2C	19-Oct-23	Ringelberg	Rucci	Zahn + Howe (back)	Davis	Guion	Mondell + Varillo	2.0	2.0	35.8	Conducted 6 FPM (mix)
15	Spiral 2C	19-Oct-23	Howe	Rucci	Zahn + Ringo (back)	Davis	Guion	Mondell + Varillo	2.0	2.0	39.8	Attempted 3 HPA-DAA, but forced to conduct HPA low-speed instead (finished all low speed runs)
16	Spiral 2C	23-Oct-23	Ringelberg	Davis	Simmeth + Howe (backK0	Fell	Guion	Mondell + Varillo	2.1	2.1	44.0	6 DAA & 1 Terminal HPA runs. Had issues with ADS-B at start: landed,fixed it, and launched again.
17	Spiral 2C	23-Oct-23	Howe	Davis	Simmeth + Ringo (back)	Fell	Guion	Mondell + Varillo	2.1	2.1	48.2	6 FPM , group 3, and SARA iGCAS2 (against virtual wall)
18	Spiral 2C	24-Oct-23	Ringelberg	Davis	Simeth+Howe (back)	Fell	Guion	Mondell + Varillo	2.2	2.4	52.8	5 FPM groups 5 & 6 & Sik Neoview 5 deg auto-land
19	Spiral 2C	24-Oct-23	Howe	Davis	Zahn + Ringo (back)	Fell	Guion	Mondell + Varillo	2.2	2.5	57.5	3 FPM (group 7) , and then 5 HPA (terminal and structured) + OPV 5° NASA auto-approach
20	Spiral 2C	25-Oct-23	Howe	Davis	Zahn + Ringo (back)	Fell	Guion	Mondell + Varillo	2.2	2.5	62.2	6 FPM (groups 1 &2), and NASA 8° auto=approach
21	Spiral 2C	25-Oct-23	Ringelberg	Davis	Zahn + Howe (back)	Fell	Guion	Mondell + Varillo	2.1	2.8	67.1	3 HPA (structered),(this completes all HPA). 1 FPM, 3 other M7 card attemped but failed. OPV: 2 NASA 12° auto-approaches
22	Spiral 2C	26-Oct-23	Ringelberg	Davis	Zahn + Howe (back)	Fell	Guion	Mondell + Varillo	1.5	2.5	71.1	One 12° NASA approach, then 5 FPM (mixed groups), then another 12° and an 8° NASA approach
23	Spiral 2C	26-Oct-23	-	-	Zahn + who? (back)	Fell	Guion	Mondell + Varillo	0.0	0.6	71.7	conducted two 8° Sikorsky auto-landing and two 12° Sikorsky auto-landings
									37.3	**34.4**	**71.7**	
											Total	

Appendix E: SPIRAL APPROACH DETAILS AND RESULTS

Before delving into the IAS test descriptions, it is important to inform the reader of the effort undertaken by NASA AFRC to capture and verify baseline Sikorsky flight and maintenance processes/procedures ahead of any flight operations. Per NASA Policy Requirements, NPR 7900.3 (ref. 2), a formal on-site NASA inspection was conducted by the AFRC Chief Engineer along with selected NASA personnel, in November of 2021, and a report was issued, per NASA in accordance with (IAW) NPR7900.3/AFRC AFOP 7900.3-023) (ref. 3) for Commercial Aircraft Services (CAS) operations, stating that the Sikorsky support for the IAS effort was deemed to be sufficient for NASA operations. A small number of findings/recommendations (all ranked minor) were documented and were all subsequently closed by NASA via clarification or team actions. Approximately 40 to 50 proprietary Sikorsky maintenance (MX) operations documents were scrutinized on-site closely by NASA personnel, and in addition, over 20 flight operations-related documents were provided electronically to NASA flight personnel for review and digital storage in protected system/folders. Of note: because the IAS test aircraft is provided to NASA via a CAS effort, the Sikorsky MX process/procedures were utilized throughout the entire IAS effort to maintain aircraft-level configuration and conduct MX operations. Lastly, NASA AFRC flight operations procedures/processes were utilized in conjunction with Sikorsky flight operation documents for all flight operations (the more stringent of the two flight-operational procedures or mutually agreed upon relaxation of one or the other were implemented for IAS flights). Similar to the NASA Technical Brief process, Sikorsky utilizes a Model Development Safety Committee (MDSC) for airworthiness approvals and aircraft design approvals. The NASA agreed to utilize MDSC outcomes/recommendations (and was invited to MDSC reviews for IAS activities) for all IAS spirals as part of the NASA Airworthiness and Technical Brief Reviews.

PATHFINDER

<u>Purpose and Objectives:</u> The purpose of the two pathfinder missions, conducted on March 22, 2022, was to demonstrate the MATRIX™ research system capabilities, the SARA aircraft capabilities including safety, and to assess the overall Sikorsky flight-test operations. For each of the two missions, a NASA research or test pilot flew in the SARA research pilot (right seat) and a Sikorsky S-76B SARA-qualified test pilot (left seat) flew as the safety pilot. The two flights were solely conducted by Sikorsky personnel from their mobile ground control station (GCS) located near their manufacturing facility in Stratford (~7 miles up the Housatonic River from the Long Island Sound).

Specific objectives of the Pathfinder missions were as follows:

- Perform the SARA disconnects (methods: pilot cyclic, research pilot cyclic, SARA panel, and if feasible, via automatic software protection (system limits)) to evaluate its overall safety.
    - Sortie 1, 0.9 hours – (inceptors and tablet (auto-route)) checkout of the SARA controls and safety overrides. **Results:** confident in SARA system protections.
    - Sortie 2, 0.6 hours – (tablet only) exercised auto-routing and safety disconnects (desired waypoint intentionally placed too close to vehicle to execute resulting desired route). **Results:** confident in SARA system protections.

- Receive an aircrew cockpit/systems familiarization (on ground prior to flight in research pilot (right seat)).
    - Reason: Obtain familiarization with the SARA cockpit and satisfy the Sikorsky requirement for the SARA research pilot qualification in pilot seat (right seat).

Results Overview: The Pathfinder objectives were fully met. The aircrew and the test team were satisfied with the aircraft flight safety and Sikorsky test operations. Planning Spiral 1 work was given the go-ahead.

Hardware/Software/Test Configuration: Baseline SARA aircraft and system – no added NASA hardware or software (see aircraft and system descriptions in Appendix C) were present on the aircraft or GCS.

As this was a Sikorsky conducted mission, no test data was collected; however, a Sikorsky system standard set of recorded data was made available, if needed, to assist in the development of NASA software interfaces.

Test Description: A standard Sikorsky familiarization 1- to 1.5-hour flight was flown in each mission. The autonomous mode was invoked, and the aircraft was flown via the onboard Sikorsky "Neoview" tablet from the pilot seat (left seat) and also via the inceptors from the research pilot (right seat). Autonomous system disconnects were performed via the various methods: A Sikorsky system controlled auto-landing was also conducted on each mission from an ~50-foot auto-hover. The NASA aircrew obtained familiarization with the surrounding airspace and airfield while members of the future NASA test team (for NASA tests) observed the Sikorsky mission control operations from within the GCS trailer.

Ops Overview: As stated previously, a NASA research or test pilot flew in the right seat of the SARA aircraft with a Sikorsky S-76-qualified test pilot in the left seat serving as the mission safety pilot. The NASA test engineering personnel had no test responsibility, and instead, were able to monitor over-the-shoulder (and headset) test operations of the Sikorsky.

SPIRAL 1A

Purpose and Objectives: The purpose of the Spiral 1A missions, conducted August 30 to 31, 2022, was as follows:

1) Verify that the IAS middleware received and interpreted all data required to satisfy the interface requirements for HPA and FPM.
2) Quantify the ability of the SARA aircraft to fly 4D trajectories that are representative of HPA and FPM commands in the presence of varying wind conditions (up to 30 knots if possible).
3) Identify if any inconsistencies exist between the IAS middleware and the HPA and FPM interfaces.
4) Secondary: Conduct Sikorsky system-controlled auto-landings and evaluate the accuracy of the auto-land feature between the commanded landing location and the actual location.

Results Overview: 1) The ability of the aircraft to follow a MW-commanded 4D trajectory/route/ Trajectory Prediction Uncertainty Bound (Tube-in-Sky), as termed by FPM, was evaluated. Winds aloft up to ~25 knots were observed (with gusts to ~30 to 35 knots) and resulting time and special deviations off the intended route were very minimal and are shown in fig. E 1.

Param	Limit	Nominal	Max	Notes
time	+/- 6 sec	0.5s	1.5s	Along-track
Lateral position	+/- 150’	<50’	<150’	Winds aloft 33-43kts
Vertical position	+/- 50’	<30’	<50’	Winds aloft 33-43kts

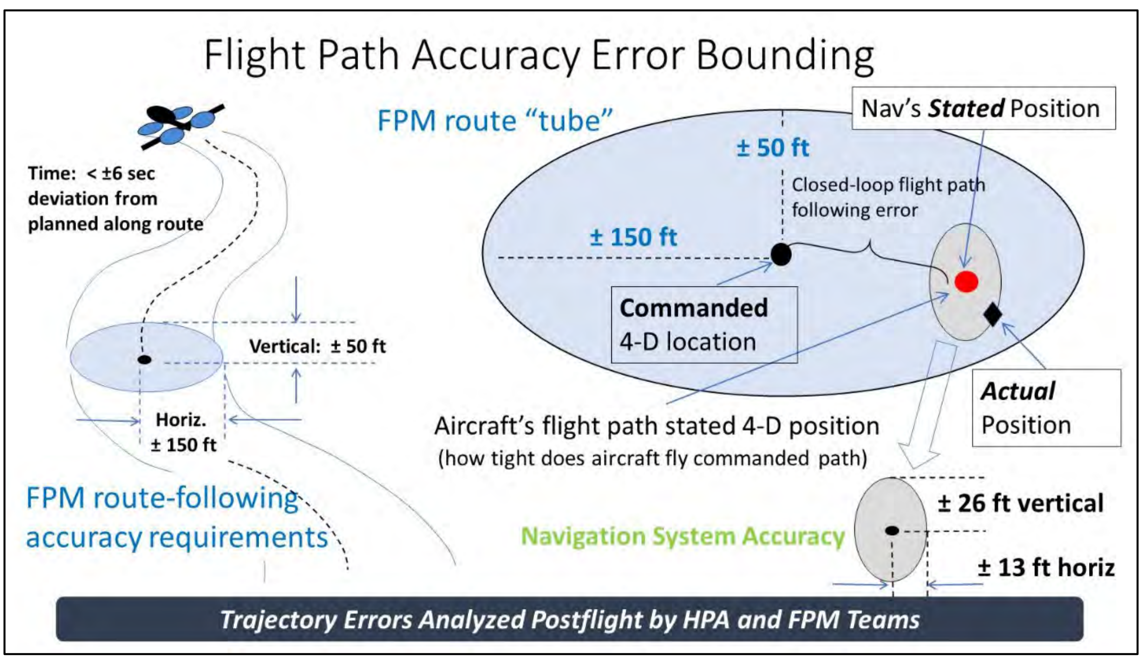


Figure E 1. FPM TPUBS adherence.

2) While the spiral objectives were fully met, a few NASA Discrepancy Reports (DRs) were written:

a. Datalink problems, thereby requiring a second Spiral 1 test be included for IAS: Spiral 2B.
b. Problems were uncovered with the SARA baseline ADS-B-Out signal parsing in the MW data stream.
c. Aircraft oscillations in the pitch and yaw axes were observed. While not severe enough to cause safety concerns (to either the aircrew or ground personnel) or preclude satisfactory HPA/FPM data collection, the team preferred to eliminate/minimize their magnitude if feasible.

3) The MW-induced low-frequency pitch and roll/yaw oscillations were observed. Figure E 2 shows one example of a roll/yaw oscillation. While not of frequency and magnitude sufficiency to give a flight safety concern, nor prevent research data collection, the oscillations were deemed to be a nuisance. A more detailed AIO discussion is provided in Appendix J.

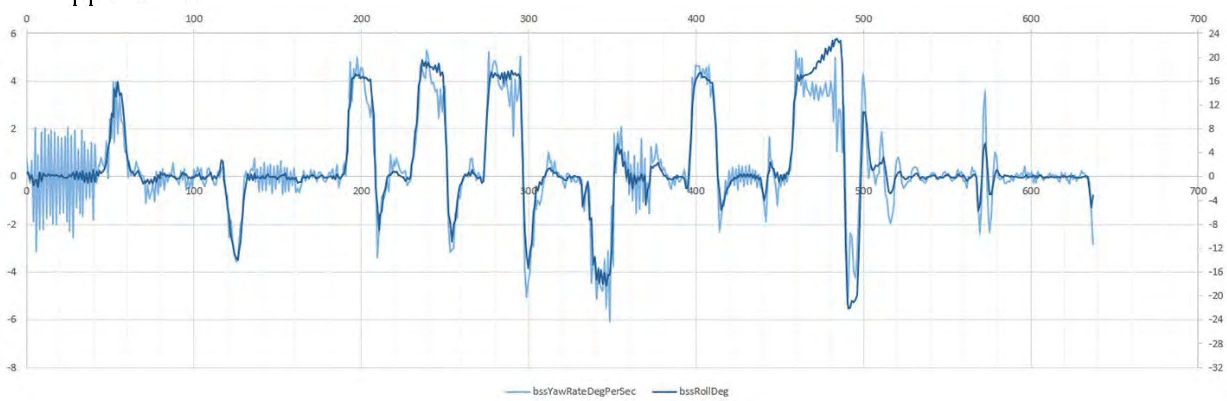


Figure E 2. Example of Automation-Induced Oscillation (AIO).

4) Two auto-landings were performed at the KJSD Sikorsky Heliport with sufficient fuel to reposition for shutdown at KBDR.

Hardware/Software/Test Configuration: A UP^2 processor (fig. E 3) hosting the Spiral 1A version NASA MW was installed in the rear/research equipment area on the SARA aircraft by Sikorsky.

Specifications: 1.2 pounds; and 3.5 inches by 3.5 inches by 2 inches. DC to AC power conversion.

Figure E 3. UP2 processor.

A description of the Spiral 1A test network configuration is provided in fig. E 4. Throughout all IAS testing, the Sikorsky-implemented Silvus (Silvas Technologies, Los Angeles, California) digital radios were utilized to provide the datalink between the aircraft and the GCS. Within the GCS and onboard the SARA helicopter the formatting and system configuration of the NASA equipment/software was controlled jointly by NASA and Sikorsky.

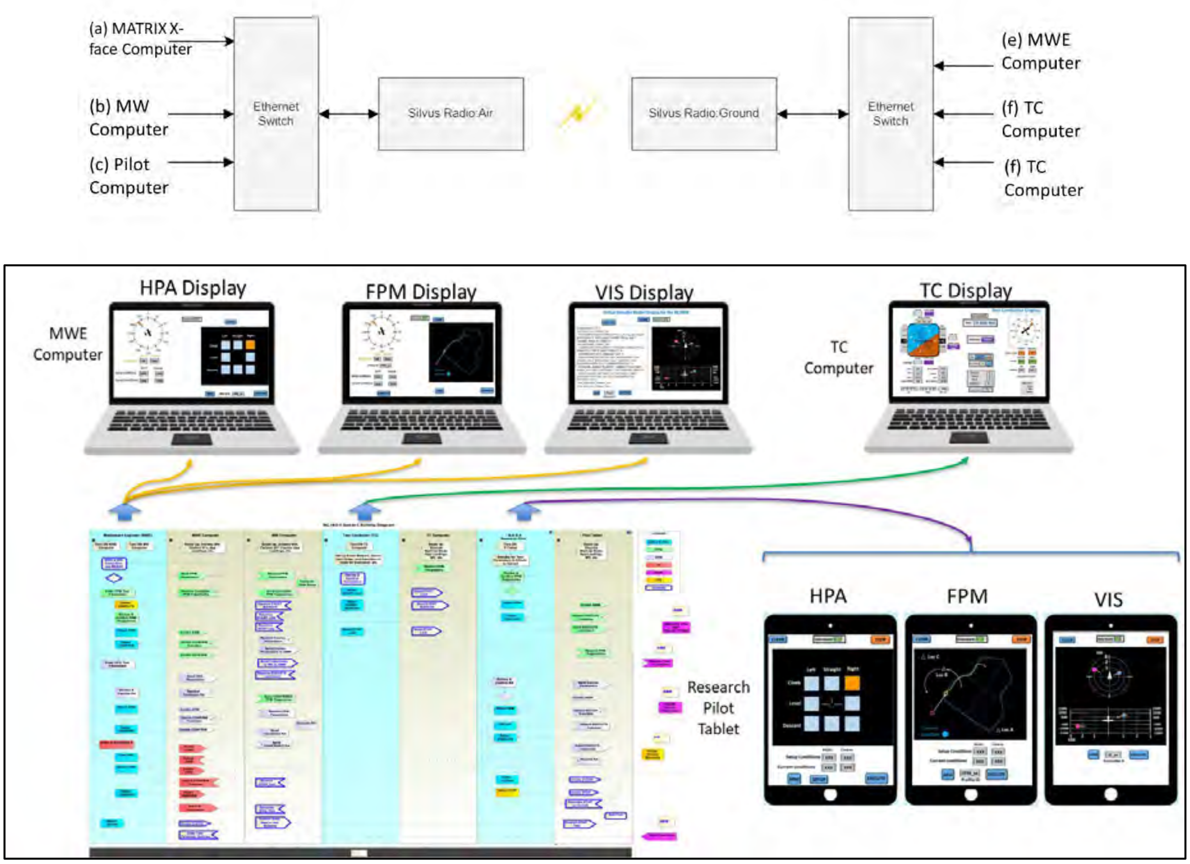


Figure E 4. Spiral 1A test network setup/configuration.

<u>Test Descriptions/Methodology (not in order of execution)</u>: Four flights were required to complete Spiral 1A, two flights on August 30, 2023, and two flights on August 31, 2023. For each of the four missions, a NASA research or test pilot flew in the SARA (right seat), and a Sikorsky S-76B SARA-qualified safety test pilot flew in SARA (left seat). The GCS was manned by a team of Sikorsky and NASA engineers: Sikorsky with baseline aircraft operations (takeoff/recovery); and NASA with research responsibilities.

The general test method developed for this Spiral 1A test was utilized for all subsequent IAS spirals (with some modifications to the method utilized in the multi-ship operations in Spirals 2B and 2C). The general test method implemented was for the aircrew to control when the MW automated test run that would be initiated and the MW Engineer (MWE), in consultation with the Mission Conductor (MC) in the GCS, would upload the requested/upcoming preplanned, uniquely identified test run from the GCS to the onboard MW and out to the research/NASA pilot tablet for display. The aircrew then executed *Yes/Stop* options via digital buttons on the tablet display. The

SARA and OPV pilot (left seat) utilized a non-NASA/independent ForeFlight® tablet in conjunction with Stratus ADS-B equipment to maintain overall flight awareness in support of flight safety responsibility. The Sikorsky pilot also carried a Sikorsky autonomous system interface tablet, termed the "Neoview" tablet, to perform Sikorsky-developed events such as auto-landings or auto flight. Lastly, the left seat safety pilot had primary responsibility for ATC and Sikorsky Eagle radar communications, whereas the right-seat NASA pilot was responsible for executing uploaded test runs via the NASA tablet.

Since the winds aloft (speed and direction) were important considerations for HPA and FPM avoidance maneuvers, it was critical that trusted computation of winds aloft be performed as close to the execution time and location of the maneuvers as possible. To satisfy this need, the MW computed the winds aloft and displayed them to the test team in real time. From this wind data, the MWE/MC team could adjust the start heading of the FPM and HPA test profiles per the 5 to 10 called-for angular offsets relative to the wind direction. A description of the winds aloft computation is provided in Section 5.1.3.

The IAS MW implemented a wind-filter algorithm that computed and averaged 5 seconds of the winds aloft in real time while the aircraft was in unaccelerated flight for a period of 5 to 10 seconds; therefore, satisfying a small set of aircraft conditional limits (bank angle, roll rate, pitch angle, true airspeed, etc.). If the aircraft conditions were satisfied within the computational filters of the algorithm to be "valid," the resulting averaged wind speed and direction was passed to the MW CVT for use by the MW, research algorithms, and the displays. When aircraft conditions did not satisfy the wind filter, then the last *valid* averaged wind value was passed to the CVT middleware CVT instead.

Test Methodology:

1) A set of six-directional HPA/ACAS-Xr preplanned avoidance maneuvers/runs (right and left turning climbs, right and left turning descents, and straight climb and descents) were developed at low ground speed (50 knots ground speed (KGS) and high speed (100 KGS) with the winds from three different angles: head on, 90-degree offset, and from the tail (fig. E 5).

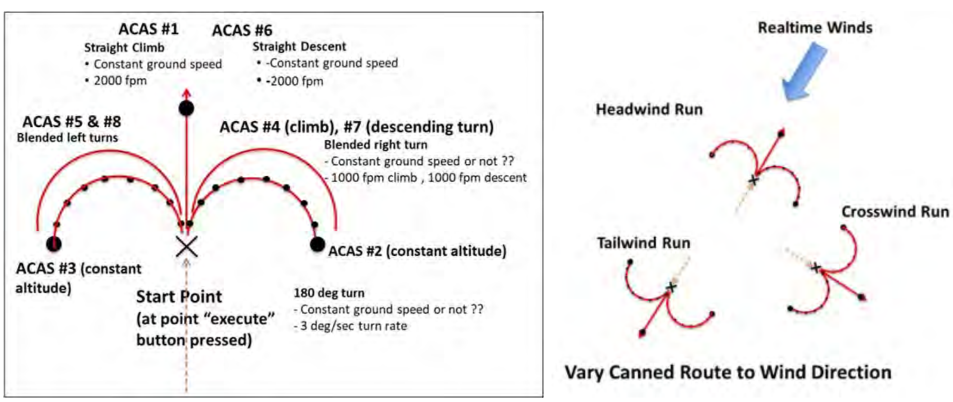


Figure E 5. Pre-planned HPA routes (utilized for Spirals 1A and 1B).

2) An FPM preplanned route (blue line in fig. E 6) was mutually designed by the FPM and the IAS team that flew a 360-degree path and was referred to by the test team as the FPM "Barn" route (fig. E 6). The FPM Barn route incorporated various speeds,

turns, and climb/descents along each segment route, and the entire route was rotated relative to the wind to obtain FPM route-adherence data as a function of wind speed and direction.

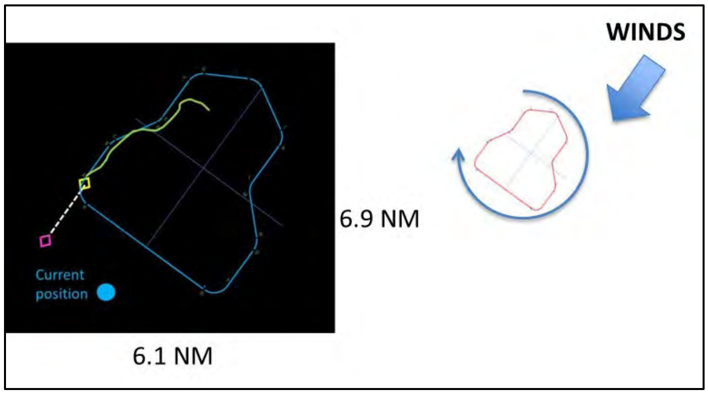


Figure E 6. Pre-planned example of FPM route (utilized for Spirals 1A and 1B).

3) Auto-landings in this phase of IAS testing were conducted using the Sikorsky auto-land capability resident within their autonomous research system and was controlled by the aircrew via the "Neoview" tablet, carried aboard the SARA. The helicopter established a hover at a Neoview set height, above ground (by the aircrew), and the system performed system built-in-tests (BIT) before executing a commanded auto-landing. The system used a combination of onboard position and sensor information (including Light Detection and Ranging (LIDAR) during the vertical descent down to a weight-on-wheels sensed landing. The test crew conducted four auto-landings during Spiral 1A.

SPIRAL 1B

Purpose and Objectives: The primary purpose of the two Spiral 1B missions, conducted on November 10, 2022, was to evaluate the DR fixes to the data communication protocols between the SARA research system and the NASA MW to improve data bandwidth capability as well as evaluate the fixes to other Spiral 1A DRs. Objectives were as follows:

1) Conduct datalink margin and bandwidth tests to determine the maximum datalink range as function of altitude.
2) Verify the changes made to the MW-MATRIX™ system interfaces to improve data bandwidth.
3) Verify that the MW reads (through MW coupler, I/O) ADS-B-In pressure altitude as well as GPS altitude and is able to distinguish between the two.
4) Further observe the MW induced oscillations uncovered in Spiral 1A, specifically the impact of wind direction and magnitude.

Results Overview: The goals of the Spiral 1B missions were fully satisfied. Multiple HPA and FPM runs were conducted gathering more data on trajectory/TPUB adherence in the presence of winds (winds aloft up to ~30 knots were observed with occasional gusts up to ~40 knots).

1) The changes made to the MW-Sikorsky research systems to improve data bandwidth were successful.
2) Datalink signal link data was collected at various altitudes and ranges to ensure sufficient datalink coverage was available for future planned testing.
3) The fix to the ADS-B-In signal strip out in the MW (between reading pressure altitude or GPS altitude) was successful.
4) Automation-Induced Oscillations (AIO) were again observed, generally most notable when flying or transitioning into a headwind.
5) Conducted one auto-landing.
6) Similar performance to the commanded trajectory that was observed in Spiral 1A was again observed nominally at a <50-foot lateral deviation; a <30-foot vertical deviation; and a <1-second timing to hit the commanded "start maneuver" time, even when in the presence of moderate to high winds (25 knots steady, ~40-knot gusts).

Hardware/Software/Test Configuration: The same Spiral 1A test configuration was again utilized for Spiral 1B, except the low-level interface protocols between, and within, the MW and the SARA research systems were modified to improve the data bandwidth.

Test Description/Methodology: Two flights were conducted on November 10, 2022, for Spiral 1A. For both flights, a NASA test pilot flew in the SARA pilot seat (right seat) and a Sikorsky S-76B SARA-qualified test pilot (left seat) as the safety pilot. The GCS was manned by a team of Sikorsky and NASA engineers: Sikorsky monitoring baseline aircraft operations (takeoff/recovery) and NASA conducting the IAS research.

The same general test procedures described in Spiral 1A, previously, were again used to execute Spiral 1A tests auto flown via MW-uploaded preplanned maneuvers and executed by the NASA pilot via the onboard NASA tablet. The HPA and FPM test runs were selected from the same test matrix/preplanned maneuvers that were developed for Spiral 1A.

SPIRAL 2A

Purpose and Objectives: The primary purpose of the Spiral 2A mission, conducted on February 15, 2023, was to evaluate the ability of the OPV to follow MW commands in the same manner as the SARA (note: the SARA was not flown for Spiral 2A) and functionality of the data network with OPV added. Secondary objectives were as follows:

1) Evaluate the AIO (if present on the OPV).
2) Evaluate datalink range (similar to SARA)
3) Evaluate trajectory/TPUBS performance, including use of the new “Bowtie” maneuver that was unsuccessful in Spiral 1B.
4) Verify the functionality of the Sikorsky-installed (NASA requirement) ADS-B equipment, including the antenna.
5) For these Spiral 2A tests, a new type of FPM route was developed, termed a “Bowtie” that was more efficient than the Barn shape route from Spiral 1A and 1B in gathering trajectory data relative to the winds, as shown in fig. E 7.

Results Overview: The goals and objectives of the Spiral 2A mission were fully satisfied. Multiple HPA and a few FPM runs were conducted gathering more data on trajectory/TPUB adherence in the presence of winds (winds aloft up to ~35 knots were observed with gusts up to ~40 to 45 knots).

1) Although not performed with NASA present, Sikorsky conducted ground tests that verified the dual-aircraft network operation and the ADS-B install.
2) As mentioned in the Hardware/Software/Test configuration section, immediately below, the NASA MW was moved from the UP2 to the Sikorsky High-Performance Computer (HPC). This move was done to further improve data bandwidth, especially needed for hosting the latest FPM software including the virtual traffic, route prediction portion of the AOP software package.
3) The new Bowtie FPM maneuvers were successful.

Hardware/Software/Test Configuration: A major change to the test aircraft configuration for Spiral 2A and onward was to move the NASA MW from the UP2 processor to a Sikorsky computer (termed by Sikorsky as the High-Performance Computer (HPC)). An additional major change was made to update/modify the network utilized (and described) in Spiral 1A and 1B to include the OPV aircraft, integration with the NASA MW and tablet displays, and its associated GCS displays (fig. E 8).

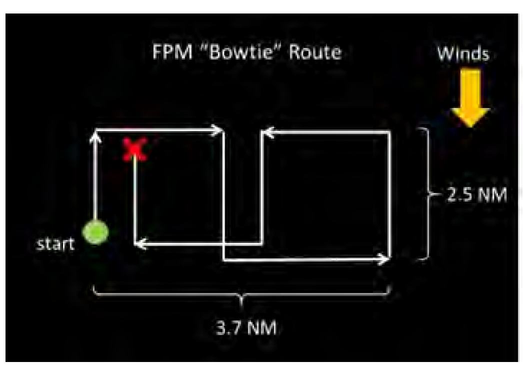


Figure E 7. The FPM Bowtie maneuver.

A modification to the FPM software was made ahead of Spiral 1B to more efficiently collect route-performance data in the presence of winds as compared to the original Barn profile. A new profile, termed the "Bowtie" was created and is shown in fig. E 8.

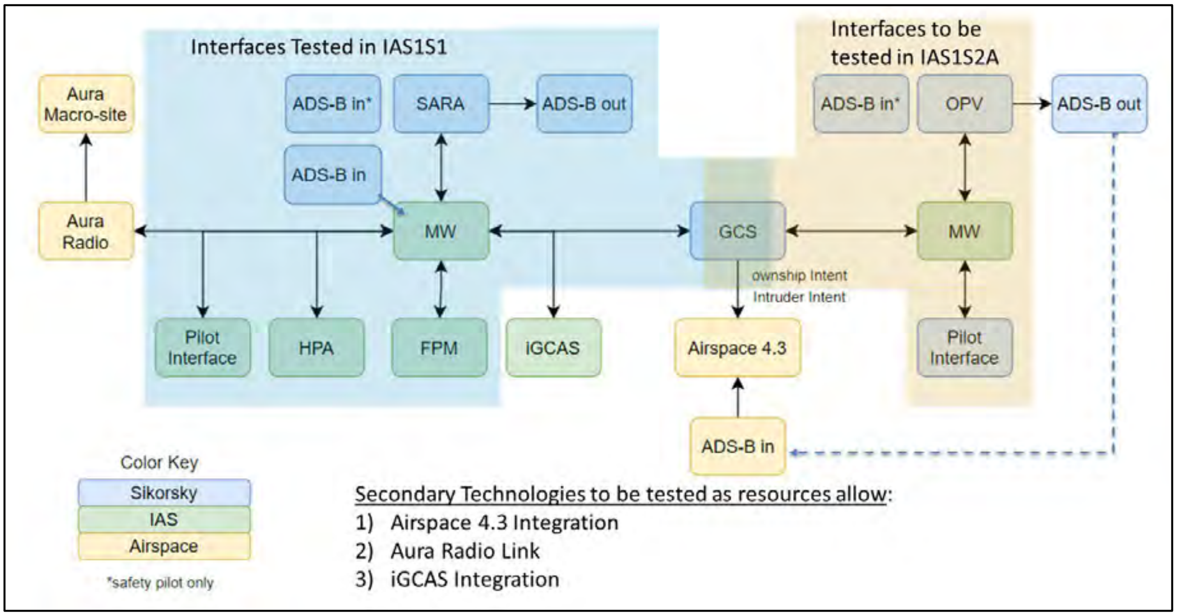


Figure E 8. Spiral 2A test network configuration.

Test Description/Methodology: Only one flight, on February 15, 2023, was required to satisfy the goals of Spiral 2A. For this flight, a NASA research pilot flew in the OPV right seat (per the FAA Experimental Certificate, the right seat pilot must be H-60 qualified and current – thereby limiting the NASA selection for manning the OPV right seat to a particular NASA research pilot for all IAS tests going forward) and a Sikorsky S-70 OPV-qualified test pilot in the left seat as the safety pilot. The GCS was manned by a team of NASA and Sikorsky engineers, Sikorsky monitoring baseline aircraft operations (takeoff/recovery) and NASA IAS research.

The same general test procedures utilized in prior Spiral 1A and 1B were again used to execute Spiral 2A tests auto-flown via MW uploaded preplanned maneuvers and executed by the NASA pilot onboard the OPV via the onboard NASA tablet. The HPA and FPM test runs were selected from the same test matrix/preplanned maneuvers that were developed for Spiral 1A.

SPIRAL 2B

Purpose and Objectives: The purpose of Spiral 2B missions conducted on June 27, 2023, was to conduct IAS Project dual-aircraft encounters for the first time and in doing so, unmask any problems ahead of Spiral 2C/Capstone testing so they may be corrected. More specifically, satisfy the following test objectives:

1) Evaluate the performance of the MW in executing the HPA (see sub-item "1a") and FPM encounters/routes timing in order to satisfy the closest point of approach (CPA)/minimal separation criteria, thereby triggering HPA and FPM avoidance maneuvers at the designed geometries and special separation.
    a. Prior to conducting Spiral 2B tests, during on-aircraft ground tests, the IAS MW software team encountered a problem with the HPA MW integration and as a result, HPA testing was removed from Spiral 2B flights. The IAS test team contemplated adding a Spiral 2B-Delta flight series sometime in future, ahead of Spiral 2C testing to exercise HPA algorithm in flight, but instead decided to rely on on-aircraft ground tests – which in the end were demonstrated to be successful.
    b. Assess the ability of the data network to support the dual-aircraft encounters.
    c. Assess data collection and data analysis.
2) Assess the mission conduct rules performance in achieving an acceptable balance between risk reduction and conducting HPA/FPM encounters in a manner that satisfied the required encounter geometries for HPA and FPM preplanned encounters (the test method is explained in detail in the Subsection *Spiral 2B Test Description/Methodology*) and preliminarily evaluate their performance. Note: the data analysis and reporting of HPA/ACAS-Xr and FPM/AOP performance is the responsibility of the HPA and FPM teams at NASA ARC and LaRC and will be provided outside this IAS report, in their own reports.

While not a NASA-conducted test, to verify the dual-aircraft data network operation prior to NASA-conducted Spiral 2B tests, Sikorsky conducted a dual-aircraft inflight test with the SARA and the OPV. This test uncovered a problem with the network configuration that passed the SARA data to/from the OPV helicopter and from there to/from the GCS data antenna. As a result of this finding, Sikorsky acquired a mobile high-lift and mounted a second data antenna atop the high-lift that relayed the SARA data between the aircraft (i.e., not passing through OPV) and the GCS (fig. E 9).

Results Overview: Spiral 2B was able to successfully complete two test encounters for FPM; however, there were problems uncovered only from flight tests, not apparent during simulation testing, that compounded together to drastically reduce test efficiency.

During the Spiral 2B encounters, a new datalink network was developed by Sikorsky, but occasionally encountered link interruptions. The MW software for Spiral 2B included a datalink connection between the SARA and the OPV that was used to coordinate their approaches to the T-0 location. The necessary coordination was communicated via TCP messages that were aperiodic, and as a result of not being continually repeated, there was high likelihood that the critical messages would be missed due to the occasional datalink drops. Another problem was the MW IFTS displays would incorrectly indicate erroneous health system indications caused by not properly checking the health of the TCP sockets. This problem then led to reduced test efficiency by proceeding with test encounters with an “unhealthy” system that indicated as “healthy."

Along with the datalink problems mentioned previously, a problem with ADS-B latencies of up to 10 seconds was also discovered (and again, only discovered during flight tests). This problem was due to a poorly worded PingStation ADS-B receiver interface control document (ICD) that led to the code parsing the output from the PingStation to get far behind in parsing messages. Lastly, another Spiral 2B problem was multiple test encounters that had to be restarted that was caused by unflyable setups for T-0/start encounter position when either the SARA or OPV orbit location was too close to their T-0 location.

Lastly, changes made to the MW to reduce the AIO magnitude were somewhat successful. The magnitude was reduced but not eliminated.

Hardware/Software/Test Configuration: The final flown configuration is shown below in fig. E 9 and utilizes a second SARA-tuned data antenna atop a high-lift connected to the GCS.

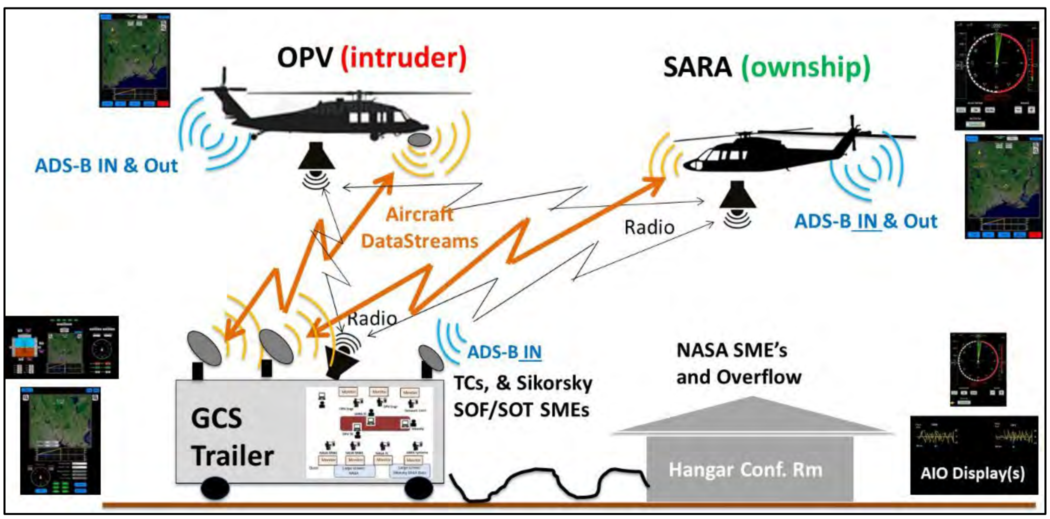


Figure E 9. Spiral 2B network configuration.

The Spiral 2B (and later the Spiral 2C) system configuration differed from prior spiral configurations in multiple aspects to provide more capabilities than all prior spirals:

1) Change to where the MW, HPA, and FPM were hosted: Reason for change: accommodate the additional bandwidth needed for FPM routing/predictions and inclusion of virtual air traffic; and because of the different OS for FPM versus HPA. The MW and HPA/ACAS-Xr research software were hosted on the SARA via a Linux OS Next Unit of Computing (NUC) Single Board Computer (SBC) that interfaced with the HPC via Ethernet connections and TCP-IP protocol. A second Windows-based NUC was also installed on SARA to host the FPM/AOP software. On OPV, only the MW was required and was hosted in an existing Sikorsky MATRIX™/ALIAS computer, termed “NASA 1” or sometimes “Perception 1,” as shown in fig. E 10 and fig. E 11.

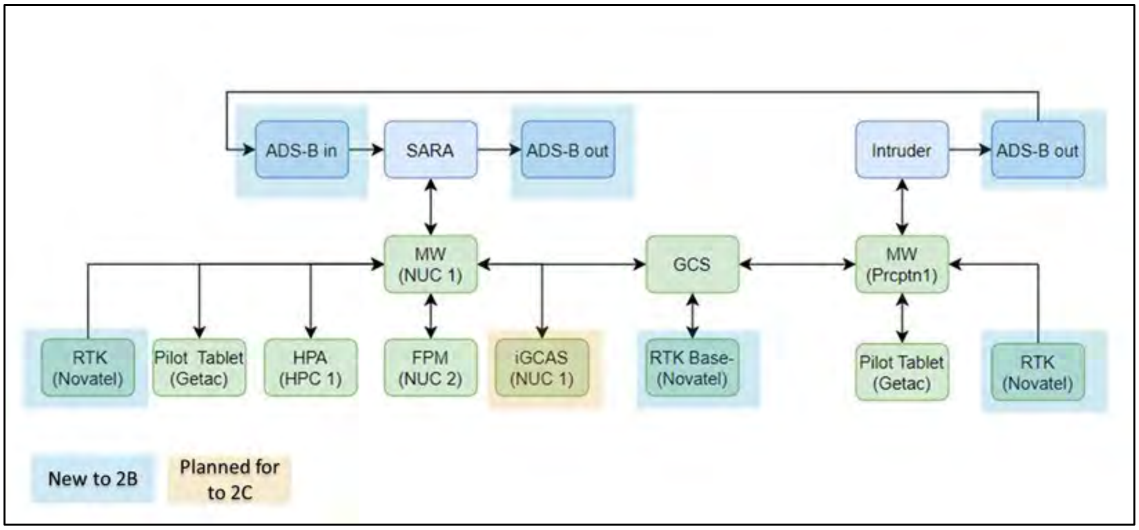


Figure E 10. Spiral 2B/C network configuration.

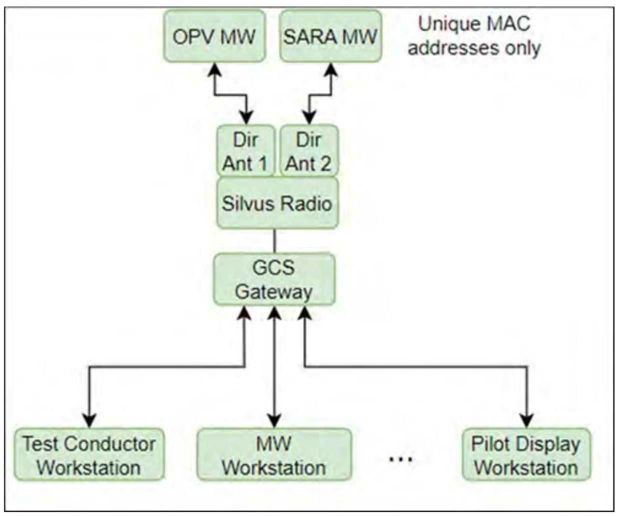


Figure E 11. Dual-aircraft datalink configuration.

2) Incorporated the most recent HPA-integrated ACAS-Xr and FPM AOP software versions (FPM now included virtual traffic). Throughout the spiral evolutions, the HPA and FPM/AOP evolved in its capabilities and associated interface, fortunately, the MW was designed to accommodate modifications to algorithm I/O. In addition, the FPM/AOP software for Spirals 2B and 2C included between 250 to 330 virtual air traffic with routes established by relocating the FPM/AOP air traffic UAM/AAM simulation of the Fort Worth/Dallas Texas area to the IAS test area near Bridgeport/Stratford, Connecticut.
3) Extensive system capabilities were incorporated into the NASA tablet software containing the HPA and FPM research displays. These changes were necessary to accommodate the need for stronger interaction between the NASA research pilot(s) onboard, the SARA and OPV with the MW for encounter setups, and with the HPA/FPM research displays on the NASA tablet aboard SARA (the same NASA tablet that hosted the MW displays was used).

Descriptions of the HPA and FPM software, including their associated research and HMI displays are provided in Appendix I.

To execute Spiral 2B testing required the implementation of a mix of control room/GCS displays, commercial ForeFlight® (ForeFlight, a Boeing Company, Houston, Texas) mobile display tablets and carry-on Stratus equipment for both aircraft Sikorsky safety pilots, which included ADS-B-In data (to ForeFlight® tablet) and the NASA tablets on both aircraft providing the HPA/FPM research and MW interface displays in which position data onboard EGI navigation systems derived from for both aircraft (fig. E 12).

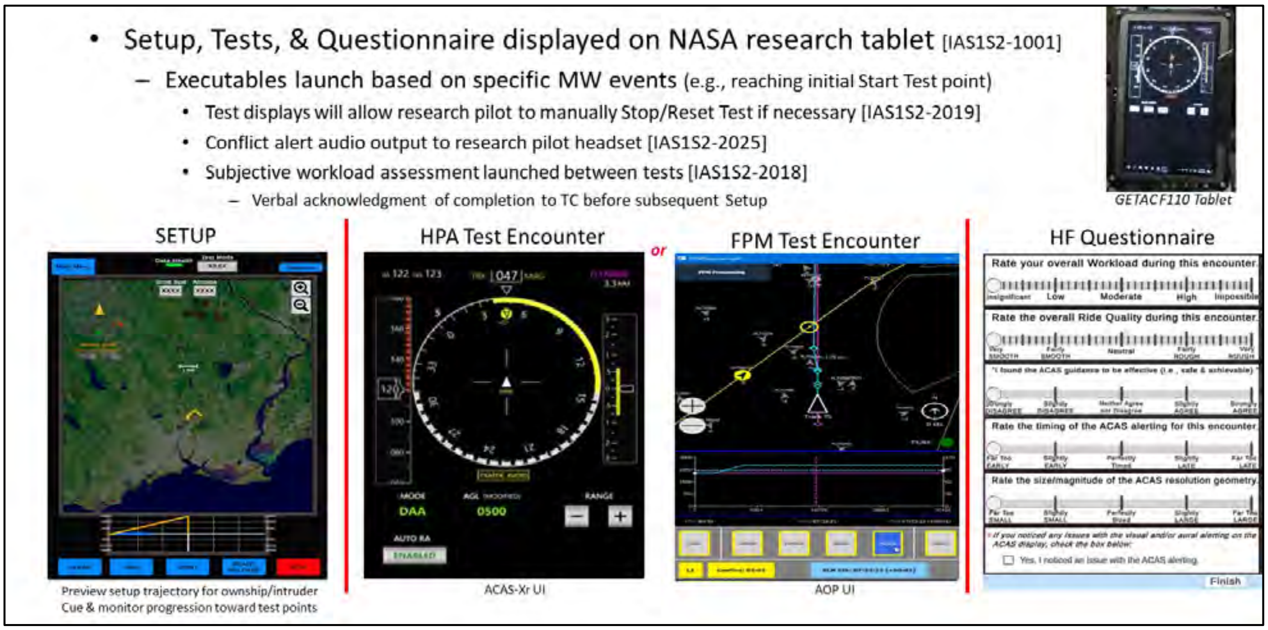


Figure E 12. Spiral 2B tablet displays (setup and research displays).

Note 1: All these displays were also utilized in Spiral 2C Capstone tests.

Detailed explanations for the HPA, FPM, and HMI tablet displays are presented in Appendix I. One other display that was critical for the aircraft encounter testing was the aircraft maneuver/test run setup display (a dual-aircraft version was also provided in the GCS). This test run setup display provided the top-down and sideview to the research pilot to assist and execute the MW commanded encounter routes. This display (shown in fig. E 13) is provided to the SARA tablet and OPV tablet and shows both MW commanded trajectories for the aircraft to provide as much situational awareness to the pilots as feasible.

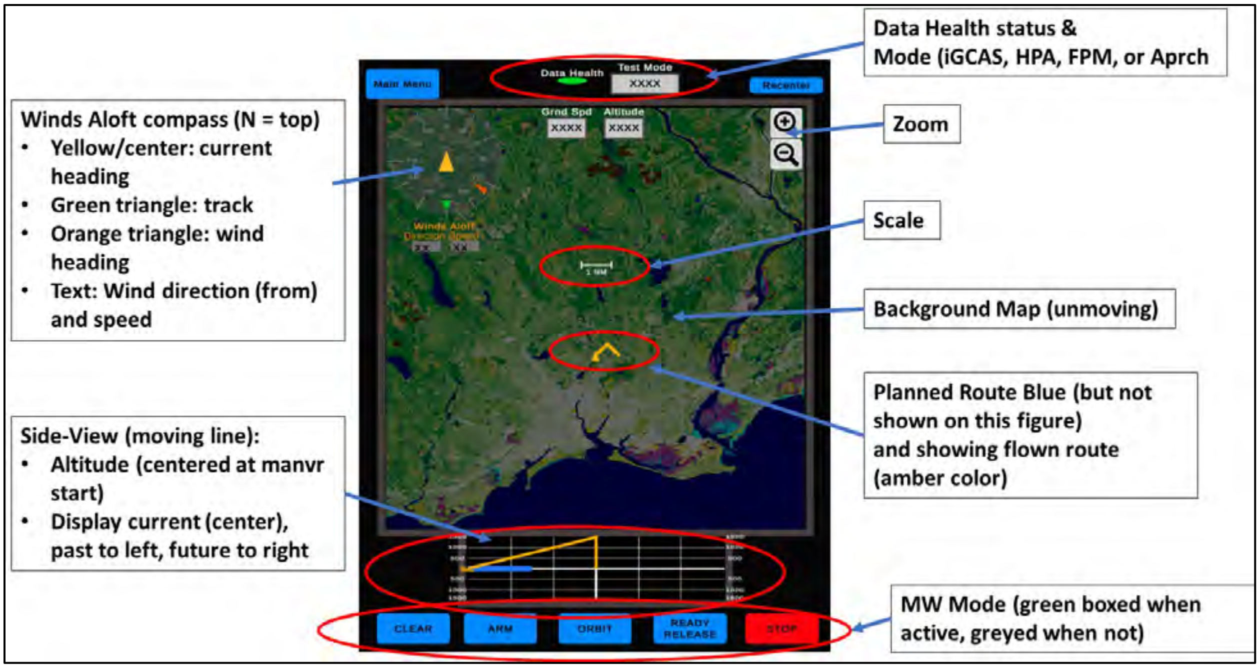


Figure E 13. Encounter setup display.

<u>Note 1</u>: The research pilot interacts with the MW/display via the buttons along the bottom.
<u>Note 2</u>: A similar Encounter display is available in the GCS for the MW Engineer, showing both the SARA and OPV simultaneously.
<u>Note 3</u>: See Subsection *Spiral 2B Test Description/Methodology* below for a more accurate representation of the entire setup route lines.

<u>Spiral 2B Test Description/Methodology</u>: Three flights, one of which was aborted due to lack of adequate visibility (resulting from Canadian fires), were required to complete Spiral 2B (Appendix D). Spirals 2B and 2C dual-ship FPM and HPA encounters required very tight control of the SARA (or "ownship") and the OPV (or "intruder") trajectories in three dimensions + time to force encounters within tight 4D constraints. To trigger the alignment framework for multiple computing (AFCM) research algorithms (ACAS-Xr and AOP) and collect the avoidance maneuver data required, the encounters between the SARA and OPV were designed to penetrate specific parameters that were dependent upon the algorithm mode and encounter geometry. Sections 3.2 and 3.3 provide more detailed descriptions of the HPA/ACAS-Xr and FPM/AOP functions and operations, including the criteria for HPA/ACAS-Xr and FPM/AOP avoidance triggering that drove the encounter separation distances (in order to trigger an avoidance) and the associated routes for the SARA and OPV. Section 5.2 also includes discussions about the HPA/FPM integration effort with IAS MW and an overview of test results.

For Spiral 2B and 2C flight-testing, minimum separation criteria were established to ensure flight safety that struck a reasonable balance between collision risk or Near Mid-Air Collision (NMAC) violation, and satisfying research demands for the AFCM algorithm triggering. The resulting FPM and HPA encounter separation distances for encounter route planning were as follows:

- The SARA/OPV coaltitude (±150 feet): a 0.2-nautical mile separation at the closest point of approach (CPA).

- The SARA/OPV vertical separation >150 feet: 0.1-nautical mile separation at CPA.

At the speeds flown for the SARA and OPV (between 20 KGS to ~140 KGS, which equated to ~0 KIAS to 120 KIAS. These speeds drove very tight encounter route timing to not violate the separation criteria. If both aircraft were traveling at ~100 KGS (170 feet per second) and executing a 90-degree encounter, then the resulting closure rate would be 240 feet per second. So, only a 2.5-second timing error would equate to a 0.1- nautical mile position error in this case. For this reason of tight timing, combined with the obvious desire to execute many encounters at a wide variety of geometries in a reliable, efficient manner, the IAS team utilized the MW to auto-fly the SARA and OPV routes. Outside of the IAS Project most air-to-air encounter tests are set up and conducted manually, relying upon a combination of sensors (radar, ADS-B, visual, etc.) to ensure safety and to execute the varied encounter geometries, but these classic methods typically present problems in repeatability and efficiency. To preclude all these problems, the IAS team chose to utilize the MW-demonstrated conformance (from Spirals 1A, 1B, and 2A) to tight, special, and temporal routing constraints (recalling from the Spiral 1A discussion, nominally, the MW held timing to <0.5 seconds; ±50-feet lateral; and ±30-feet vertical). To provide additional safety through a layered approach, both aircraft were equipped with carry-on Stratus devices that relayed ADS-B data to handheld ForeFlight® tablets for display. In addition, within the GCS there was a NASA-Sikorsky display that provided a top-down view of the air display and provided current distance separation (horizontal and vertical) between the SARA and OPV as well a display of the nonplayer air traffic altitude and direction (ADS-B data).

An explanation and pictorial description of the methodology used to execute spiral 2B and 2C air-to-air encounter tests is as follows:

Step 1a. GCS/MWE and Test Conductor (TC): upon TC/MWE coordination, the MWE uplinks card-specified orbit locations from a preplanned set of orbit locations (a standard 3-degree per second turn).

Step 1b. As part of the GCS/MWE uplink, specify unique maneuver identification number (MW implements the run parameters associated with each unique encounter identification number) and utilize MW-computed winds to adjust the encounter ground or airspeed speed (ground speed used for HPA cards, indicated airspeed used for FPM cards).

- GCS review card with aircrew over radio.
- From the displayed MW-computed winds, GCS will specify the quantized wind speed and direction to the MW as part of the data upload to the SARA and OPV. This specification will slightly change the no-wind IP location (fig. E 14) and track slightly for FPM test runs.
- Before enabling the orbit and route for the aircraft, MW will verify the ability to exit both aircraft from their orbit and control the timing of the encounter trajectories/ routes for both aircraft to the necessary constraint.

Step 2: NASA pilots: select “Orbit Enable” on the tablet display and verify that a track to the orbit is displayed. The aircraft will auto-fly to its designated orbit location and establish an orbit. The display will show an “Orbit Idle” message when the aircraft reaches the orbit.

Step 3. NASA Pilots and TC: When both aircraft are in steady orbit and ready for the run, TC requests the NASA pilots to select “Ready Release” on the tablet display.

Step 4. MW: Following release, when MW coordinates between the two aircraft that each can reach wind-adjusted IP on track and speed, the entire flight path is presented to the NASA pilot, and after >10 seconds, the aircraft will begin flying a path to the IP location.
Step 5. MW: After reaching IP, both aircraft will fly to their respective start point (preplanned to be 10 seconds after IP) defined by MW as "T-0," then follow the planned route until the research software commands take over when triggered by either the ACAS-Xr or AOP algorithm, depending upon which run/card is being executed.

- Note: An ACAS-Xr triggered command could either be auto-flown by MW or hand flown via the SARA inceptors, depending upon what was prespecified by the maneuver identification number. The AOP triggered command can only be auto-flown.

Step 6. Upon conclusion of the run (either upon call from the TC for the pilot to select "Stop" or automatically by the MW), **MW** will roll the aircraft to wings level and hold current heading.

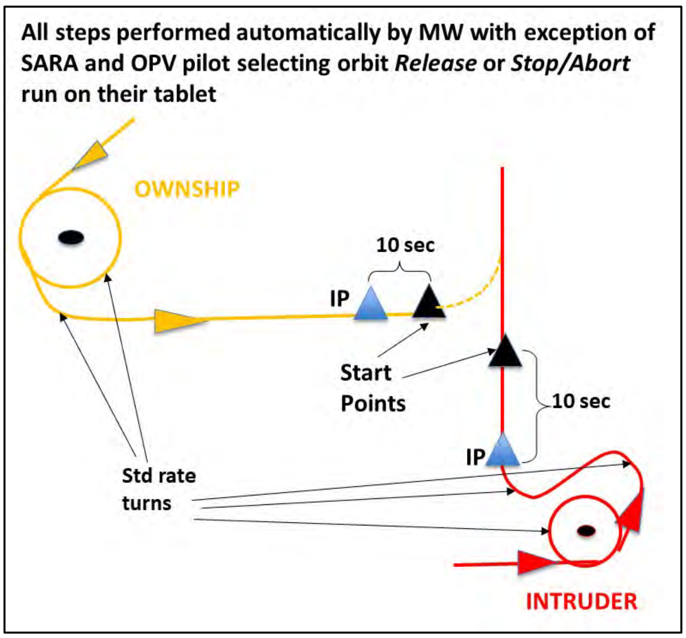


Figure E 14. Example air-to-air encounter methodology.

SPIRAL 2C (Project Capstone Tests)

Purpose and Objectives: The overall purpose of Spiral 2C as a Capstone event was to exercise the final versions of the AOP and ACAS-Xr algorithms in flight utilizing real aircraft as the ownship and the intruder to provide sufficient data to the HPA and FPM research teams ("sufficient" was agreed to between the IAS and AFCM test teams). Demonstrating iGCAS and auto-flown examples of UAM approaches to a Sikorsky auto-landing were additional lower-priority objectives of opportunity.

The FPM objectives were to verify selected functionality and performance of the AOP under simulated UML-4 conditions in flight, establish the functional technical readiness of the FPM evaluation toolset in a future UML-4 environment, and validate the system functional and performance requirements to refine correctness and completeness.

The HPA objectives were to demonstrate an automated tactical separation technology that could eventually be integrated into the strategic flight planning technology (FPM/AOP) and provide data to standards bodies RTCA to support development of a UAM tactical avoidance system. The main contribution from the HPA to the RTCA SC-147 and -228 for ACAS-Xr is pilot impressions and pilot feedback on ACAS-Xr viability, usability, and acceptability gleaned from real-time pilot-in-the-loop operations.

The test points/matrices for these Spiral 2C tests can be found in Appendix H and the system hazards/mitigations are provided in Appendix G.

Results Overview: The two-week flight-test deployment was very productive with 33 of 33 total HPA test points and 34 of 51 total FPM test points accomplished, having logged 28.5 total hours on the OPV and 24 hours on the SARA for these Spiral 2C tests. The AOP and ACAS-Xr generally performed their intended functions as expected, and the MW generally functioned as expected with some known problems and some intermittent networking problems (i.e., occasional AIOs and sporadic network problems, both of which contributed to the need to repeat a few test runs).

The aircrew never had a problem acquiring visual; typically, the first aircraft (usually SARA) acquired visual of the other aircraft while the two aircraft were still 4 to10 nautical miles away, and a mutual visual was typically acquired between 1.5 to7 nautical miles. General aviation traffic was frequent in the test area, especially around the southwest corner of the text box near Long Island (as shown in the flight-test areas in fig. 8. It was never necessary, however, to abort a test point and with the Sikorsky Eagle radar assistance, the team was always able to successfully monitor and communicate the traffic to test aircrew for deconfliction. The knock-it-off (KIO) criteria per mission rules (Appendix F) proved adequate for test safety; two total test points resulted in a KIO, one quite early on due to the OPV transponder being misconfigured, and the other late in an HPA structured-flagged encounter after the SARA had initiated the ACAS RA. In that case it appeared that the auto-RA maneuver would have prevented a collision but might not have provided the separation stipulated by the KIO criteria in our mission rules. That encounter is under further review by the HPA team to determine if the RA maneuver would have provided the desired/expected separation or if the maneuver was inhibited/minimized undesirably. Note: a table of the entire IAS test effort flight hours, aircrew, and dates are provided in Appendix D, and a detailed breakdown of just Spiral 2C is provided in Appendix H. All the prior spiral risk reduction efforts were shown to be helpful in reducing flight and technical risks, including the use of the NASA MW to precisely control the encounter timing for both aircraft to very tight FPM-driven levels, which was unlikely to be satisfied had the routes been flown manually or by relying solely upon supporting data/displays such as ForeFlight®/Stratus ADS-B display to setup encounters. Going into Spiral 2C there were five open DRs (none were safety critical).

Hardware/Software/Test Configuration: The Spiral 2B section provided a complete description of the test configuration also utilized for Spiral 2C. The HPA and FPM software configurations differed, however, from Spiral 2B in the greater number of preplanned encounter routes (51inches total) and the implementation of the final IAS versions of the algorithm. The Spiral 2C FPM included eight groups of tests (as opposed to only three in Spiral 2B) and the fine-tuning of their preplanned routes to accommodate winds from different headings and speeds in order to meet the constrained timing of <3 seconds at the CPA, all the while adhering to the SARA and OPV speeds specified to knots indicated airspeeds (KIAS), not ground speeds. The Spiral 2C HPA included five groups of cards (see Appendix H for FPM and HPA test matrices). There was a set of run/card geometries for each of the four HPA modes, plus another group of cards for low-speed/near-hover tests that had to be hand flown (including the setups via inceptors) instead of auto-flown via MW.

Lastly, there were quite a few differences between the Spiral 2C and 2B MW, but not in the overall test methodology to rely upon the MW to set up and fly the routes. Specifically, the Spiral 2C MW included the ability to select ADS-B (for HPA) and the OPV navigation data for FPM or for HPA if ADS-B was problematic – which it was not for Spiral 2C. Other differences were as follows:

- Ability to separate the encounter orbit locations for the SARA and OPV from their associated routes.
- Added/integrated iGCAS and auto-approaches (5-, 8-, 12-degree descents) with the MW.
- Incorporated DR fixes.

Test Description/Methodology: The test methodology described in the prior Spiral 2B section for using the MW to control the encounter setups, including orbiting at fixed locations until the two aircraft coordinated their timing for the encounter before releasing each aircraft to their respective start points (fig. E 14), was utilized for the Spiral 2C/Capstone tests. This method proved to be successful but did stress the data network at times due to the range from the antenna, resulting in sporadic problems necessitating run repeats in those cases. There was a set of HPA-encounter types added to Spiral 2C that resulted in a change to the test methodology utilized for those specific encounters. The Spiral 2C included a set of encounters in which the ownship/SARA flew at low-/near-hover speeds (20 KGS) oriented into the wind to ensure safe low speed flight while intruder/OPV approached SARA from the various called-for geometries. For these low-speed encounters, both aircraft were hand flown throughout the encounter until the ACAS software commanded the avoidance RA/TA maneuver. Figure E 15 shows a pictorial of the test method used for these low-speed HPA encounters. Since for these tests the ownship/SARA aircraft was moving very slow (20 KGS) the OPV aircrew were able to visually fly the encounters and provide the required HPA encounter geometry at the CPA after their onboard-handheld ADS-B device aided in setting up the encounter.

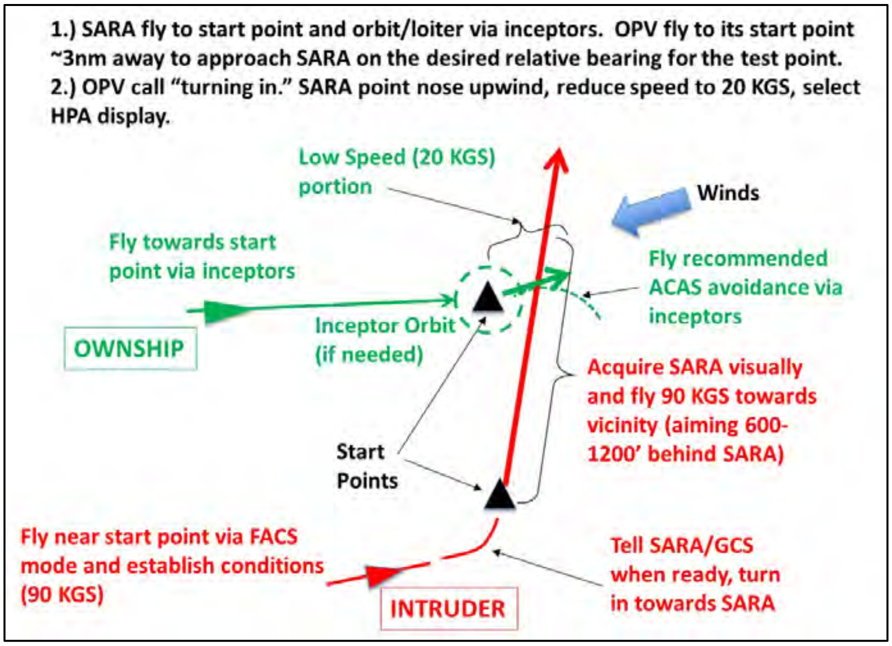


Figure E 15. The HPA low-speed test methodology.

Appendix F: MISSION RULES

The IAS team developed mission rules to ensure safe test conduct. The mission rules were especially helpful with planning the two-ship encounter tests. The rules evolved with the sequential IAS spirals. The encounter rules were informed by the rules, planning, and lessons learned documented in the UAS in the NAS test report. Below is the final set of rules used for the IAS Spiral 2C.

PREFLIGHT MISSION RULES

1	Missions will be conducted for IAW Sikorsky mission flight operations manuals, guides (Sikorsky FTOPS, etc.), and NASA AFOPs. If conflicts between the two exist, the combined test team will resolve the conflict, preferred consideration will be given to the most conservative/stringent procedure.
2	All mission cards shall be reviewed to ensure that all test points are within published vehicle limits and demonstrated safe via software tests in the NASA AFRC software-in-the-loop (SIL) or Sikorsky hardware-in-the-loop (HITL).
3	A preflight tabletop review shall be conducted, and the mission hazards briefed.
4	The NASA mission cards have been executed in either the NASA SIL or the Sikorsky HITL.
5	Day-of-flight procedures completed, any discrepancies dispositioned, and all required go-no-go systems/data have been verified as functional.

FLIGHT MISSION RULES

The IAS General Mission Rules

1	**IAS-Gen-01:** All test points shall remain within the published vehicle and the SARA-/OPV-engaged limits. *Rationale: This ensures safe operation of the aircraft.*
2	**IAS-Gen-02**: A knock-it-off will be called if any baseline vehicle aircraft limits are exceeded. In this context, the project is not referring to maneuvers that exceed the Sikorsky "smoother" research algorithms or the research system limiters that bring the aircraft back into limits. If, however, the S-76B (in the case of the SARA helicopter) and the S-70 (in the case of OPV) baseline limits or research system limits are exceeded in more than a transient manner, the vehicle will RTB. *Rationale: Ensures safe operation of the aircraft following inadvertent exceedance of aircraft/system limits.*
3	**IAS-Gen-03:** Missions shall be conducted during the day with visual meteorological conditions. All takeoffs and landings must occur between the published sunrise and sunset times of the airfield. *Rationale: Ensures good aircraft visibility from the ground and good lighting conditions for landings and takeoffs.*
4	**IAS-Gen-04:** No operations within 10 miles of lightning.
5	**IAS-Gen-05:** Continuous very high frequency (VHF) or ultra-high frequency (UHF) communication and data link between the SARA/OPV test helicopter and the Ground Control Station (GCS) shall be maintained for test runs. The vehicle shall KIO if communication and data link with the GCS cannot be restored following a loss. *Rationale: Safe test mission execution cannot be assured without voice communication with the aircrew.*
6	**IAS-Gen-06:** The SARA/OPV system engagement shall always occur within its experimental (X)-cert requirements (basically anywhere in Connecticut).

7	**IAS-Gen-07:** Flights with the SARA/OPV engaged shall not be conducted over densely populated areas and shall avoid congested airways (both per FAA X-certificate).
8	**IAS-Gen-08:** The mission go/no-go list (Appendix B) shall be utilized to determine a course of action in the case of loss of specific data, systems, et cetera.
9	**IAS-Gen-09:** Aircrew and Control Room personnel will monitor for potential low-frequency oscillations. The safety pilot shall determine when any oscillations exceed safety of flight conditions and call a KIO.

THE HPA/FPM ENCOUNTER MISSION RULES

1	The KIO/safe separation procedures will be established, captured in the test cards and reviewed before each encounter. The KIO procedures will be manually executed by the pilots.
2	The same planned KIO procedures will be applicable throughout the duration of a test run encounter. If the maneuvering aircraft is blind, pilots with visual will direct the maneuvering aircraft or maneuver their aircraft as required.
3	ForeFlight® (ADS-B) on pilot tablets in the cockpit; Sikorsky telemetry displays of downlinked aircraft avionics data in GCS; NASA middleware research displays in GCS; any other sources of ADS-B; and Eagle radar (when available) will all be used to maintain situational awareness on the location of each Sikorsky aircraft and surrounding traffic. The information source showing the least separation will be given prioritized consideration.
4	The test run will call a KIO if: 1) At least one pilot with access to flight controls does not obtain visual by 0.75nm (Rule 5) 2) Aircraft come within <0.25-nautical miles lateral and <500-feet vertical, unless the resolution maneuver has started, and separation is increasing. 3) Aircraft ever come within <0.25-nautical miles lateral and <250-feet vertical. 4) Any anomalous behavior occurs during a test run (Rule 8, 11).
5	The GCS will call out when aircraft achieve a 1-nautical mile separation by judging the distance primarily using the Sikorsky telemetry display. The test run will be knocked off if visual ID by at least one pilot in either aircraft is not acquired by 0.75 nautical miles (unless vertically separated by ≥ 500 feet, and in which case aircraft will not dwell vertically stacked), judging the distance primarily using the ForeFlight® tablet. The layered approach of using all available sources for overall SA in number 3 will be used.
6	1) All nominal HPA test point geometries will be designed to provide at least either 0.1-nautical miles lateral and 150-feet vertical separation; or 0.2-nautical miles lateral separation if at coaltitude. 2) Structured and terminal test point geometries will be designed with at least a 0.25-nautical mile lateral separation and a 250-foot vertical separation.
7	All FPM encounter geometries are coaltitude and will be designed with at least a 0.1-nautical mile lateral offset. All FPM test points will be knocked off with no less than a 0.25-nautical mile separation unless aircraft are separated vertically by ≥ 500 feet.
8	Test cards will include expected system behavior.
9	If any nonparticipating aircraft are observed within a 2,000-foot vertical separation and a 3-nautical mile lateral separation of either Sikorsky aircraft and cannot be determined to be a nonfactor, then the test run will be terminated. Any test team member may make observation. Terminate call at mission conductor or pilot discretion.

10	Altitude floor of 500-feet AGL will apply to encounter profiles.
11	Encounters will only be flown when the ownship and the intruder navigation accuracy is nominal, which is determined by the absence of any navigation related (EGI error) warning, caution, or advisory (WCA) messages. Navigation-related WCAs will result in knocking off the test run.
12	All encounters will be preprogrammed with latitudes, longitudes, and geometric altitudes for both vehicles defined using the GPS coordinate planes common to both vehicles. Note: encounter altitudes are defined using geometric altitude, and AFCM algorithms will be fed aircraft state data (i.e., intruder ADS-B) also referencing geometric altitude.
13	As tests unfold, the ownship will call out the aircraft trajectory changes as the AFCM deconfliction commands are generated. *Rationale: provide clear awareness to the intruder and GCS of the aircraft trajectory as it responds to the system under test (AOP/ACAS).*
14	Encounters require the horizon be visually discernible to both pilots.

THE IGCAS MISSION RULES

1	A minimum vertical clearance buffer of 1,500 feet will be used to demonstrate terrain avoidance. *Rationale: keep the helicopter high above the actual ground to prevent any chance of collision while still demonstrating full iGCAS functionality.*

DEPROACH MISSION RULES

1	Approaches/auto-lands will be flown in a build-up approach with respect to glideslope (shallower before steeper).
2	Approaches/auto-lands will use a minimum descent height / missed approach point of 200 feet – a missed approach will be executed at 200 feet if the pilot decides it is unsafe to continue with the approach.
3	Approaches/auto-lands will only be conducted with winds <30 knots.

The IAS team put considerable thought into developing clear knock-it-off (KIO) criteria as captured in the rules as well as the specific KIO procedure. The KIO procedure and rationale was as follows:

Procedure:

1) Both aircraft disengage following the trajectory during these circumstances:
    a. The SARA reverts to mechanical controls.
    b. The OPV reverts to Flight Augmentation and Cueing System (FACS).
2) The SARA crew recovers to wings level; zero Vertical Speed Indicator (VSI) and maintains; calls out via radio current GPS altitude and heading.
3) The OPV maneuvers to increase an altitude difference by 500 feet.
    a. If below SARA: descend to at least 500 feet below.
    b. If above SARA: climb to at least 500 feet above.

4) The OPV turns away from the SARA to a heading at least 90 degrees from the SARA heading.

Rationale:

- The SARA disengagement is a higher workload than the OPV disengage; crew has to recover to wings-level from current commanded attitude trajectory.
- The OPV crew is essentially "along for the ride" on a simple trajectory; they have more bandwidth to commence a maneuver.
- Appropriately dividing the workload between the crews improves SA for both crews.
- The OPV crew will always be keenly aware of rough azimuth of the SARA, facilitating an initial turn away of the OPV.
  - Once the SARA calls heading, the OPV can stop turn when 90-degrees apart.
  - As is the same with altitude, the OPV will know if they are already above or below SARA, so the OPV can start maneuver immediately. Once the SARA calls altitude, the OPV will know when to stop climb/descent.
- This approach is similar to how military formations are trained to react if sight is lost.
- One simple procedure increases likelihood of correct execution.

Appendix G: HAZARDS/MITIGATIONS

Flight research and test safety reviews were conducted for safety and mission assurance. Hazards were analyzed for probability and severity as well as causes, effects, and mitigations. The AFRC hazard analyses for Spiral 2C were as follows (previous spirals were a subset of these that are listed):

AFRC NC-IAS-1 Spiral 1 Hazard Count:

- Pathfinder hazard analysis was used as a baseline.
- Three hazards.
- No accepted risks.

AFRC NC-IAS-1 Spiral 2 Hazard Count:

- Spiral 1 hazard analysis was used as a baseline.
- Four new hazards.
- Total of seven Spiral 2 hazards.
- No accepted risks.

AFRC NC-IAS-1 Spiral 2 Hazard Summary	**Hazard Category: Human**	**Hazard Category: Asset/ Mission**
AFRC NC-IAS Spiral 2-01**:** Loss of Aircraft Control (updated for Spiral 2C)	**I E**	**I E**
AFRC NC-IAS Spiral 2-02**:** Disengagement of SARA System within Close Proximity to Ground	**II E**	**III E**
AFRC NC-IAS Spiral 2-05: Smoke & Fumes in the Cockpit from NASA Spiral 2 Required Hardware	**I E**	**I E**
AFRC NC-IAS Spiral 2-06: Loss of Separation leading to MIDAIR Collision with Intruder Aircraft	**I E**	**I E**
AFRC NC-IAS Spiral 2-07: Early Termination of a Test Profile	**IV E**	**III E**
AFRC NC-IAS Spiral 2-08: Automation Induced Oscillations	**IV C**	**IV C**
AFRC NC-IAS Spiral 2-09: Settling with Power/ Vortex Ring State	**I E**	**I E**

Hazard Categories: I Catastrophic; II Critical; III Moderate; IV Negligible; A Frequent; B Probable; C Occasional; D Remote; and E Improbable.

Advanced Air Mobility (AAM) National Campaign (NC-1)
IAS-1 Spiral 2 Flight Test Hazard Analysis

AFRC NC-IAS Spiral 2-01: Loss of Aircraft Control

Scenario Based Hazard Description: During NC IAS Spiral 2 flights, the SARA & OPV systems could experience an anomaly that causes a loss of aircraft control. As a result, damage/loss of aircraft and/or injury/death to aircrew could occur.

Causes

A. Anomaly/Failure in the SARA/OPV system.
B. Un-commanded SARA/OPV System Disengagement
C. An Un-commanded SARA/OPV System Engagement occurs.
D. SARA/OPV System performs erratically.
E. NASA Tablet is dropped by Pilot and Jams in the Flight Controls Linkage. (Not test unique)
F. Commanding an Auto-Approach/Auto-Land under certain flight conditions (i.e., down to 50 ft AGL) may lead to AIO.
G. Low Speed ACAS Xr maneuver performs erratically (planned at 1500 ft GPS)
H. IGCAS to simulate surface/descent towards water

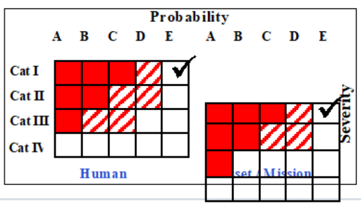
Effects

EF1. Damage/Loss of Aircraft (Non-NASA Asset)
EF2. Damage/Loss NASA of Assets
EF3. Injury/Death to Aircrew
EF4. Loss of Mission (RTB)

Mitigations

1. Triplex Monitoring Architecture (A, B, C, D, EF1 - EF4)
2. DO-178B Level A Monitor Software (A, B, C, D, EF1 - EF4)
3. Flight Instrument Panel shows positive control authority (B, EF1 - EF4)
4. Independent switch(s) to engage/disengage the SARA/OPV System (A, B, C, D, EF1 - EF4)
5. Multiple Disengagement mechanisms for SARA & OPV (A, B, C, D, EF1 - EF4)
6. Pilots will maintain vigilance for bringing devices on board the aircraft (E, EF1-EF4)
7. Wind Limits: ref. Mission Rule (30 knots). Aircrew and control room personnel will monitor for potential low-frequency oscillations. Any unacceptable sustained, unexpected or divergent oscillations of a magnitude that inhibits safe continued test execution or diminishes situational awareness shall be cause for KIO (RTB). Perform a Build Down & Decel. Speed M/W Approach to Hover at 50 feet altitude prior to conducting Flight Test Point. (F, EF1 – EF4)
8. Decel. To Low Speed to into the Wind, 20 knots ground speed Minimum (G, EF1-EF4)
9. For IGCAS points, if IGCAS does not trigger by Vertical Clearance Buffer, then KIO (H, EF1-EF4)

AFRC Hazard Action Matrices



Notes:
•During Spiral 2A the SARA/OPV Engage/Disengage functionality was demonstrated acceptably.
•During Autoland maneuvers, the M/W is commanding the aircraft only until 50' at which point the Sikorsky Autonomous Mission Manager controls the aircraft from 50' down to the ground, which is a maneuver that was completed in Spiral 1B as well as numerous times in the past by Sikorsky in their own testing.

Final Hazard Category Justification Statements

Final Severity Justification

Personnel: In the event of a loss of aircraft control, the aircrew could sustain a catastrophic injury.
NASA Asset/Mission: In the event of a loss of aircraft control resulting in damage or loss of aircraft, NASA assets could be damaged or lost, and as a result, the project could incur costs of up to $20K per Aircraft. In addition, the cost of an RTB (< $50K) has also been factored in.
Non-NASA Asset: In the event of a loss of aircraft control with either the SARA/OPV, damage or loss of aircraft could occur. The contractor has valued these assets to be at approximately $2M each.

AFRC NC-IAS Spiral 2-02: Disengagement of SARA System within Close Proximity to Ground

Scenario Based Hazard Description: During NC IAS Spiral 2 flights, the SARA system could disengage resulting in the pilot experiencing Heavy Flight Controls and Unexpected Handling Qualities. As a result, a Hard Landing could occur leading to damage of the Aircraft and/or injury to the Aircrew.

Causes

A. Unexpected SARA System Disengagement:
  - Surface Hard-Over
  - Rate limit exceeded

B. Manual Disengagement for Safety of Flight

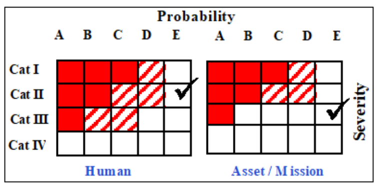
Effects

EF1. Heavy Flight Controls
EF2. Damage to Aircraft (Non-NASA Asset)
EF3. Damage to NASA Assets
EF4. Injury to Aircrew

Mitigations

1. SARA performs an automatic disengage upon detection of out-of-bounds data, the Safety Pilot will detect/react to an IAS Middleware anomaly and take control from SARA (A, B, EF1 - EF4)
2. The Safety Pilot has training and familiarity with aircraft characteristics during SARA Engagement/Disengagement (A, B, EF1 - EF4)

AFRC Hazard Action Matrices



Notes:
- OPV is Fly-by-Wire and is not a factor for this hazard

Final Hazard Category Justification Statements

<u>**Final Severity Justification**</u>

Personnel: In the event of a SARA system disengagement resulting in a transient with possible Heavy Flight Controls and Unexpected Handling Qualities , the aircrew could sustain a critical injury as a result of a hard landing.

NASA Asset: In the event of a Hard Landing, minimal damage or losses to NASA assets is expected, the project could incur costs of up to $20K.

Non-NASA Asset: In the event of a Hard Landing, damage to the SARA aircraft could occur and would be expected to exceed $50K

<u>**Final Probability Justification**</u>

Personnel/Asset: The SARA flight critical systems are triple redundant. All flight critical software in SARA has been developed to DO - 178B Level A, and all flight critical hardware has been qualified to DO-160 and DO-254 Level A. In addition, SARA has conducted > 500 flight test hours. Therefore, the project considers the likelihood of this hazard being realized to be improbable. Consequently, damage/loss of NASA assets and/or loss of mission is considered to be the same.

Rev. 9-28-2023

Advanced Air Mobility (AAM) National Campaign (NC-1)
IAS-1 Spiral 2 Flight Test Hazard Analysis

AFRC NC-IAS Spiral 2-05: Smoke and Fumes in the Cockpit from Spiral 2 NASA Required Hardware
Scenario based hazard description: The Aircrew Experiences Smoke and Fumes due to Malfunctioning NASA Spiral 2 Equipment.

Causes

A. Malfunction of NASA Equipment
B. Short Circuit of Wiring or Avionics Components

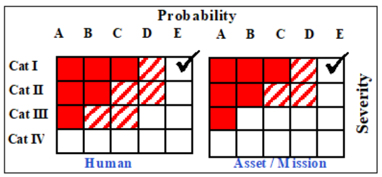
Effects

EF1. Damage/Loss of Aircraft (Non-NASA Asset)
EF2. Damage/Loss of NASA Assets.
EF3. Injury/Death to Aircrew/NASA Personnel.
EF4. Loss of Mission (RTB)

Mitigations

1. Ensure NASA Equipment is installed and checked out on Sikorsky SARA/OPV per Test Aircraft Management Document and Novatel/NUC Electrical Drawings. (A, B, EF1 - EF4)
2. Perform NASA Equipment Ground Checks to ensure correct operation prior to IAS Spiral -2 Flight Test Activities. (A, B, EF1 - EF4)
3. If Smoke & Fumes are present during Flight Testing, execute S76B/S70 Rotor-Craft Flight Manual Emergency Procedures for Smoke & Fumes (Including pulling associated circuit breaker and landing as soon as practicable). (EF1 - EF4)
4. The NASA Equipment will be operated in a thermal environment below the 140-degree F Operating Limit. (A, B, EF1 - EF4)
5. A fire extinguisher is on-board. (EF1 - EF4)

AFRC Hazard Action Matrices



Final Hazard Category Justification Statements

<u>Final Severity Justification</u>
Personnel: In the event of a loss of aircraft control, the aircrew could sustain a catastrophic injury.
NASA Asset/Mission: In the event of a loss of aircraft control resulting in damage or loss of aircraft, NASA assets could be damaged or lost, and as a result, the project could incur costs of up to $20K per Aircraft. In addition, the cost of an RTB (< $50K) has also been factored in.
Non-NASA Asset: In the event of a loss of aircraft control with either the SARA/OPV, damage or loss of aircraft could occur. The contractor has valued these assets to be at approximately $2M each.
<u>Final Probability Justification</u>
Personnel/Asset: The SARA/OPV flight critical systems are triple redundant. All flight critical software in SARA/OPV has been developed to DO - 178B Level A, and all flight critical hardware has been qualified to DO-160 and DO-254 Level A. In addition, SARA has conducted > 500 flight test hours, and OPV has conducted > 290 flight test hours. Therefore, the project considers the likelihood of this hazard being realized to be improbable. Consequently, damage/loss of NASA assets and/or loss of mission is considered to be the same.

Rev. 9-28-2023_Draft

Advanced Air Mobility (AAM) National Campaign (NC-1)
IAS-1 Spiral 2 Flight Test Preliminary Hazard Analysis

AFRC NC-IAS Spiral 2-06: Loss of Separation leading to MIDAIR Collision with Intruder Aircraft

Scenario based hazard description: During Spiral Flight Testing an Intruder Aircraft will be utilized to exercise Middleware, HPA & FPM algorithms on SARA with intentional airspace conflicts between the two. A miscalculation/error in Test Planning could lead to a MIDAIR Collision. This hazard is only applicable to Spiral 2B & 2C.

Causes

A. Pilot makes an unexpected/unsafe maneuver in the direction of the intruder (e.g., Human Error)
B. Loss of SARA/OPV Situational Awareness
C. Non-Player Aircraft penetrates Test Airspace
D. Inaccurate NAV Solution on aircraft
E. Unexpected Behavior from the S/W under test
F. Unexpected Behavior from the H/W under test

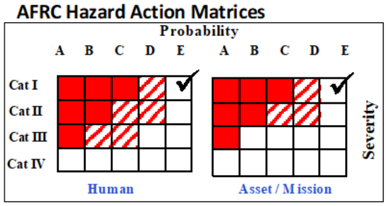
Effects

EF1. Damage/Loss of Aircraft(s) (Non-NASA Assets)
EF2. Damage/Loss of NASA Assets
EF3. Injury/Death to Aircrew
EF4. Loss of Mission (RTB)

Mitigations

1. Cross-check the NASA Research Tablet with Primary Cockpit Displays, ADS-B, Eagle Control, Safety Pilot. (A, B, C, D, E, F, EF1 - EF4)
2. Time Tags mitigate Stale Data on the NASA Tablet (E, F, EF1 - EF4)
3. Perform Altitude Crosschecks between SARA & Intruder Aircraft during preflight & during the mission (A, B, C, D, E, F, EF1 - EF4)
4. Expect visual acquisition of Intruder by 1 NM, required by ¾ NM separation, knock-it-off (Mission Rule) (A, B, C, EF1 - EF4)
5. Automated encounters are referenced to GPS ALT, which is displayed to the pilot on both Aircraft (A, B, E, F, EF1 - EF4)
6. Test set-ups with S/W AGL Offsets (HIGHER from GND) will be validated prior to execution (E, EF1 - EF4)
7. Pre-Flight Briefing including Mission Rules & Knock it Off Criteria (A, B, C, EF1 - EF4)
8. If a non-player aircraft is within 3 NM and within Altitude safety box (2000 ft of the formation) and it cannot be determined that they are not in a conflict, then this results in a knock-it-off (rely on Eagle radar and own-ship's commercial ADS-B) (C, EF1 - EF4)
9. Altitude Floor utilization of 500 ft during Intruder maneuvering (A & B, EF1 - EF4)
10. Encounters are designed to minimum separation (A, B, E, F, EF1 - EF4)
11. System Under Test H/W integrated per Sikorsky MDSC Process (F, EF1 - EF4)
12. System Under Test H/W designed & reviewed per best engineering practices (F, EF1 - EF4)
13. Pilot FAM & Orientation for System under Test (E, F, EF1 - EF4)
14. Test Cards includes Expected Behavior & Knock it Off Procedures (E, F EF1 - EF4)
15. Aircraft Pre-flight determines NAV solution Quality, WCAs call out NAV degradation, Knock it Off (D, EF1 - EF4)
16. All S/W is tested and Simulated prior to Flight Test (E, EF1 - EF4)

AFRC Hazard Action Matrices



Final Hazard Category Justification Statements

Final Severity Justification
Personnel: In the event of a MIDAIR Collision, the aircrew could sustain a Catastrophic Injury.
NASA Asset/Mission: In the event of a MIDAIR Collision resulting in damage or loss of aircraft, NASA assets could be damaged or lost, and as a result, the project could incur costs of up to $20K per Aircraft. In addition, the cost of an RTB (< $50K) has also been factored in.
Non-NASA Asset: In the event of a MIDAIR Collision with either the SARA/OPV, damage or loss of aircraft could occur. The contractor has valued these assets to be at approximately $2M each.
Final Probability Justification
Personnel/Asset/Mission: The SARA/OPV flight critical systems are triple redundant. All flight critical software in SARA/OPV has been developed to DO - 178B Level A, and all flight critical hardware has been qualified to DO-160 and DO-254 Level A. In addition, SARA has conducted > 500 flight test hours, and OPV has conducted > 290 flight test hours. Therefore, the project considers the likelihood of this hazard being realized to be improbable. Consequently, damage/loss of NASA assets and/or loss of mission is considered to be the same.

Rev. 9-28-2023

Advanced Air Mobility (AAM) National Campaign (NC-1)
IAS-1 Spiral 2 Flight Test Hazard Analysis

AFRC NC-IAS Spiral 2-07: Early Termination of a Test Profile

Scenario Based Hazard Description: During NC IAS-1 Spiral 2 flights, the SARA/OPV system could experience an anomaly that causes an Early Termination of a Test Profile, RTB

Causes

A. Outer-loop Command Anomaly from Experimental S/W into SARA/OPV VMC.
B. NASA Middleware Anomaly (e.g., Stale Data, Misleading Information displayed to the Crew, Incorrect Output)
C. Unintended Vehicle Response to Commands
D. Unexpected Maneuver from Middleware
E. NASA Tablet Freezes/INOP
F. Loss of Link

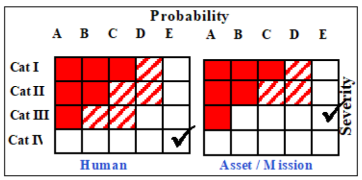
Effects

EF1. Unintended Flight Path
EF2. Aircrew Discomfort
EF3. Loss of Mission (RTB)

Mitigations

1. Triplex Monitoring Architecture (A, B, C, D, EF1 - EF3)
2. DO-178B Level A Monitor Software (A, B, C, D, EF1 - EF3)
3. Flight Instrument Panel shows positive control authority (C, EF1)
4. Independent switch(s) to engage/disengage the SARA/OPV System, RTB (A, B, C, D, E, EF1 - EF3)
5. SARA/OPV performs an automatic disengage upon detection of out-of-bounds data, Safety Pilot will detect/react to S/W Middleware anomaly and take control from SARA/OPV, RTB (A, B, C, D, E, EF1 - EF3)
6. Safety Critical H/W & S/W Partitioning will prevent corruption of SARA/OPV Flight Control Laws (A, B, C, D, E, EF1 - EF3)
7. HPA & FPM V&V S/W Testing (A, B, C, D, E, EF1 - EF3)
8. Carry Spare NASA Tablet (E, EF1)
9. System Under Test H/W integrated per Sikorsky MDSC Process (A, B, C, D, E, EF1 - EF3)
10. System Under Test H/W designed & reviewed per NASA best engineering practices (A, B, C, D, E, EF1 - EF3)
11. All S/W will be tested and Simulated prior to Flight Test (A, B, C, D, E, EF1 - EF3)
12. Reposition aircraft for better TM coverage to reacquire Data Link (F, EF1)

AFRC Hazard Action Matrices



Notes:

- Stale/Incorrect HPA/FPM Data displayed to Aircrew from the Tablet was considered at the SSWG, but the NASA Tablet is NOT being used to maintain Safe Separation or as a Safety Critical Flight Display. It is a System Under Test.
- During Spiral 2A the OPV Engage/Disengage functionality worked acceptably.

Final Hazard Category Justification Statements

Final Severity Justification

Personnel: In the event of a SARA/OPV Anomaly, the Aircrew could experience Discomfort.
Mission: In the event of a Loss of Mission (RTB), the project is not expected to incur costs that exceed $50K.

Final Probability Justification

Personnel/Asset: The SARA/OPV flight critical systems are triple redundant. All flight critical software in SARA/OPV has been developed to DO - 178B Level A, and all flight critical hardware has been qualified to DO-160 and DO-254 Level A. In addition, SARA has conducted > 500 flight test hours, and OPV has conducted > 290 flight test hours. Therefore, the project considers the likelihood of this hazard being realized to be improbable. Consequently, damage/loss of NASA assets and/or loss of mission is considered to be the same.

Rev. 9-28-2023

Advanced Air Mobility (AAM) National Campaign (NC-1)
IAS-1 Spiral 2 Flight Test Hazard Analysis

AFRC NC-IAS Spiral 2-08: Automation Induced Oscillations

Scenario Based Hazard Description: During NC IAS-1 Spiral 1 flights, the SARA system experienced oscillations, that can cause rider discomfort. This could happen on OPV Fly by Wire as well.

Causes

A. Velocity vs. Time Calculations translation in Middleware leads to oscillations
B. Route Trajectory Points Density is insufficient to represent the route.

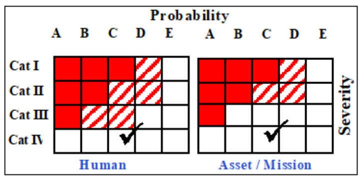
Effects

EF1. Aircrew Discomfort
EF2. Loss of Mission (RTB)

Mitigations

1. SARA/OPV performs an automatic disengage upon detection of out-of-limits data, Safety Pilot will detect/react to S/W Middleware anomaly and take control from SARA/OPV (A, B, EF1, EF2)
2. Independent switch(s) to engage/disengage the SARA/OPV System (A, B, EF1, EF2)
3. Aircrew and control room personnel will monitor for potential low-frequency oscillations. Any unacceptable sustained, unexpected or divergent oscillations of a magnitude that inhibits safe continued test execution or diminishes situational awareness shall be cause for KIO (RTB) (A, B, EF1, EF2)

AFRC Hazard Action Matrices



Notes:

- Pathfinder Flight Test demonstrated SARA Engage / Disengage Functionality worked acceptably.
- During Spiral 2A the OPV Engage/Disengage functionality was demonstrated.
- This will be monitored to ensure it does not escalate into a higher hazardous situation.

Final Hazard Category Justification Statements

Final Severity Justification

Personnel: In the event of Automation Induced Oscillations, the aircrew could sustain Aircrew Discomfort.

Mission: In the event of a Loss of Mission (RTB), the project is not expected to incur costs that exceed $50K.

Final Probability Justification

Personnel/Mission: The SARA/OPV flight critical systems are triple redundant. All flight critical software in SARA/OPV has been developed to DO - 178B Level A, and all flight critical hardware has been qualified to DO-160 and DO-254 Level A. In addition, SARA has conducted > 500 flight test hours, and OPV has conducted > 290 flight test hours. This is a corner condition based on high winds aloft causing slow SARA/OPV speed. When higher speeds are established, this condition goes away. Therefore, the project considers the likelihood of this hazard being realized to be improbable.

Rev. 9-28-2023

Advanced Air Mobility (AAM) National Campaign (NC-1)
IAS-1 Spiral 2 Flight Test Preliminary Hazard Analysis

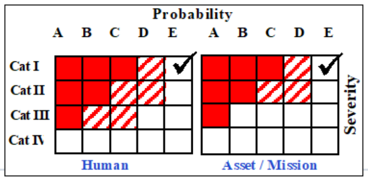
AFRC NC-IAS Spiral 2-09: Settling with Power / Vortex Ring State

Scenario Based Hazard Description: During NC IAS-1 Spiral 2 flights, the SARA/OPV aircraft could experience Settling with Power / Vortex Ring State that could lead to a loss of aircraft control. As a result, damage/loss of aircraft and/or injury/death to aircrew could occur.

Causes

A. Commanding a rapid deceleration under certain flight conditions may lead to Settling with Power / Vortex Ring State.

AFRC Hazard Action Matrices



Effects

EF1. Damage or Loss of Aircraft (Non-NASA Asset)
EF2. Damage or Loss of NASA Assets
EF3. Injury or Death to Aircrew
EF4. Loss of Mission (RTB)

Mitigations

1. Pilot Situational Awareness, Knock it off (RTB) (A, EF1 - EF4)
2. Pilots are trained to recover from VRS through standard piloting techniques (A, EF1 - EF4)

Notes:

- The autopilot system was originally developed by Sikorsky Aircraft as part of UH60M Fly-By-Wire program. It has been reused for S-70 OPV, with minor adjustments to gains / control laws. The UH60M Fly-By-Wire program was developed to DO-178B Level A/C standards. The S-70 OPV implementation has been through over 290 flight hours of flight test, in addition to the over 500 flight hours accomplished during the UH-60M FBW program.
- During Spiral 2A the OPV Engage/Disengage functionality was demonstrated.
- VRS is a common phenomena that can occur under a variety of conditions for all helicopters, even when only Class A software is commanding the aircraft (i.e., not specific to the SARA/OPV automation capabilities). While the Middleware never caused the aircraft to get into VRS, a discussion occurred that caused the team to change the middleware such that it never commands an aggressive deceleration and descent combination to ensure that the middleware does not put the helicopter into conditions that could lead to VRS. So, while the team no longer deems this a test-specific hazard, it was decided to keep it in the list to ensure any middleware changes that may be made in the future incorporate VRS into consideration.
- The Middleware is designed to not command rapid Deceleration/Descent Commands at the same time.

Final Hazard Category Justification Statements

Final Severity Justification

Personnel: In the event of Settling with Power / Vortex Ring State, the aircrew could sustain a catastrophic injury.

NASA Asset/Mission: In the event of Settling with Power / Vortex Ring State, resulting in damage or loss of aircraft, NASA assets could be damaged or lost, and as a result, the project could incur costs of up to $20K per Aircraft. In addition, the cost of an RTB (< $50K) has also been factored in.

Non-NASA Asset: In the event of Settling with Power / Vortex Ring State, with either the SARA/OPV, damage or loss of aircraft could occur. The contractor has valued these assets to be at approximately $2M each.

Final Probability Justification

Personnel/Asset: Though theoretically possible for damage or loss of aircraft and/or injury/death to aircrew to occur as a result of Settling with Power / Vortex Ring State, pilot situational awareness, required training, and a change to the middleware such that it never commands an aggressive deceleration and descent combination to ensure that the middleware does not put the helicopter into conditions that could lead to VRS, makes the likelihood of an occurrence to be improbable.

Appendix H: SPIRAL 2C TEST MATRICES/DESCRIPTIONS

HPA Test Organization Summary

There were five categories/types of HPA test points:

Collision Avoidance System (CAS) (legacy configuration):

- Crewed class of Xr, similar to TCAS II – collision avoidance (CA) only.
- Anticipates an onboard pilot receiving caution-level alerting without guidance (traffic advisories or TAs) and warning-level alerting and guidance (RAs) in the vertical and horizontal dimension.
- Pilots do not maneuver from TAs; only preparatory for possible RAand to help visually acquire traffic.
- RAs are warning-level alerts that command specific maneuvers that must be flown.

Detectand Avoid (DAA) Configuration:

- Uncrewed class of Xr, similar to Airborne Collision Avoidance System – for unmanned aircraft (ACAS-Xu): DAA + CA.
- Caution-level DAA alerting and guidance replaces TAs. Pilots may manually maneuver using DAA suggestive bands.
- RAs issued if DAA threat not resolved.

DAA with Terminal Area Label – DAA with vertical RA-only alerting.

- Vertical RAs based on terminal area DWC criteria - reduced sensitivity compared to enroute.
- Inhibits descends, increase descends and do-not-descends.
- No caution-level alerting/guidance, only warning-level RAs.
- Results in later RAs closer to closest point of approach CPA.
- DAA with Structured Label – horizontal RA and vertical RA-only alerting.
- This label represents targets in urban airspace with densely structured traffic patterns.
- Horizontal and vertical RAs have reduced sensitivity.
- No caution-level alerting/guidance, only warning-level RAs.
- Results in later RAs closer to closest point of approach CPA.

Low Speed DAAand CAS – Tests with ownship at low speed (20 KGS) – No MW, hand flown using available ALIAS automation.

The HPA test point matrix was as follows:

Card identifiers: **C**=CAS, **D**= DAA, **T**= Terminal, **S**= Structured, **L**=low speed

HPA 2C Test Matrix

										Ownship			Intruder							Sim Results					
Card	Priority	V&V	Pilot Sim	ACAS Config	Intruder Flag	Ownship Maneuver	Intruder Maneuver	AGL Offset	Disengage Automation	Geo Alt Start	Geo Alt CPA	GS	Geo Alt Start	Geo Alt CPA	GS	Rel. Alt	App. Angle	Horiz. Miss Dist.	Expected RA	Sec. to CPA	Sec. to TA/ DAA	nmi at TA/ DAA	Sec. to RA	nmi at RA	Encounter Description
C1	1	Yes		CAS	Nominal	None	None	0	No	3000	3000	90	3000	3000	90	0	180	0.2	Right	150	70	4	100	2.5	Co-altitude, head-on
C2	1			CAS	Nominal	None	None	0	No	3000	3000	90	2850	2850	90	-150	-45	0.1	Climb	150	60	1.75	80	2.5	Overtake with nominal offsets
C3	2		Yes	CAS	Nominal	None	None	0	No	3000	3000	90	3000	3000	90	0	-90	0.2	Climb	150	70	2.75	90	2	Crossing with Climb RA
C4	1	Yes		CAS	Nominal	None	None	-2600	No	3000	3000	90	3250	3250	90	250	135	0.1	Descend	150	70	3	90	2.5	AGL offset with Descend RA
C5	1	Yes		CAS	Nominal	None	None	0	Yes	3000	3000	90	3150	3150	90	150	-135	0.1	Descend	150	70	3.75	90	2.5	Intentional auto-RA disengagement for manual RA
C6	3		Yes	CAS	Nominal	None	None	-2600	No	3000	3000	90	3250	3250	90	250	180	0.1	Descend	150	70	3.75	90	2.5	Additional AGL offset with Descend RA encounter
C7	3		Yes	CAS	Nominal	None	None	0	Yes	3000	3000	90	2850	2850	90	-150	-90	0.1	Climb	150	70	2.75	85	2.5	Additional auto-RA disengagement encounter
C8	3		Yes	CAS	Nominal	None	None	0	Yes, then re-engage	3000	3000	90	2850	2850	90	-150	180	0.1	Climb	150	70	3.75	90	2.5	Additional auto-RA disengagement - pilot will *re-engage Auto RA* function while RA is still active
D1	1	Yes		DAA	Nominal	None	None	0	No	3000	3000	90	3000	3000	90	0	180	0.2	Right & Descend	150	50	5	100	2	Co-altitude, head-on
D2	1		Yes	DAA	Nominal	None	None	0	No	3000	3000	90	2850	2850	90	-150	-45	0.1	Climb	150	50	2	80	1.25	Overtake with nominal offsets
D3	2		Yes	DAA	Nominal	None	None	0	No	3000	3000	90	3000	3000	90	0	-90	0.2	Climb	150	55	3	85	2.5	Crossing with Climb RA
D4	1			DAA	Nominal	None	None	0	No	3000	3000	90	3250	3250	90	250	135	0.1	Descend	150	55	4	90	2.5	AGL offset with Descend RA
D5	1		Yes	DAA	Nominal	None	None	0	No	3000	3000	90	3500	3500	90	500	-90	0.1	N/A	150	N/A	N/A	N/A	N/A	Preventive DAA alert encounter (*should* result in no DAA/RA alert)
D6	3			DAA	Nominal	None	None	0	No	3000	3000	90	3250	3250	90	250	180	0.1	Descend	150	55	5	90	2.5	Additional AGL offset with Descend RA encounter
D7	3			DAA	Nominal	None	None	0	No	3000	3000	90	2500	2500	90	-500	135	0.1	N/A	150	N/A	N/A	N/A	N/A	Additional preventive DAA alert encounter (*should* result in no DAA/RA alert)
T1	1	Yes		DAA	Terminal	Descend	None	-1100	No	3000	1500	90	1250	1250	90	-250	180	0.1	Climb	150	N/A	N/A	120	1.25	Pilot in descent, terminal area intruder will go straight to RA
T2	1			DAA	Terminal	Descend	None	-1100	Yes	3000	1500	90	1250	1250	90	-250	-90	0.1	Climb	150	N/A	N/A	120	1	Pilot in descent, terminal area intruder goes straight to RA. Auto-RA disengaged
T3	1		Yes	DAA	Terminal	Descend	None	-1100	No	3000	1500	90	1250	1250	90	-250	-135	0.1	Climb	150	N/A	N/A	115	1.5	Pilot in climb, terminal area intruder goes straight to RA. Auto-RA disengaged
T4	2		Yes	DAA	Terminal	Climb	None	-1100	No	1500	3000	90	3250	3250	90	250	90	0.1	Level Off	150	N/A	N/A	120	1	Pilot in descent, terminal area intruder will go straight to RA
T5	2		Yes	DAA	Terminal	Climb	None	-1100	Yes	1500	3000	90	3250	3250	90	250	180	0.1	Level Off	150	N/A	N/A	120	1	Pilot in descent, terminal area intruder will go straight to RA
S1	1			DAA	Structured	None	None	-2100	No	3000	3000	90	3250	3250	90	250	180	0.1	Descend	150	N/A	N/A	120	1	Structured airspace intruder will go directly to RA
S2	1			DAA	Structured	None	None	-2100	No	3000	3000	90	3250	3250	90	250	135	0.1	Level Off	150	N/A	N/A	130	1	Structured airspace intruder will go directly to RA
S3	1	Yes		DAA	Structured	None	Climb	-1100	No	3000	3000	90	1500	2750	90	-250	-135	0.1	Climb	150	N/A	N/A	120	1.5	Intruder climbing toward ownship's altitude. Structured airspace intruder will go directly to RA
S4	2		Yes	DAA	Structured	None	Descend	-1100	No	1500	1500	90	3000	1750	90	250	180	0.1	Descend	150	N/A	N/A	120	1.5	Intruder descending toward ownship's altitude. Structured airspace intruder will go directly to RA
S5	2		Yes	DAA	Structured	None	Climb	-1100	Yes	3000	3000	90	1500	2750	90	-250	-90	0.1	Climb	150	N/A	N/A	110	1	Intruder climbs toward ownship's alt. Structured airspace intruder goes directly to RA. Auto-RA off.
L1	1	Yes		CAS	Nominal	None	None	0	N/A	1500	1500	20	1500	1500	90	0	180	0.2	Right	120	40	2.5	50	2.5	Both a/c flown fully by inceptors (auto-RA disabled). Pilots manually fly RA when issued
L2	1		Yes*	CAS	Nominal	None	None	0	N/A	1500	1500	20	1350	1350	90	-150	-90	0.1	Right	120	40	2.3	54	2	Both a/c flown fully by inceptors (auto-RA disabled). Pilots manually fly RA when issued
L3	1		Yes*	CAS	Nominal	None	None	-1100	N/A	1500	1500	20	1650	1650	90	150	45	0.1	Descend	120	40	2	60	1.5	Both a/c flown fully by inceptors (auto-RA disabled). Pilots manually fly RA when issued
L4	2			CAS	Nominal	None	None	0	N/A	1500	1500	20	1750	1750	90	250	-135	0.1	Descend	120	40	2.4	60	2	Both a/c flown fully by inceptors (auto-RA disabled). Pilots manually fly RA when issued
L5	1		Yes*	DAA	Nominal	None	None	0	N/A	1500	1500	20	1500	1500	90	0	180	0.2	Right	120	25	2.7	50	2	Both a/c flown fully by inceptors (auto-RA disabled). Pilots manually fly DAA and possible RA guidance
L6	1		Yes*	DAA	Nominal	None	None	0	N/A	1500	1500	20	1350	1350	90	-150	-90	0.1	Right	120	25	2.5	45	2	Both a/c flown fully by inceptors (auto-RA disabled). Pilots manually fly DAA and possible RA guidance
L7	1			DAA	Nominal	None	None	0	N/A	1500	1500	20	1650	1650	90	150	45	0.1	Descend	120	25	2.1	60	2.5	Both a/c flown fully by inceptors (auto-RA disabled). Pilots manually fly DAA and possible RA guidance
L8	2			DAA	Nominal	None	None	0	N/A	1500	1500	20	1750	1750	90	250	-135	0.1	Descend	120	30	2.6	60	2	Both a/c flown fully by inceptors (auto-RA disabled). Pilots manually fly DAA and possible RA guidance

The FPM Test Organization Summary

The FPM identified 51 test points organized in eight groups (table H 1, second column). The different groups involved slightly different parameters, test methods and evaluation criteria.

Group 1 was to test the AOP conflict detection as the encounter progresses without the pilot executing a resolution. The pilot would only preview the different resolutions that were provided without executing any.

Group 2 was to test AOP conflict resolution; this group involved the same encounter geometries from Group 1, but the pilot would execute a resolution from the first set.

Group 3 was to test Required Time of Arrival (RTA) change compliance and involved the SARA only; OPV was not required. In Group 3 test points, the SARA was given a new RTA ±1 min, and the test was to verify that AOP identifies the problem and provides a new trajectory free of conflicts to meet the new RTA.

Group 4 involved RTA changes in the presence of a traffic conflict with OPV. The SARA RTA was changed, and the test were to verify AOP detections, create a new trajectory to meet the new RTA, resolve the traffic conflicts, and relax the RTA to resolve a conflict if both aren't possible.

Group 5 was to assess the performance of different AOP time horizons and conflict resolution refresh rates and identify tradeoffs.

Group 6 involved intruder intent change stressor encounters, where the conflicts occurred inside the AOP conflict detection look-ahead horizon.

Group 7 was to test conflict resolution and prevention in UAM traffic corridors. These test points did not involve any additional AOP functionality. The AOP always avoids special use airspace (SUA) to compute resolutions and in this case, the aircraft was surrounded virtually by SUA (which creates a corridor), so the AOP options are restricted. Test points involved the following encounters: 1) merging trajectories; 2) delaying the arrival time via a slow-down or path alteration maneuver once the ownship exits the corridor; and 3) head-on trajectories.

Group 8 involved high-traffic density stressors. Simulated traffic was increased to the higher end of the UML-4 traffic range. The tests were to assess stability, effectiveness, domino effect, sensitivities, and computational requirements for AOP.

The FPM test point matrix is shown in table H 1.

Table H 1. FPM test matrix.

IAS-1 FPM Flight Test Experiment Matrix																
TC Matrix			Variable Parameters				Scenario Overview		Ownship - Zero Winds				Intruder - Zero Winds			
Test Point No.	Test Group	Mnvr No.	AOP Config	Bkgd Traffic	RTA Change	Intruder Intent Change	Description	Encounter Type	Ownship Vert.	Ownship Initial Alt	Ownship Initial IAS	Ownship End Alt	Intruder Vert.	Intruder Initial Alt	Intruder Initial IAS	Intruder End Alt
										feet	kts	feet		feet	kts	feet
1	1	1	Nominal	Nominal	None	None	Traffic Conflict. Includes SUAs. Ownship lateral TCP. Intruder Lateral TCP.	Crossing	Level	2000	96	2000	Level	2000	96	2000
2		2	Nominal	Nominal	None	None	Traffic Conflict. Includes SUAs. Intruder Lateral TCP.	Head-on	Level	2000	96	2000	Level	2000	96	2000
3		3	Nominal	Nominal	None	None	Traffic Conflict. Includes SUAs. Intruder Lateral TCP.	Acute crossing	Level	2000	96	2000	Level	2000	96	2000
4		4	Nominal	Nominal	None	None	Traffic Conflict. Includes SUAs. Intruder Lateral TCP.	Intruder Overtake	Level	2000	96	2000	Level	2000	106	2000
5		5	Nominal	Nominal	None	None	Traffic Conflict. Includes SUAs. Intruder Lateral TCP.	Ownship Overtake	Level	2000	96	2000	Level	2000	85	2000
6		6	Nominal	Nominal	None	None	Traffic Conflict. Includes SUAs. Ownship lateral TCP. Intruder Lateral TCP. Intruder descends throug	Crossing	Level	2000	96	2000	Descending	2500	96	1500
7		7	Nominal	Nominal	None	None	Traffic Conflict. Includes SUAs. Intruder Lateral TCP. Intruder descends through Ownship altitude.	Head-on	Level	2000	96	2000	Descending	2500	96	1500
8		8	Nominal	Nominal	None	None	Traffic Conflict. Includes SUAs. Ownship lateral TCP. Intruder Lateral TCP. Intruder climbs through	Crossing	Level	2000	96	2000	Climbing	1500	95	2500
9		9	Nominal	Nominal	None	None	Traffic Conflict. Includes SUAs. Intruder Lateral TCP. Intruder climbs through Ownship altitude.	Head-on	Level	2000	96	2000	Climbing	1500	95	2500
10	2	1	Nominal	Nominal	None	None	Traffic Conflict. Includes SUAs. Ownship lateral TCP. Intruder Lateral TCP.	Crossing	Level	2000	96	2000	Level	2000	96	2000
11		2	Nominal	Nominal	None	None	Traffic Conflict. Includes SUAs. Intruder Lateral TCP.	Head-on	Level	2000	96	2000	Level	2000	96	2000
12		3	Nominal	Nominal	None	None	Traffic Conflict. Includes SUAs. Intruder Lateral TCP.	Acute crossing	Level	2000	96	2000	Level	2000	96	2000
13		4	Nominal	Nominal	None	None	Traffic Conflict. Includes SUAs. Intruder Lateral TCP.	Intruder Overtake	Level	2000	96	2000	Level	2000	106	2000
14		5	Nominal	Nominal	None	None	Traffic Conflict. Includes SUAs. Intruder Lateral TCP.	Ownship Overtake	Level	2000	96	2000	Level	2000	85	2000
15		6	Nominal	Nominal	None	None	Traffic Conflict. Includes SUAs. Ownship lateral TCP. Intruder Lateral TCP. Intruder descends throug	Crossing	Level	2000	96	2000	Descending	2500	96	1500
16		7	Nominal	Nominal	None	None	Traffic Conflict. Includes SUAs. Intruder Lateral TCP. Intruder descends through Ownship altitude.	Head-on	Level	2000	96	2000	Descending	2500	96	1500
17		8	Nominal	Nominal	None	None	Traffic Conflict. Includes SUAs. Ownship lateral TCP. Intruder Lateral TCP. Intruder climbs through	Crossing	Level	2000	96	2000	Climbing	1500	95	2500
18		9	Nominal	Nominal	None	None	Traffic Conflict. Includes SUAs. Intruder Lateral TCP. Intruder climbs through Ownship altitude.	Head-on	Level	2000	96	2000	Climbing	1500	95	2500
19	3	10a	Nominal	Nominal	Later	None	RTA Compliance. Includes SUAs. Ownship Straight Route. No Intruder.	N/A	Level	2000	96	2000	N/A			
~~20~~		~~11~~	~~Nominal~~	~~Nominal~~	~~Earlier~~	~~None~~	~~RTA Compliance. Includes SUAs. Ownship Straight Route. No Intruder.~~	~~N/A~~	~~Level~~	~~2000~~	~~96~~	~~2000~~				
21		12	Nominal	Nominal	Later	None	RTA Compliance. Includes SUAs. Ownship lateral TCP. No Intruder.	N/A	Level	1500	95	1500				
22		13a	Nominal	Nominal	Earlier	None	RTA Compliance. Includes SUAs. Ownship lateral TCP. No Intruder.	N/A	Level	1500	95	1500				
~~23~~		~~14~~	~~Nominal~~	~~Nominal~~	~~Earlier~~	~~None~~	~~RTA Compliance. Includes SUAs. Ownship lateral TCP. No Intruder.~~	~~N/A~~	~~Level~~	~~2000~~	~~93~~	~~2000~~				
24		10b	Nominal	Nominal	Later	None	RTA Compliance. Includes SUAs. No Ownship lateral TCP. No Intruder. w/ Execution	N/A	Level	2000	96	2000				
25		13b	Nominal	Nominal	Earlier	None	RTA Compliance. Includes SUAs. Ownship lateral TCP. No Intruder. w/ Execution	N/A	Level	1500	95	1500				
26	4	15	Nominal	Nominal	Earlier	None	RTA Compliance. Includes SUAs. Ownship & Intruder to Separate Vertiports.	Intruder Overtake	Level	2000	96	2000	Level	2000	96	2000
27		16	Nominal	Nominal	Later	None	RTA Compliance. Includes SUAs. Ownship & Intruder to Separate Vertiports.	Ownship Overtake	Level	2000	96	2000	Level	2000	96	2000
28		17	Nominal	Nominal	Earlier	None	RTA Compliance. Includes SUAs. Ownship & Intruder to Separate Vertiports.	Intruder Overtake	Level	2000	96	2000	Level	2000	86	2000
~~29~~		~~18~~	~~Nominal~~	~~Nominal~~	~~Later~~	~~None~~	~~RTA Compliance. Includes SUAs. Ownship & Intruder to Separate Vertiports.~~	~~Ownship Overtake~~	~~Level~~	~~2000~~	~~96~~	~~2000~~	~~Level~~	~~2000~~	~~86~~	~~2000~~
30	5	19	Short	Nominal	None	None	Traffic Conflict. Includes SUAs. Ownship lateral TCP. Intruder Lateral TCP.	Crossing	Level	2000	96	2000	Level	2000	96	2000
31		20	Long	Nominal	None	None	Traffic Conflict. Includes SUAs. Ownship lateral TCP. Intruder Lateral TCP.	Crossing	Level	2000	96	2000	Level	2000	96	2000
32		21	Very Long	Nominal	None	None	Traffic Conflict. Includes SUAs. Ownship lateral TCP. Intruder Lateral TCP.	Crossing	Level	2000	96	2000	Level	2000	96	2000
33		22	Short	Nominal	None	None	Traffic Conflict. Includes SUAs. Intruder Lateral TCP.	Head-on	Level	2000	96	2000	Level	2000	96	2000
34		23	Long	Nominal	None	None	Traffic Conflict. Includes SUAs. Intruder Lateral TCP.	Head-on	Level	2000	96	2000	Level	2000	96	2000
35		24	Very Long	Nominal	None	None	Traffic Conflict. Includes SUAs. Intruder Lateral TCP.	Head-on	Level	2000	96	2000	Level	2000	96	2000
36		25	Short	Nominal	None	None	Traffic Conflict. Includes SUAs. Intruder Lateral TCP.	Acute crossing	Level	2000	96	2000	Level	2000	96	2000
37		26	Long	Nominal	None	None	Traffic Conflict. Includes SUAs. Intruder Lateral TCP.	Acute crossing	Level	2000	96	2000	Level	2000	96	2000
38		27	Very Long	Nominal	None	None	Traffic Conflict. Includes SUAs. Intruder Lateral TCP.	Acute crossing	Level	2000	96	2000	Level	2000	96	2000
39		28	Short	Nominal	None	None	Traffic Conflict. Includes SUAs. Intruder Lateral TCP.	Intruder Overtake	Level	2000	96	2000	Level	2000	106	2000
40		29	Long	Nominal	None	None	Traffic Conflict. Includes SUAs. Intruder Lateral TCP.	Intruder Overtake	Level	2000	96	2000	Level	2000	106	2000
41		30	Very Long	Nominal	None	None	Traffic Conflict. Includes SUAs. Intruder Lateral TCP.	Intruder Overtake	Level	2000	96	2000	Level	2000	106	2000
42	6	31	Nominal	Nominal	None	conflict <= 2 min until LOS	Traffic Conflict (Intruder change stressor). Includes SUAs. Ownship lateral TCP. Intruder Lateral TCP.	Crossing	Level	2000	96	2000	Level	2000	96	2000
43		32	Nominal	Nominal	None	conflict<=1 min until LOS	Traffic Conflict (Intruder change stressor). Includes SUAs. Ownship lateral TCP. Intruder Lateral TCP.	Crossing	Level	2000	96	2000	Level	2000	96	2000
44		33	Nominal	Nominal	None	conflict <= 2 min until LOS	Traffic Conflict (Intruder change stressor). Includes SUAs. Intruder Lateral TCP.	Head-on	Level	2000	96	2000	Level	2000	96	2000
45		34	Nominal	Nominal	None	conflict<=1 min until LOS	Traffic Conflict (Intruder change stressor). Includes SUAs. Intruder Lateral TCP.	Head-on	Level	2000	96	2000	Level	2000	96	2000
46		35	Nominal	Nominal	None	conflict <= 2 min until LOS	Traffic Conflict (Intruder change stressor). Includes SUAs. Intruder Lateral TCP.	Acute crossing	Level	2000	96	2000	Level	2000	96	2000
47		36	Nominal	Nominal	None	conflict<=1 min until LOS	Traffic Conflict (Intruder change stressor). Includes SUAs. Intruder Lateral TCP.	Acute crossing	Level	2000	96	2000	Level	2000	96	2000
48		37	Nominal	Nominal	None	conflict <= 2 min until LOS	Traffic Conflict (Intruder change stressor). Includes SUAs. Intruder Lateral TCP.	Intruder Overtake	Level	2000	96	2000	Level	2000	106	2000
49		38	Nominal	Nominal	None	conflict<=1 min until LOS	Traffic Conflict (Intruder change stressor). Includes SUAs. Intruder Lateral TCP.	Intruder Overtake	Level	2000	96	2000	Level	2000	106	2000
50	7	39	Nominal	Nominal	None	None	Traffic Conflict at Merge into Corridor	Intruder Overtake	Level	1500	89	1500	Level	1500	106	1500
51		40	Nominal	Nominal	Later	None	Traffic Conflict After RTA Delay in Corridor. Constrained Vertically.	Intruder Overtake	Level	2000	96	2000	Level	2000	96	2000
52		41	Nominal	Nominal	None	None	Traffic Conflict When Exiting Corridor	Head-on	Level	2000	96	2000	Level	2000	96	2000
53	8	42	Nominal	1.25 Times	None	None	Traffic Conflict. Includes SUAs. Ownship lateral TCP. Intruder Lateral TCP.	Crossing	Level	2000	96	2000	Level	2000	96	2000
54		43	Long	1.25 Times	None	None	Traffic Conflict. Includes SUAs. Ownship lateral TCP. Intruder Lateral TCP.	Crossing	Level	2000	96	2000	Level	2000	96	2000

Appendix I: IAS DISPLAY DETAILS

MIDDLEWARE INTERFACES

The middleware (MW) required various interfaces for human monitoring and interaction to facilitate efficient and safe flight tests. While these interfaces were critical for maintaining situational awareness during the flight test and ensuring its success, they were not considered critical to the safety of flight. All MW displays were developed using the Unity3D cross-platform game engine (Unity Technologies, San Francisco, California). Six distinct graphical user interfaces (GUIs) were designed for the ground control station. These consisted of the Gateway, Test Conductor display, MWE display, Variable Plotting display, and two Ground Research displays (HPA and FPM). Additionally, we created a dedicated display for the pilots (IAS Pilot display), which served as the primary point of interaction with the research software (HPA, FPM, etc.).

The MWE controlled both the Gateway and the MWE display, serving as the only displays to communicate up to the aircraft-hosted MW via the Sikorsky datalinks. The Gateway operated as a single “ground subscriber” to the airborne MW, while the other ground displays accessed data streams through the gateway, reducing data link traffic. Initially, the flight-test campaign was conducted without the Gateway, but the team determined that each ground station display receiving its own data stream from the MW consumed too much of the available data link bandwidth. The Graphics User Interface (GUI) for Gateway was straightforward, featuring two health indicators for the status of the two data streams (one for each aircraft); input fields for the IP addresses; and ports for the appropriate subscriptions. The MWE display (fig. I 1) was the only display that subscribed to both the Gateway and the MW and was also the only display that could send commands to the MW; thus, requiring a direct link to the MW. The MWE display had standard situational awareness of the aircraft states including a map with a “Bird’s Eye” view of the aircraft position and heading, details of winds, speed, altitude, and a clock tracking the T-0 conditions (T-0 was the point in space and time at which the research algorithm encounter started). The MWE display featured multiple input fields associated with the different research modes, accessible through tabs at the top of the display. The MWE could switch between research types via the tabs while maintaining situational awareness via the map. After all input fields were populated for the given research type, the MWE would hit an “ARM” (unlocking the UPLOAD button), and subsequently hit “UPLOAD” to send the command to the MW.

Figure I 1. Spiral 2C example MWE display.

The remaining ground control station displays were purely for situational awareness and had to subscribe to the gateway for access to the relevant data stream. The Test Conductor display was originally meant for the Test Conductor to monitor and time-stamp events via an event marking button; however, the event marking led to task saturation (fig. I 2 shows an example of the Test Conductor display). Consequently, the Test Conductor display was solely a monitoring station of both aircraft that included attitude indicators, speed, altitude, and heading tapes, and a variety of other aircraft-specific information. Like the MWE display, the Test Conductor display had a map in the middle (similar to the MWE display) as well as a time series display of the pitch and roll of each aircraft.

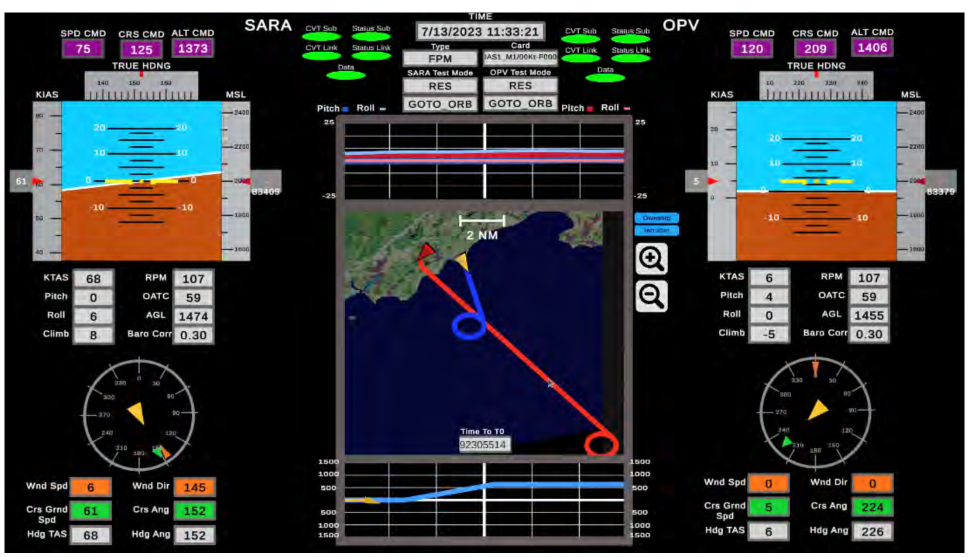


Figure I 2. Example test conductor display.

The variable plotter display is exactly what the name implies and provided a list of all MW-published variables and enabled users to select and plot. This display was not only instrumental for troubleshooting purposes during development but also for flight dynamics monitoring during the flight test. Lastly, the ground research displays provided situational awareness specific to research algorithms. These displays were used by the research groups to monitor the research algorithm state and health.

The IAS pilot tablet automatically displays the network configuration page when launched and is designed to accommodate features according to which aircraft was on the display. This page included toggles for the running platform (Windows versus other) and the aircraft (SARA versus OPV). On the SARA, the display used .NET framework functions to start and stop the pilot research displays at T-0 and at the end of the scenario, respectively. Additionally, after the end of the scenario, the IAS pilot display prompted a questionnaire for the pilot to assess different components of the run (discussed in greater detail in Section 5.4.1). This consolidated display design was vital to reduce cockpit clutter; an earlier solution had been to use separate tablets for each display. Beyond research display control, the IAS pilot display provided the same situational awareness including a predominantly full-screen map (with same features as MWE and Test Conductor) and buttons at the bottom for the pilot-triggered MW transitions ("ORBIT," "READY," "STOP," etc.).

RESEARCH/PILOT DISPLAYS OVERVIEW

This section provides an overview of the HPA and FPM research displays hosted on the NASA GTAC F110 tablet that communicated with the ACAS and AOP software, which was integrated within the MW. As stated earlier in the HPA and FPM software overviews, the displays not only provided the research pilot with the data central to the HPA/FPM algorithm deconfliction/collision avoidance but also provided the necessary interfaces and mode control (via digital buttons) to conduct the tests. Both the HPA and the FPM research teams were very interested in collecting human-machine interface data between their respective display and the NASA research pilot (though the FPM display was not operationally representative as it was meant, only as an engineering interface at this stage). In both sets of tests, a short five-question top-level HMI questionnaire appeared automatically (driven by MW) on the NASA tablet at the end of each test run to provide high-level comments regarding the display. In addition, following the test series, more extensive and detailed HF-/HMI-related table-top discussions and comments were collected from the three NASA research pilots.
Besides the HF/HMI studies related to research displays, further HF studies were performed utilizing biometric measurement equipment, as shown in fig. I 3.

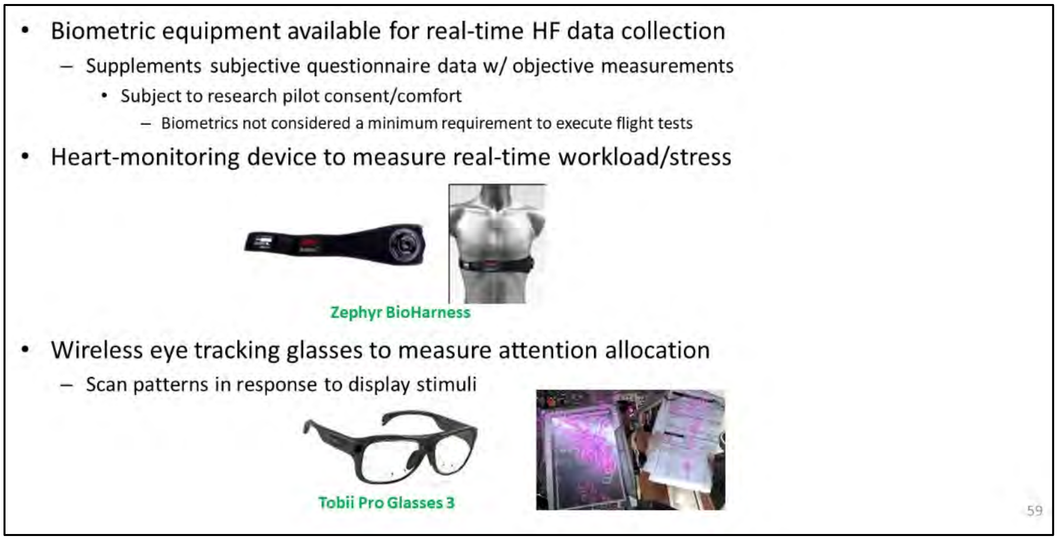


Figure I 3. Human factors/biometrics test equipment utilized in IAS Project.

HPA Display Overview

The HPA display (fig. I 4) is largely based on the display requirements developed as part of the RTCA SC-228 UAS DAA standards (DO-365B). The primary section of the display contains an inner and outer range ring; a vertical speed tape (on the right side of the display); an airspeed tape (on the left side of the display) as well as the ownship traffic symbol; nearby traffic symbols; and any associated alerting and guidance. The intruder symbols shift into alert icons in the event that they present a DAA well clear or collision avoidance threat. Complimentary caution or warning-level “banding” also appear during DAA and RA alerts. The banding is color coded, where white = unassessed by HPA; amber = predicted to result in a DAA well-clear violation; red = predicted to lead to an NMAC; and green = the region to be achieved in order to comply with an RA. Depending upon the mode engaged (CAS, DAA, etc.), there are variances to what information is provided, but generally the pilot or MW (when auto-RA is engaged) maneuvers the aircraft to reach the green banding in the horizontal and/or vertical dimension(s). Near the bottom portion of the display is where the current mode and any MW-injected altitude offset is provided. Lastly, the very bottom left of the display shows the button the pilot uses to enable/disable the MW to auto-fly the RA maneuver commanded by ACAS-Xr.

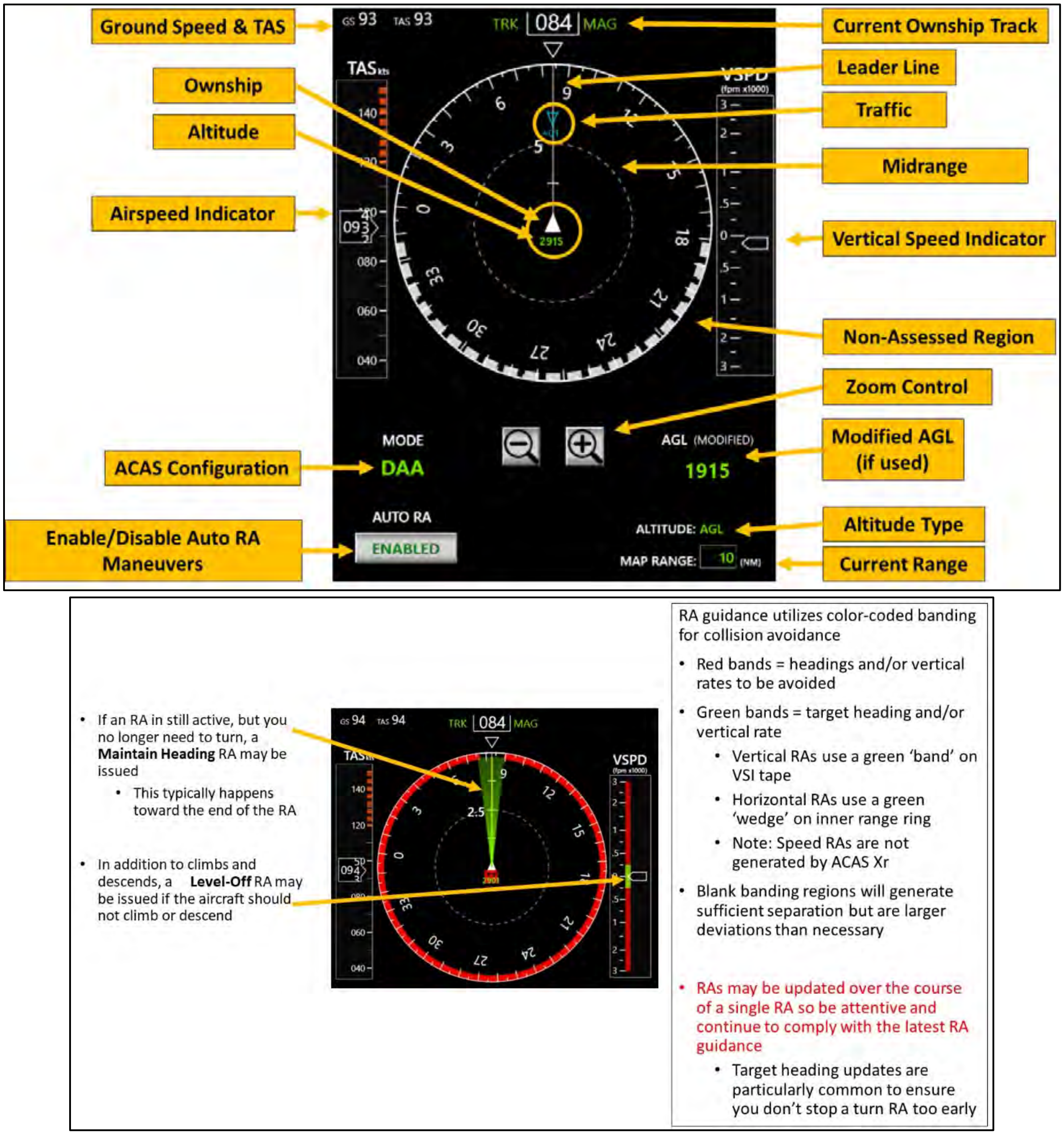


Figure I 4. The HPA/ACAS-Xr research display.

FPM Display Overview

The FPM display, shown in fig. I 5, was a research display developed by the FPM team based on their envisioned dynamic route-planning inflight aids (not yet established by industry standards/FAA). The display is divided into three main sections: The top section provides a comprehensive top-down (or "plan view") of the air traffic picture. In the IAS case, all the gray background traffic and vertiports are virtual – derived from UAM/AAM simulation studies of the envisioned future UML-4 level air traffic for the Dallas, Fort Worth, UML-4 area. The magenta line represents the current ownship route ("active route"), and the cyan line represents the AOP-computed conflict resolution route for the specific option selected by the research pilot in the area at the bottom of the display. Below the top-down view of the air traffic picture is a “profile” display (current state at the left edge) side view of the ownship vertical trajectory (solid lines) and speed (dashed lines) using the same magenta/cyan color screen as the top-down view. Like the HPA display, the bottom portion of the display is used for the research pilot to “preview,” “select,” or “execute” the AOP lateral-, vertical-, speed-, or hybrid-provided conflict resolution options, and also to clear/cancel the AOP options.

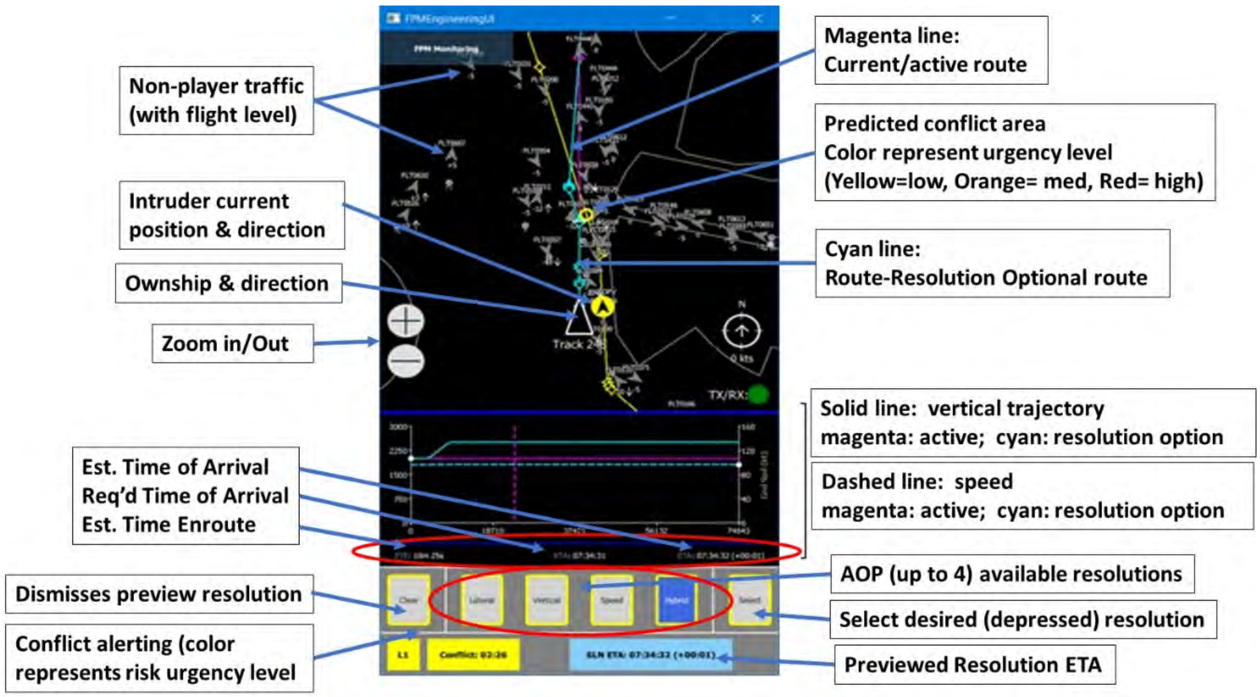


Figure I 5. The FPM/AOP research display.

HMI Questionnaire Display Overview

The MW automatically presents this display (fig. I 6) to the NASA tablet on the SARA once the AFCM (HPA/ACAS-Xr or FPM/AOP) research encounter has completed. The display is self-explanatory. Although this HMI questionnaire automatically appeared on the SARA NASA tablet following each HPA- or FPM-auto-flown encounter, however, the FPM tests were more of a research effort to validate their design approach and simulations. Instead, postflight face-to-face discussions with the aircrew to capture their HMI related research were relied upon.

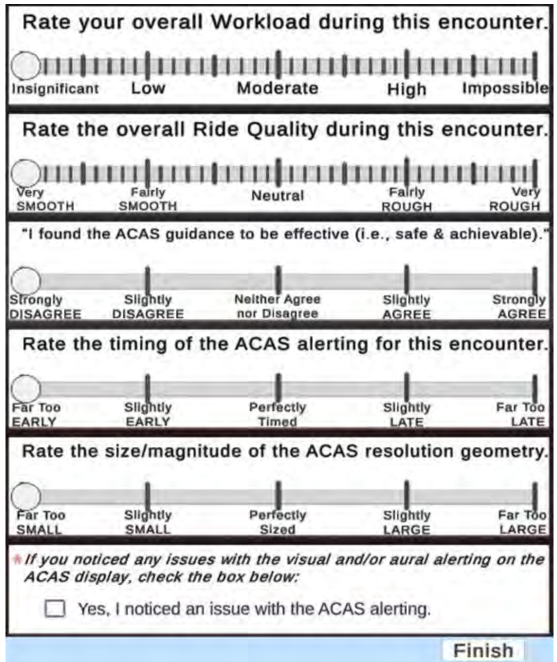


Figure I 6. The NASA tablet human factors questionnaire.

Appendix J: AUTONOMY INDUCED OSCILLATIONS

The AIO Causes and Mitigations Overview

As was introduced in Section 5.3, AIOs occurred within the various spirals, expressed differently, and were indirectly caused by the MW commands. To achieve time conformance, the 4D trajectory commands (ground-based referenced) contained a ground speed command that varied depending on the difference ("error" in control terminology) between current position and commanded position. This position error was known to be caused by either a problem with satisfying the commanded trajectory or a problem with ground speed input. Ground speed command-limit cycling occurred most frequently when stimulated by headwinds. Oscillations in roll were caused by an insufficient MW command trajectory point density and was corrected following Spiral 1A data analysis. Figure J 1 provides an example AIO from Spiral 1A and a similar example from Spiral 1B. By Spiral 2C, following incorporation of a PID controller in the MW in Spiral 2B, the oscillations were reduced, and their severity depended on trajectory command initial conditions. The oscillation duration was ~30 seconds and typically dampened out soon after initiation.

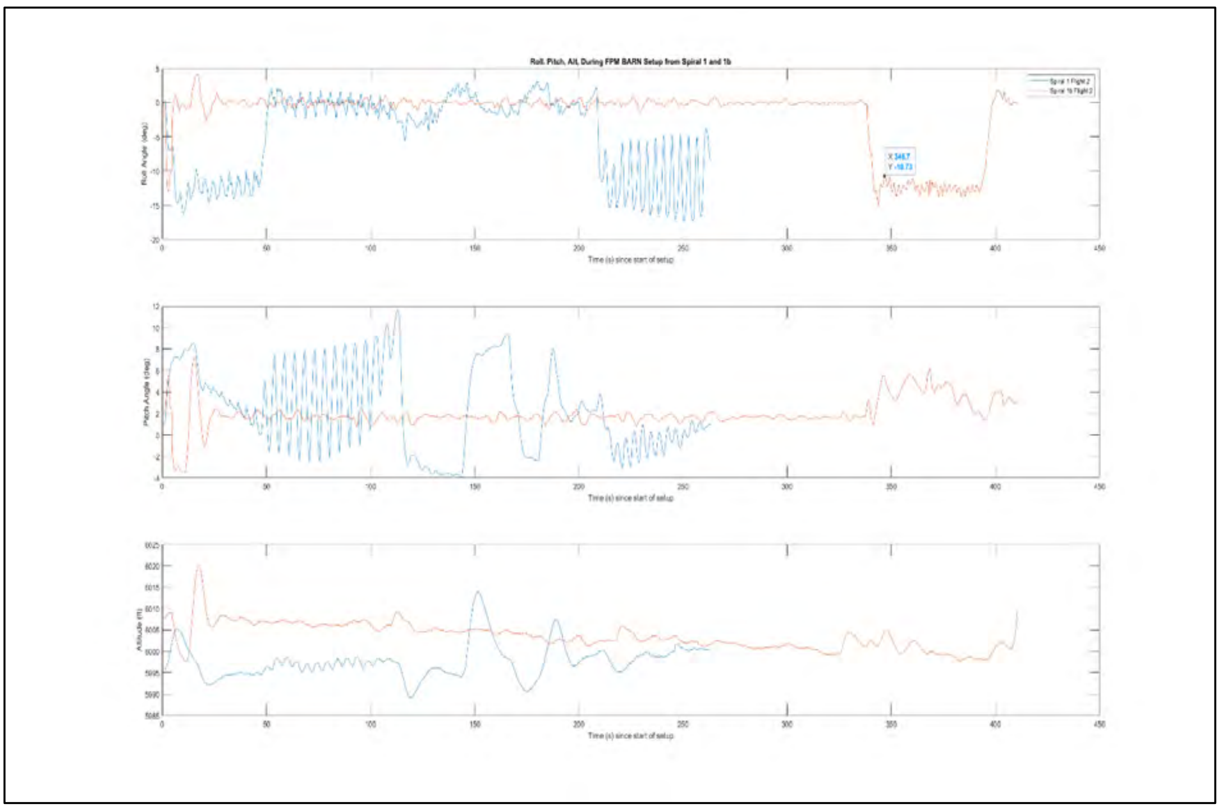


Figure J 1. The AIO seen in Spiral 1A and Spiral 1B during an FPM Barn setup maneuver.

6.9.1 The AIO in Flight Test

During Spiral 1A, nuisance-level oscillations were encountered in all axes. These oscillations had a time period of ~5 seconds (0.2 hertz) with amplitudes of roughly ±5 to 6 degrees. The AIO was partly caused by how the MW transformed the time-based 4D trajectories from the research algorithms into the velocity-based 4D trajectories required by the autopilot. The conversion was accomplished by calculating the velocity needed to get to the next position along the trajectory that satisfied its timing requirements. This meant that the MW sent a lower-velocity command if the aircraft was ahead in the trajectory, and a higher-velocity command if the aircraft was behind the trajectory timeline. The roll AIO was caused by a low-point density within the commanded trajectory.

In Spiral 1B, a control loop was added to the MW 4D trajectory to smooth out the velocities calculated during the conversion and achieve a high level of time conformance (i.e., be at this latitude/longitude/altitude at this point in time). The loop followed a PID controller structure with a desired target time as the reference input and the calculated time to target as the feedback.

In Spiral 2A and 2B, the gains for the velocity were tuned during NASA software V&V to further reduce oscillation amplitude and frequency. In Spiral 2A, sustained oscillations were observed during low-speed maneuvers and were caused by nonlinearities (crossing speed transition zones) in the OPV internal control laws.

In Spiral 2C, the trajectory ground speed command limits were modified, and another round of MW PID gain tuning occurred. While the PID structure remained during Spiral 2C tuning, the velocity controller became a PD controller because the “I” (integral) windup was not implemented properly and would have required a code change requiring reaccomplishing V&V/documentation (see Lesson Learned 4); however, the PD values chosen did significantly reduce the AIO experienced during simulation testing. During the Spiral 2C flight tests, 20-plus-knot winds aloft were common, and the AIO was most likely to occur if the commanded encounter setup trajectory began in a headwind. To maintain the trajectory time conformance, as was described earlier, the aircraft speed had to be modulated, but this MW commanded speed modulation sometimes encountered at aircraft speed limits, especially when initiating the command into a headwind (requiring the aircraft ground speed to increase). This nonlinear speed limit hysteresis then led to the observed AIO limit cycle. The larger the headwind, the larger the difference between ground speed and airspeed, thereby increasing likelihood of encountering airspeed related limits while commanding ground speed (fig. J 2).

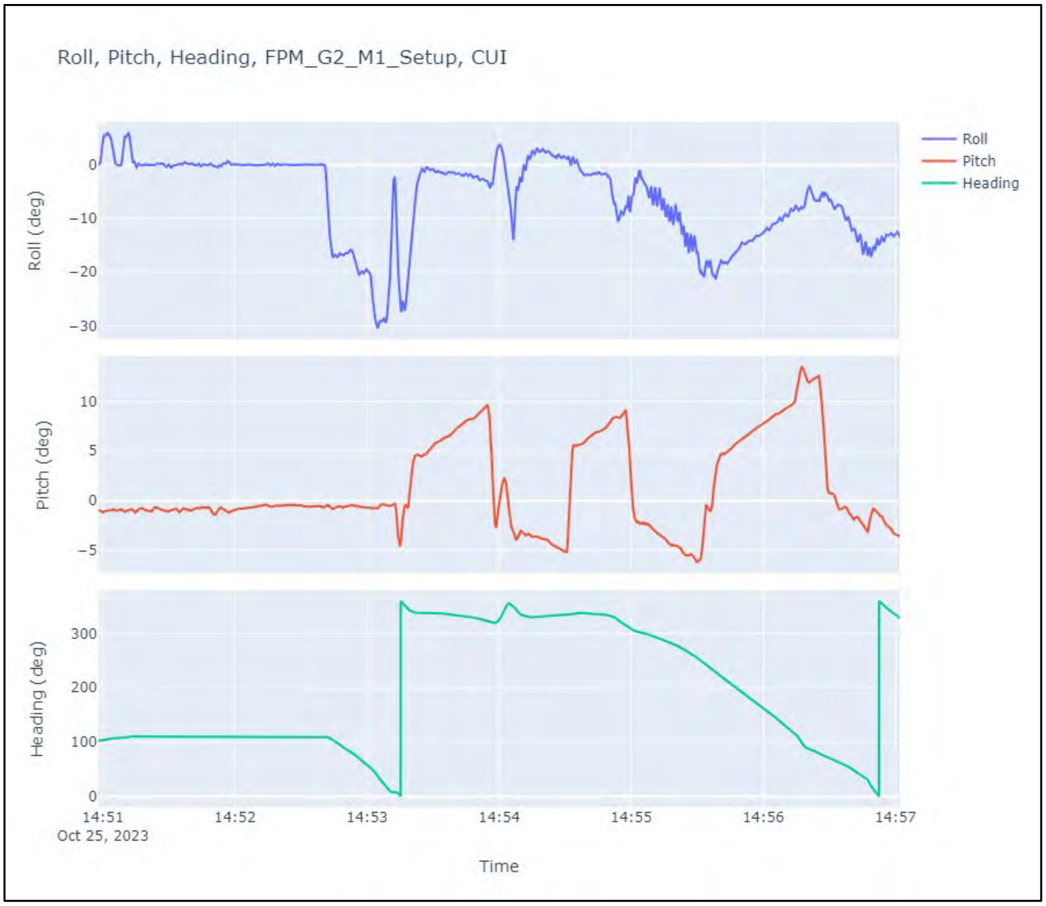


Figure J 2. Limit cycle and nominal response in Spiral 2C.

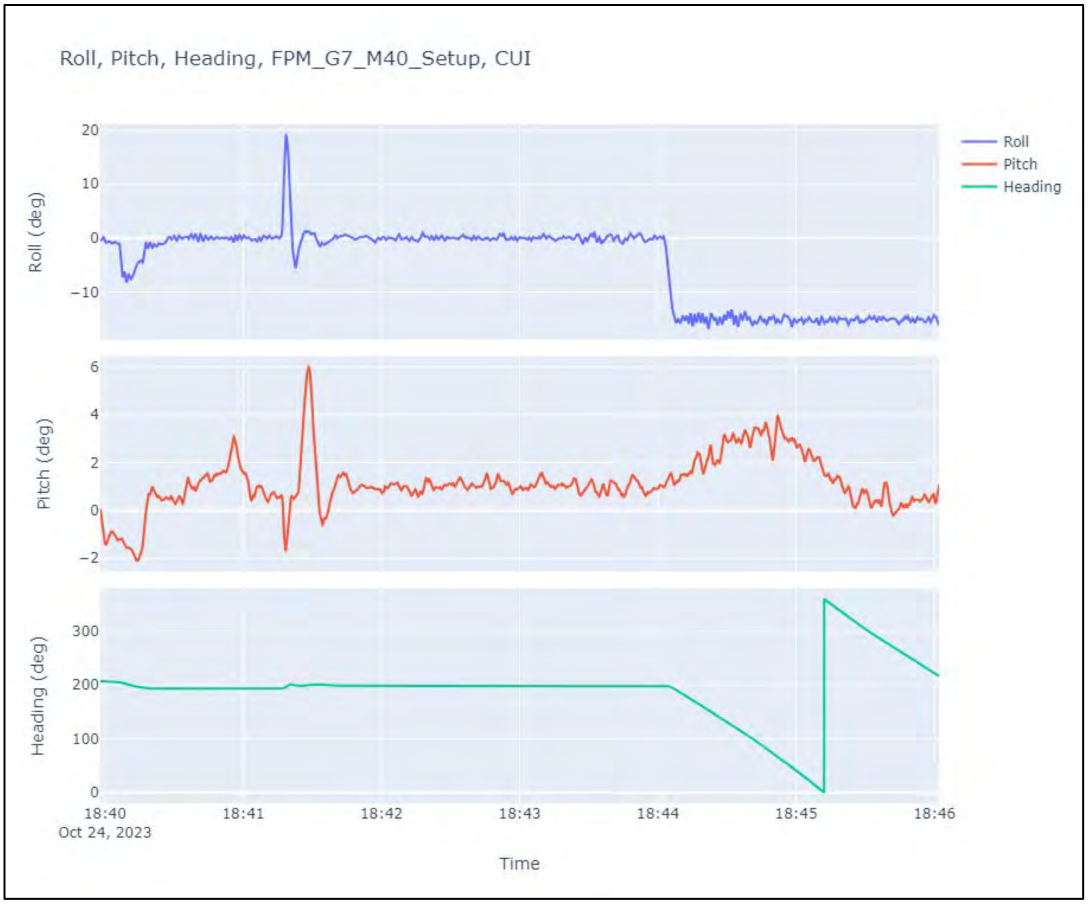


Figure J 2. Limit cycle and nominal response in Spiral 2C (concluded).

6.9.2 Challenges in Mitigating AIO

Part of the challenge to solve the AIO problem was investigating potential causes and determining how to mitigate them. Due to limited time with the high-fidelity GenHel simulator (NASA did not obtain a GenHel until just prior to Spiral 2C) and the inability to obtain inner-loop control data, most problems were only found during the V&V process or in flight, rather than earlier in the software test cycle. Since this problem was not a safety-of-flight problem and did not curtail the primary objective to conduct encounter tests, because the 4D trajectory conformance was still satisfied with the AIO present, time and priority were limited for AIO investigation/fixes. Since headwinds played a role in the AIO limit cycle initiation and magnitude, a correction was made to procedures for the MWE/GCS (using their displays that presented winds aloft speed and direction) to provide instructions to the aircrew for when to release their respective aircraft from its encounter-setup or orbit (and thereby trigger the MW to begin computing/issuing its run-in trajectory commands).

6.9.3 Velocity Controller Discussion

The MW velocity controller was created to convert the time-based 4DT (latitude/longitude/altitude/time) from the HPA and FPM algorithms into a velocity-based 4DT that the AMM required. The first iteration of this conversion directly translated the changes in time between each point along the trajectories into ground speed commands along the trajectory. This design sometimes created a bang-bang response leading to some of the initial pitch-axis AIOs. In

Spiral 1B, the initial framework for the velocity controller was introduced along with adjustments to the controller, this led to a reduction in AIO amplitudes. The velocity controller computes the difference between the time to a target point in the trajectory and a reference time, termed the controller "TimeError," and uses a PID loop to create a command ground speed to maintain good time conformance. This reference time is an adjustable MW CVT parameter and was set to 3 seconds for Spiral 2 flights. The target point along the trajectory was computed by using linear interpolation to calculate the latitude and longitude at 3 seconds from the current time position/location. The next step in the control loop was to calculate the distance between the current ownship location and the target point, which was termed the "PathDistance." Using PathDistance and the reference time, a ground speed value was then calculated. This ground speed value was modified by the control loop into the commanded ground speed to minimize time error. The resulting time-error value affected the AIO magnitude. Large time errors caused the velocity controller output encounter, maximum or minimum allowable airspeed, and ground speed commands. Figure J 3 shows the level of time conformance achieved.

Figure J 3. Example of time conformance achieved in Spiral 2C.

Appendix K: SOFTWARE MANAGEMENT APPROACH

The National Campaign software management plan (AAM-NC-065-001) was developed as an overarching document to guide software development, integration, and tests geared towards maturing research software intended to be flown under the NC Project and to satisfy the requirement of NASA Software Engineering Requirement (NPR-7150.2) (ref. 4). The strategy was to streamline the processes for multiple efforts under the NC without requiring each activity to develop its unique software development or management plan, and to allow software developers the flexibility and agility needed to meet project deadlines and projected milestones.

Some NC Subprojects, which include FPM, HPA, and ATI, had legacy software development plans that were followed to develop their software at NASA LaRC and NASA ARC, respectively, and there was no need to levy extra requirements for software development and assurance upon them since these software developments were already complete. One exception was requiring the subprojects to test and provide IAS with test results of planned flight-use cases and scenarios prior to release of their software for integration. Once the software was released to IAS, the responsibility for proper integration of the software into the flight-test infrastructure became that of IAS; however, if there were changes to be implemented on any of the legacy software, those changes were communicated to the stakeholders. Upon implementation, regression testing was performed by the responsible subproject involved with the change, which ensured the implemented change did not impact the safety assumption of the software team and the functionality of the software.

While the NC software management plan was tailored towards a “waterfall” implementation to account for all the life cycle stages with adequate controls (minimum success criteria and expected reviews), each subproject was granted the freedom to choose the development methodology that worked best for them. Consequently, each subproject defaulted to their legacy development method that the developers had used previously. The IAS, therefore, used a spiral development approach (a legacy software development method that was used by a prior NASA project) or the *Resilient Autonomy* Project to develop EVAA and the IAS middleware.

Due to the complexities in handling software development and testing at various Centers where IAS did not have full insight on what the developers did, IAS had to conduct multiple unit tests to characterize the received software and ensure interoperability of the systems. Released software from HPA (ACAS-Xr) and FPM (AOP) was first integrated at AFRC and tested to ensure the software could run and communicate with the middleware. A second verification to ensure the released software could communicate and pass commands to the Sikorsky MATRIX™ through the middleware was conducted at Sikorsky using their GenHel simulator. This second verification was the official software verification and validation (V&V), and all of the intended software use cases were verified to be safe, flyable, and with contained clarity of modes and displays.

To continuously monitor the implementation of the software changes, iterations, and integration, the IAS Project utilized weekly Software Brainstorming Sessions to ensure the safety assumptions upon which the software classification was based remained valid. The brainstorming sessions involved software developers from IAS, FPM, and HPA, as well as software quality assurance, systems engineering, and integration representatives across the NC. Also, a Daily Scrum Meeting, a core instrument of the Spiral Methodology was used to burn down tasks of IAS software developers and communicate problems as they arose.

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