Flight Test Evaluation of Autonomous Descending-Decelerating Precision Point-in-Space Approach to the Ground

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New forms of highly automated Advanced Air Mobility (AAM) aircraft, such as electric vertical take-off and landing (eVTOL) vehicles, could transform transportation, cargo delivery, and a variety of public services. The National Aeronautics and Space Administration (NASA) conducted a series of flight demonstrations in collaboration with the Defense Advanced Research Projects Agency (DARPA) and Sikorsky Aircraft (a Lockheed Martin company) to progressively evaluate autonomous technologies. The autoland flight test research is a first in series for investigating the world's first procedural descending-decelerating automated landing with vertical guidance Instrument Flight Procedures (IFP). The Sikorsky Optionally Piloted Vehicle (OPV) experimental UH-60 Black Hawk was used to evaluate a flight path's four-dimensional trajectory (4DT) management into primitive commands and then follow those commands to a Point-in-Space (PinS) landing to the ground. All flight procedures were manually flown to the ground at 12 degrees with a 20-knot tail wind to ensure flight safety before automation was engaged. New and novel high precision approach procedures could pave the way for all future VTOL operations.

Keywords—AAM, eVTOL, autoland, IFP, automation, 4DT

I. Introduction

The increased AAM demand for all weather operations, traffic density, and landing ubiquity drives the need for IFP research for vertically performing aircraft. If implemented, the procedures developed for this research will not only enable scalable AAM operations but also provide a safety infrastructure for current rotorcraft operations, which presently have the highest accident/incident rating of any aviation operation [1]. Given higher levels of automation and tighter tolerances in flight path conformance, the avionics market has matured enough to provide automation-assisted vertical landings to a PinS approach all the way to the ground. With this level of maturity in mind, human-to-machine and machine-to-machine interfaces and interactions, flight path algorithms, as well as middleware software to provide the interface to the flight control computer for automated execution of maneuvers, were evaluated for flight maneuvers via selected 5-, 8-, and 12-degree approach profiles. Specifically, 4DT (latitude, longitude, altitude and time) were evaluated against the automation 4DT. For further NASA software and vehicle descriptions, reference "Flight Test Evaluation of Automation-Induced Oscillations" [2].

Flight crews consisted of four (4) Sikorsky safety pilots and three (3) NASA research pilots that were outfitted with biometric kits which included eye tracking, brain activity monitoring, heart rate, body temperature, and respiratory data. All flights were launched and recovered to, and from, class D airspace at Bridgeport Airport (KBDR). The area of operation for the flight test was 10 NM southwest of the airfield over the Long Island Sound from 700 ft to 0 ft above ground level (AGL). All flights were also conducted over unpopulated areas above the water in daytime visual meteorological condition (VMC). The targeted vertiport landing site was selected and surveyed on taxiway G between K and J [3].

The first flight was a manual inspection from the 5-degree final approach fix (FAF) to the 12-degree approach procedure (Fig. 1). Five-degree descent was selected as it had the longest final approach segment out of the different approach angles under test. An altitude of 500 ft AGL was maintained until the 12-degree FAF, in which the estimated 12-degree descent/deceleration was tested to ensure procedure flyability with respect to a tailwind and with the most aggressive descent and deceleration rates. The approach path was clear of terrain or any vertical obstructions and the variable 12-degree descent/deceleration approach was suitable for coupled autoland IFP testing.

(a)

(b)

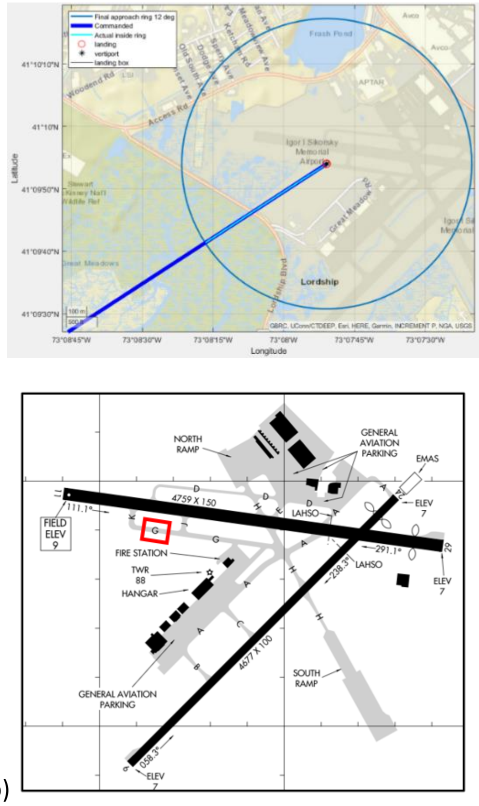

Fig. 1. 12-degree approach path (a) at KBDR (b).

II. Test Description

This section outlines a description of the aircraft under test, the landing site evaluation and the approach procedure construction. This section also provides a high level summary of the NASA-designed architecture and software configuration used to execute the autoland testing.

A. Aircraft Description

The NASA Integration of Automated Systems (IAS) test program utilized a single autonomous-capable aircraft, which hosted NASA research algorithms to develop software to maintain a low flight-safety risk. Sikorsky Innovations (the Advanced Concepts group within Sikorsky), located in Stratford, Connecticut provided the research aircraft: the Optionally Piloted Vehicle (OPV) S-70 Black Hawk^{TM} helicopter as the IAS research platform. The OPV avionics incorporate the Sikorsky software package MATRIX^{TM} and the DARPA-Sikorsky Aircrew Labor In-flight deck Automation System (ALIAS) systems. The IAS team built the approach procedures specific to the aircraft. Interfacing with the MATRIX^{TM} system was achieved through a Sikorsky-developed software called the Autonomy Mission Manager (AMM), which served as the interface point for external commands to be sent to the Vehicle Management Computer and for state data to be made available. The aircraft was operated by a NASA research pilot and a Sikorsky safety pilot.

B. Landing Site Evaluation

The landing surface at KBDR was evaluated using the FAA's heliport dimension matrix. Since the S-70 OPV aircraft information was already in the FAA system as part of a certified aircraft, the data was auto-populated to generate the required take-off/landing and safety area dimensions. Currently no criteria exist for helicopter or heliport IFR operations with autoland (coupled touchdown) capabilities, so visual flight rule parameters were used to maintain dimensional accuracy as well as contrast the precision approach proportionality that is reserved for manually landings. A spatial data analysis was conducted at taxiway G between K and J, which resulted in high precision latitude, longitude, mean sea level and ellipsoidal elevations. The center of the helipad, which for the experiment also referred to as vertiport reference point (VRP), was used as the target for dynamically generating trajectories from a given aircraft altitude, airspeed and environmental condition. A heliport evaluation worksheet was produced for use in the final procedure construction and landing scatter plot analysis (see annex Fig. 3.)

C. Experimental Approach Plate Design

An instrument approach plate was developed for the flight test. It serves as a navigation form for the pilot while manually controlling the aircraft and as a cross-reference module when coupled to the autopilot during the procedure (see Appendix Fig. A-2). The approach plate serves as a human-machine interface between the automation and pilot and was evaluated as a Flight Inspection Graphic for procedure complexity, pilot comprehension, and adequate guidance. The intent is to maintain applicable, current FAA formatting to the extent possible, leverage the legacy of FAA human factors research while also accommodating research for a first-of-a-kind experimental flight test procedures. The tools in use for the approach plate evaluation are pilot feedback and the use of eye tracking glasses during the approach to assess the information attracting the pilot's vision. Although the approach plate contained a missed approach section, the missed approach was not evaluated as part of this test. In contrast to legacy missed approach set of instructions, this missed approach procedure provides instruction for the 'real world' knock-it-off (KIO) in which the pilot would manually take control of the aircraft and maneuver away from any traffic or object on the active runway or taxiway.

D. Procedure Construction

The experimental PinS approach procedure was constructed backwards from the intended point of landing or VRP, which is the surveyed center of the pad. Due to well established lateral containment area criteria, focus was given to the vertical track tolerances to account for the steeper approach angles of the experimental procedure. From the established VRP boundary, a 15-degree vertical splay extends from the edge of the touchdown and lift-off area (TLOF) upwards towards the hover termination waypoint located above the intended landing surface. To complete the vertical containment area, the FAF waypoint must be defined and referenced by AGL and distance from the VRP. A 50 ft vertical deviation, or bias error, is applied to the AGL of the FAF. Next, lines are drawn from the low- and high-end portions of the FAF fix displacement area and connected to the vertical 15-degree splay extending from the helipad boundaries that create the experimental primary flight path limits that connect with the lateral required navigation performance (RNP) distances that can then generate a 3-dimensional (3D) corridor or “hamster tube” in the sky. Additionally, a Delayed Deceleration Point (DDP) was applied as a function of 1/3 the vertical distance traveled between the FAF and hover termination point. The hypothesized airspace architecture construct was generated to measure 2- and 3-sigma containment areas as an initial measurement to begin the discussion on requirements for obstacle evaluation, terrain and airspace clearances.

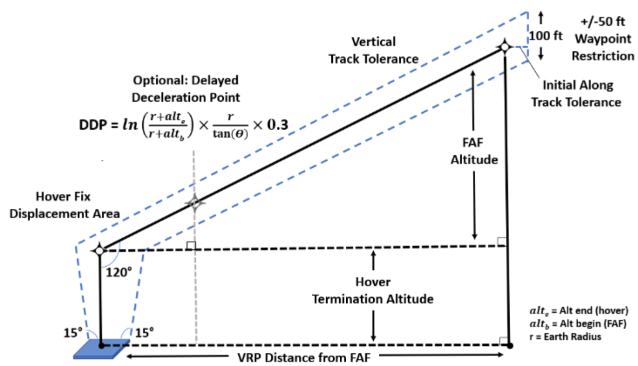

Fig. 2. Autoland PinS Approach Procedure Construction with optional delayed deceleration point.

III. Methodology

The purpose of the flight test was to conduct a flight evaluation of an experimental procedure design for a descending/decelerating precision (with vertical guidance) PinS approach to the ground while utilizing the FAA’s procedure lifecycle to the greatest extent possible through mimicking the aeronautical data chain of airspace evaluation, validation coding, charting and publication, which culminated with a flight check. The experimental procedure was manually flown with a constant-rate deceleration and delayed deceleration to hover with a greater than 20-knot tailwind abuse case. Once the procedure was manually baselined, the next phase was to enable the automation to generate a 4DT and evaluate the software’s ability to execute the route generation and subsequent human-machine interface, via an approach plate, to cross-monitor the automation performance.

A. Simulation, Verification and Validation

In order to maintain the current procedure development lifecycle, a notional FAA Form 8260-7A Special Instrument Approach Procedure was produced for the landing site evaluation [4]. The procedure was then flown using a fixed-base simulator at NASA Armstrong Flight Research Center to define route generation parameters as well as manage the different deceleration rates for any variable wind condition. Once the 4DTs were defined, the procedures were flown in the hangar using the aircraft onboard flight control computer serving as the simulator with high-fidelity visual screens placed in front of the flight deck. This step was important to visually affirm actuator movement correctly corresponded with the given procedure. Flying within the hangar also provided opportunity for the flight and ground crew to rehearse verbal KIO protocols from each assigned seat positions before the flight test. Once the simulator verification and validation was complete, an experimental FAA Form 8260-30.1 Simulator Validation Checklist was used to manage the proposed approach sequence.

After the procedures passed the ground control checks and simulator evaluations, they were manually flown at 12-degrees with both a delayed deceleration and constant-rate deceleration to assess the safety of each approach profile as well as the suitability of the deceleration rates under test. The FAA Form 8260-30.2 Obstacle Assessment Checklist was used to evaluate the obstacle clearance and terrain spatial data accuracy. However, closure rates and visibility or field of view from the flight deck for the intended landing area were noted as significantly degraded because the landing environment was not in sight due to the steep approach angle and height of the hover termination point. This was noted as a delta on the experimental FAA Form 8260-30.3 Flight Validation Checklist with an open-ended question and need to confirm or deny via flight test, the automation’s ability to augment the visual segment requirement. The NASA MW and Sikorsky AMM system’s precision landing and route conformance ability was assumed to satiate the autoland procedure accuracy requirements akin to a Category III Instrument Landing System (CAT III ILS). An experimental FAA Form 8260-30.4 Instrument Flight Procedure Validation (IFPV) Evaluator Check Record was produced at the end of the flight test to help in mapping research objectives to current IFR procedure requirements, standards, policy and regulations [5].

The FAA aeronautical data services have over seventy years of vetted human factor and technical check and balances that has produced the safest airspace in the world. As such, the process was used experimentally applied and documented to the greatest extent possible to result in the notional completion of a procedure lifecycle as part of the process for IFPV (Appendix Fig. A-3):

Experimental

- ✓ FAA Form 8260-7A Special Instrument Approach Procedure
- ✓ FAA Form 8260-30.1, Simulator Validation Checklist
- ✓ FAA Form 8260-30.2, Obstacle Assessment Checklist
- ✓ FAA Form 8260-30.3, Flight Validation Checklist
- ✓ FAA Form 8260-30.4, IFPV Evaluator Check Record

B. Objective Assumptions and Test Limitations

Given the experimental nature of the descending and decelerating flight procedure, certain assumptions were made concerning the flyability of the procedure. Although all of the flight maneuvers were within the limitation of the airframe, the experiment assumed regulatory acceptance in the transition from a 3D waypoint or “goal-following system” into a dynamically generated 4DT approach procedure. These assumptions included waypoint restrictions such as required time of arrival, airspeed, altitude, and meet or exceed criteria. Different leg-type mechanisms were not evaluated as the autonomous system utilized track-to-fix navigation between trajectories. However, the vertical track tolerance (VTT) was assumed to be the mitigating feature of the early/late entry point for the deceleration to a hover as previously visualized in Fig. 2.

Apart from procedure flyability, the second objective of the research was to evaluate assumed passenger ride quality and passenger acceptance of various glidepath angles and deceleration rates, to include a steeper 12-degree approach with a delayed deceleration point low and close into the landing site (Fig. 2). Flight test data was provided to the FAA Civil Aeronautical Institute (CAMI) to verify if the procedures produced any perceptible discomfort against a healthy male pilot. The CAMI G-Effects Model (CGEM) software used acceleration data and participant (pilot, centrifuge test subject or other person) physiology to calculate medical symptom onset and recovery times for the most notable symptoms of sustained high-Gz accelerations [6]. The flight test data was run through CGEM and used to evaluate the safety of several flight segments provided by Sikorsky OPV UH-60 inertia data for final approach, descent, hover, and touchdown. For the passenger comfort simulations, a male pilot physiology of normal g-resistance was used without countermeasures or other influences. Each flight segment was examined for safety of the vehicle pilot and occupants with respect to acceleration along the z-axis experienced during the maneuvers. For all segments, the simulation analysis indicated no expected symptoms or significant deviations from normal flows in any tracked regions. Thus, no significant impacts on pilot performance or passenger comfort due to experienced Gz accelerations are expected during the proposed experimental flight procedure.

Due to flight time constraints, not all the planned procedures (5-, 8- , and 12-degree) and variants (constant-rate and delayed deceleration) and automation generators (NASA MW and Sikorsky AMM) were flown. Instead, the NASA MW was used to perform all of the constant-rate deceleration profiles and the Sikorsky AMM was used to perform all of the delayed deceleration procedures. The intent of the test was to evaluate the suitability of the procedure and not compare automation or route-generative systems. Additionally, all flights were performed in day VMC without a hood for the subject pilot. All flights during test were flown in Class D airspace in coordination with the air traffic control tower.

IV. Findings

Several aspects of the experimental procedure were evaluated to include biometrics of the pilot, tailwind abuse cases, 4DT route conformance, as well as hover and landing accuracy. Nineteen approaches were conducted throughout the campaign. The landings applied a range from 5-, 8-, and 12-degree approach path angles which included constant-rate deceleration and delayed deceleration initiated low and close into the landing area. For the purpose of brevity, only the 12 -degree approach data follows and is featured because it is the most aggressive of the procedures and most widely applicable for any adaption with a lesser descent/deceleration angle. The flight test data was interpolated into a 3D visualization, and due to the automation dynamically autogenerating trajectories, the deviation between the commanded trajectory and the actual flight paths generated were aggregated and proved to be minimal (Fig. 3).

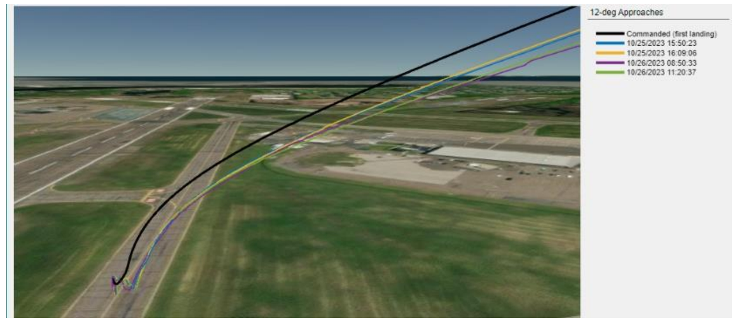

Fig. 3. 12-degree approach profile.

A. *Biometric Evaluation*

The NASA research pilots were equipped with various biometric devices before each flight. Specifically, the pilots were outfitted with mobile functional near-infrared spectroscopy (fNIRS) (Artinis PortaLite fNIRS, Einsteinweg, Netherlands), the Zephyr Performance Bioharness (Medtronic Zephyr, Boulder, CO, USA), and the Tobii Pro 3 wireless eye trackers (Danderyd Municipality, Sweden). Since biometric acquisition and autoland data were secondary objectives in this flight test series, limited biometric data was obtained in the context of this report. Consequently, this report focuses solely on the summary results of the eye-tracking data.

The raw eye-tracking data were processed using Tobii Pro Lab software to generate automated mappings of gaze over time. The snapshots used for the automated mapping and visualization in the result graphs were created by cropping frames from the first-person view of the acquired Tobii data. Given the dynamic nature of the data collection environment, eye-tracking data was filtered using Tobii's built-in Velocity-Threshold Identification Gaze Filter, with the velocity threshold parameter set to 100 degrees-per-second for attention tracking and a duration limit of 100ms. All other filter parameters were left at their default settings. The data presented in this report are limited to a single autoland approach. For further details and results regarding biometric data acquisition during this flight test series, reference Monk et al., 2024 [7].

Fig. 4 displays a heatmap overlay of the flight deck, including the research tablet and the approach plate, illustrating the eye-tracking attention distribution during a single NASA software autoland procedure. The attention distribution is detailed by varying color intensities, with areas shaded in red indicating regions where the pilot's gaze lingered the longest and most frequently. These red zones highlight the areas of greatest cognitive engagement, representing critical information or procedural check that demand prolonged and repeated scrutiny by the pilot.

The approach plate is enlarged in Fig. 4 for better visibility, with the heatmap overlaid to emphasize the document's contents. The attention heatmap on the approach plate reveals focus on three vital sections: the overhead view and the profile view of the approach (when combined referred to as the Approach Diagram), the Missed Approach section, and the Connecting Vertiports section. The Approach Diagram serves as a visual guide through the precise flight path, encompassing key fixes and altitudes necessary for a smooth and secure descent and landing. The Missed Approach and Connecting Vertiports sections provide information for contingency planning. The pilot's greatest fixation was on the condensed Sikorsky primary flight display on the far-right side of the flight deck. This directly relates to the pilot cross- monitoring the aircraft performance with the approach plate and route generator. This confirms the use of the approach plate as a primary information source as the window becomes secondary for the pilot on a coupled approach under VMC.

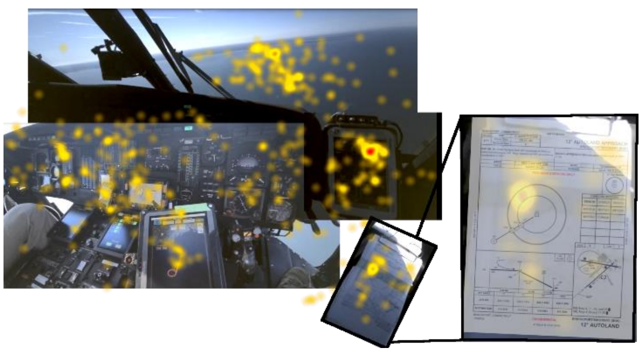

Fig. 4. Attention-tracking heatmap results across flight deck and approach plate during 12-degree autoland approach procedure.

Fig. 5 shows the saccades (quick, simultaneous movement of both eyes between two or more phases of fixation in the same direction) in between fixations (over 100ms). The analysis concludes that the majority of the approach plate fixations either preceded or occurred after looking out the window. As such, the window, vehicle parameters, and approach plate become the center of the pilot scan. As more automation is introduced to the flight deck for lower altitude operations, pilot scanning techniques may need to change to cross-monitor the engine performance akin to an IFR operation utilizing the window to confirm the waypoint or 4DT conformance (Fig. 5).

Overall, this type of data not only documents the pilot's visual behavior, but also underscores the importance and utility of the approach plate in the process of a software-driven autoland procedure. Although in this particular trial attention was more heavily oriented out of the window and at the Sikorsky research display (above the approach plate), the usage of the approach plate still indicates it as an important navigational tool. By highlighting where the attention is predominantly directed, it offers insights into the design and informational relevance of approach plates, which can inform improvements for future procedural human-machine interfaces used in aviation.

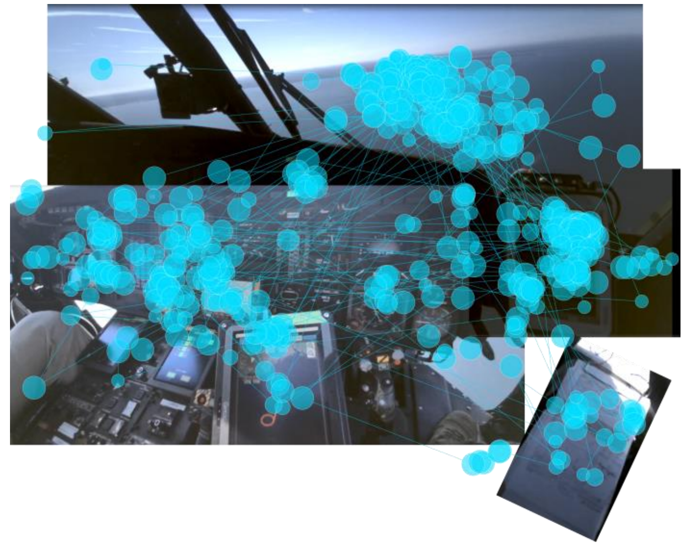

Fig. 5. Attention-tracking scan results across flight deck and approach plate during 12-degree autoland approach procedure.

B. Tailwind Abuse Case

Every approach was flown with a greater than 20 knot direct tailwind to exercise the tailwind abuse case for the experimental autoland approach procedure. The rule of thumb for conducting a tailwind approach is that for every 10 knots of direct tailwind one degree is added to the final approach path. The OPV was able to execute every procedure and was not environmentally limited by the tailwind condition nor the rapid deceleration tested.

Fig. 6 highlights the 20-knot tailwind evident in the disparity between the ground speed deceleration to zero and the indicated airspeed deceleration to zero. Five knots was used to indicate when the aircraft was in an aerodynamic hover, which defines the use of out-of-ground effect (OGE) or in-ground effect (IGE) required increase for torque, respectively. In Fig. 6, the airframe almost immediately entered an aerodynamic hover after it crossed the FAF. This can be important when dealing with a power-limited aircraft such as a high-altitude, high temperature and maximum gross weight environmental condition which would require the aircraft to generate more than anticipated power required for the safe approach and landing. This can also be of particular importance when considering alternate energy sources such as electric propulsion for the eVTOL community. As evident by the data in Fig. 6, an approach with such a tailwind could be detrimental for an eVTOL by introducing a hover that is required earlier than anticipated for which the aircraft system may not have the thermal envelope protection to manage the unanticipated prolonged hover time while on the constant-rate or delayed deceleration [8]. The main mitigation for this would be to optimize wind alignment for a power-limited or temperature-limited aircraft operating within such margins.

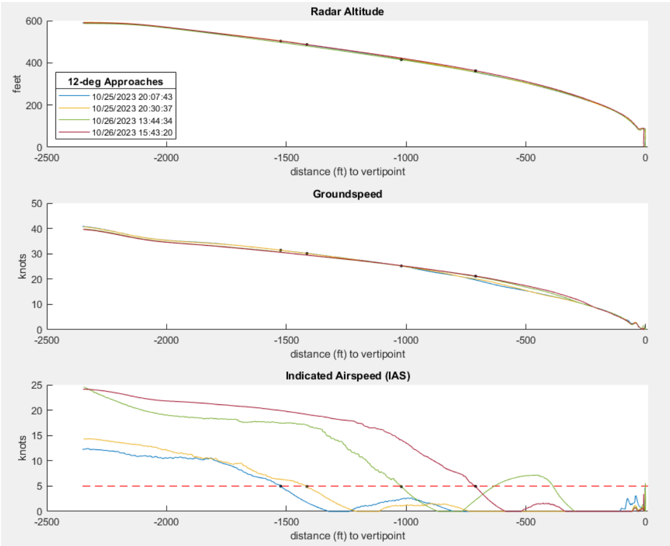

Fig. 6. Aggregate profile view of airspeed, altitude, and deceleration.

C. Hover point termination and landing accuracy

The automated termination to a hover and subsequent transition to land without the pilot on the controls is the greatest delta from traditional instrument approach procedures and the experimental procedures flown for the flight test. Due to this uncharted territory, the approach was evaluated in two ways: 1) fore/aft, lateral, and vertical accuracy with time duration in hover and 2) actual scatter plot of the landing characterized by the activation of the weight on wheels switch.

Fig. 7 showcases the three dimensionally accuracy of the automation when transitioning to a hover, defined by zero forward airspeed and zero vertical velocity. Once stabilized, the aircraft was allowed to execute the land command that was verbally approved from the ground control station. When attempting to validate a procedure, the NASA IAS team attempted to characterize notional containment areas that were predicted from simulation exercises in order to baseline 2- and 3-sigma deviations.

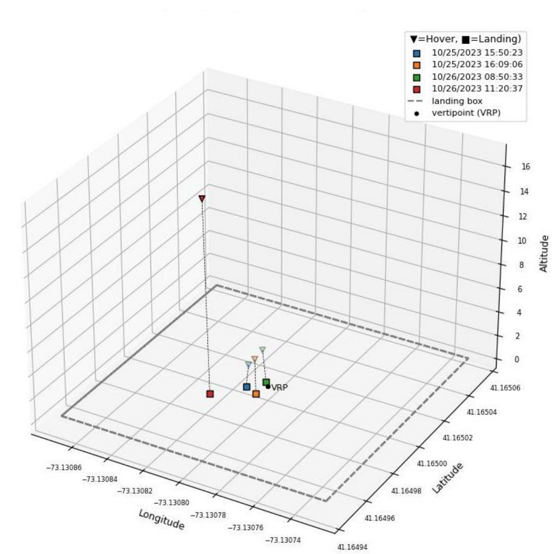

Fig. 7. 3D hover termination point scatter plot.

Fig. 8 is a collection of 12-degree autoland approaches and the deviations from the VRP. The system is given the same high-precision latitude and longitude target located at the center of the landing surface. The center point of the aircraft was defined by the middle of the airframe between the forward landing gear. Although success criteria is defined by a center point range anywhere in the 54 ft by 54 ft landing area (Fig. A-3), all landings were withing a 12 ft radius of the VRP. The landing point groupings substantially exceeded expectation for the flight test. Due to all procedures terminating to a hover, the landing accuracy appears to be independent of the approach angle and deceleration rate.

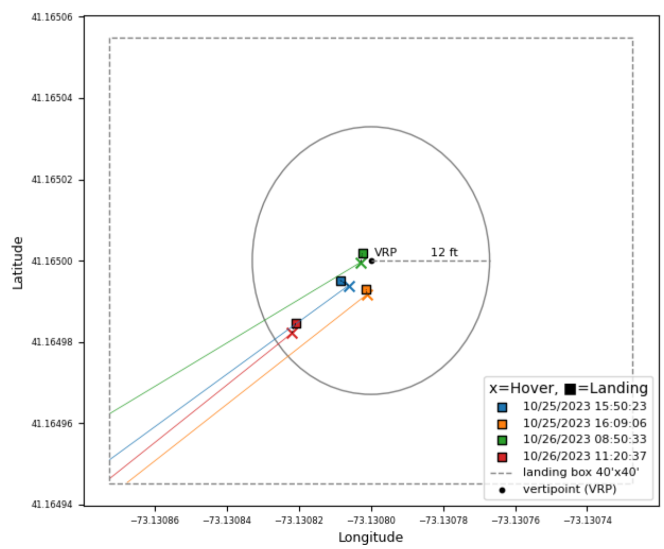

Fig. 8. Overhead landing scatter plot.

D. Conformance to approach trajectories

The 4DT for the approaches can be checked for the aircraft's ability to follow the trajectory with both position and time as conformance metrics.

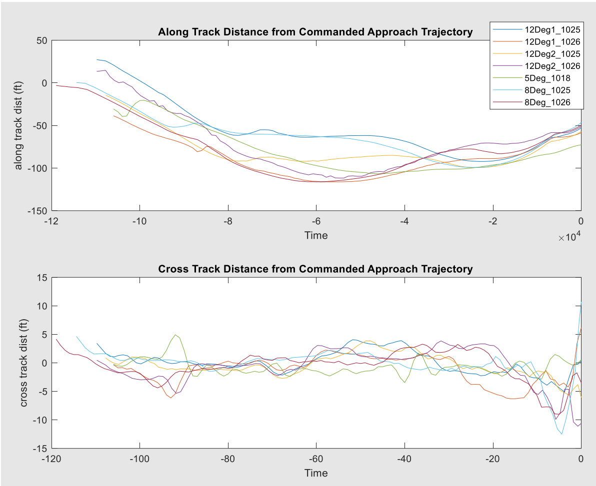

Fig. 9. Postion conformance to commanded approach trajectory.

Fig. 9 above shows cross-track and along-track distances. The aircraft was compared to where it should have been according to the time-based 4DT created for the approach. The conformance was calculated using each point in the 4DT and the actual location of the aircraft at the corresponding time. Positive along-track errors indicate that the aircraft was ahead of where it should be on the trajectory. For the majority of the approach, the aircraft is behind,which is most likely due to a combination of the deceleration required and the tailwinds present during each approach. The cross-track distances are typically within 5 ft of the trajectory path (positive values means to the left of the path). The time conformance to the trajectory is shown in Fig. 10 and is estimated by taking the distance between the point in the 4DT and actual position and dividing by the current ground speed. As the aircraft approaches hover, it causes the time conformance to shoot up even as the distance lowers.

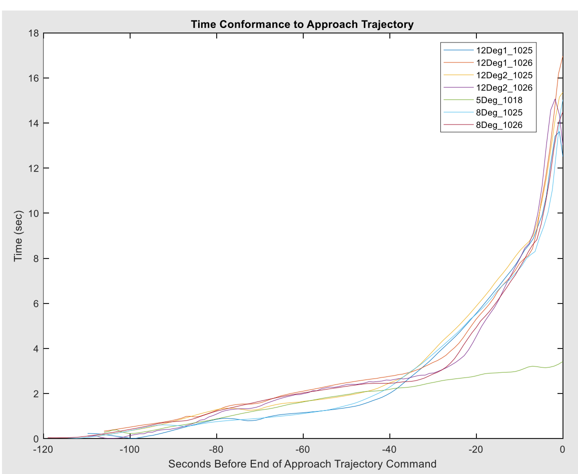

Fig. 10. Time conformance to approach trajectory

E. Summary of Findings

Although data is collected for all of the approaches, data from the 12-degree approaches is analyzed for this report. The biometrics provide useful information from the flight deck, which highlights specific instrumentation utilized to monitor the performance of the vehicle and cross-monitor the conformance of the automation for the dynamically generated routing/trajectories. Additionally, the eye-tracker glasses provide useful information indicating the experimental instrument approach plate is paramount during the approach maneuvers and emphasizes utilization of specific subcomponents of those parts. The tailwind abuse case provides critical information to incorporate the optimization of wind alignment for aircraft operating within close power margins and/or with unique propulsion mechanism limitations, such as battery thermal envelope protection. The route conformance is well within the highest precision approach 2-sigma containment area and exceeds all primary and secondary area configurations while operating in 3D waypoint (or "goal following") as well as every 4DT dynamically generated procedure. The landing accuracy of the NASA MW and Sikorsky AMM 4DT exceeds every existing allotted autopilot deviation in the fore-aft, lateral, and vertical axis. Due to the procedures terminating for a hover before final descent to touchdown, the landing accuracy of the aircraft is independent of the approach angle and/or deceleration rate applied during the final approach to land.

V. Conclusion

The flight test evaluation of autonomous descending-decelerating precision PinS approach to the ground is the first procedural PinS flight test of its kind. The research and findings are applicable to existing rotorcraft, the emerging eVTOL industry and barriers that need to be overcome to enable the integration of AAM. The autoland procedures tested explore the optimization required to align into the wind to protect the vehicle performance envelope. Future automated landing procedures may be architected with an omni-directional 'wheel' approach and departure to enable safe landings considering dynamic wind conditions. Additional research is also required to evolve approach plate interfaces towards calculations and updates for changing atmospheric and traffic conditions. Furthermore, passenger comfort will be a key factor for the types of approaches that will ensure flyability and public acceptance for ride quality to enable the future business cases for increasingly automated operations. If implemented the precision PinS approach research could save lives by making IFR approaches widely available to any location that can be accessed vertically. The approach design and methodology could directly impact the vertically performing medical evacuation, military, and air taxi services that have traditionally sustained the lowest safety rating of any aeronautical operation. This research will have an immediate economic and tactical impact, where implemented, and greatly increase the safety margins for compensation-for-hire, passenger-carrying operations that have been plagued by degraded visual environment accidents.

APPENDIX

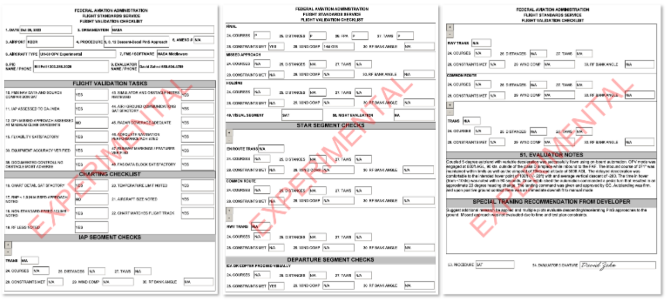

Fig. A-1 Experimental FAA Form 8260-30.4, IFPV Evaluator Check Record.

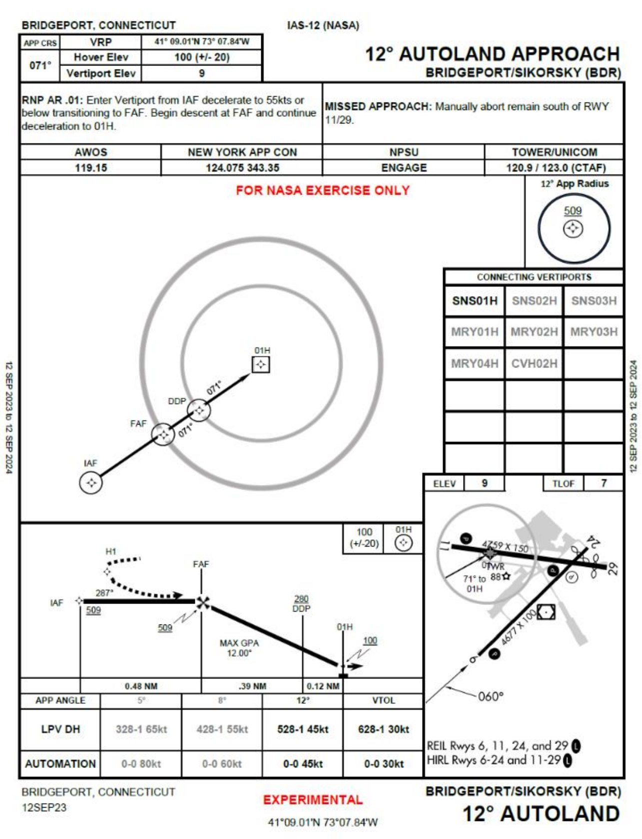

Fig. A-2 Experimental 12-degree Autoland Approach Plate.

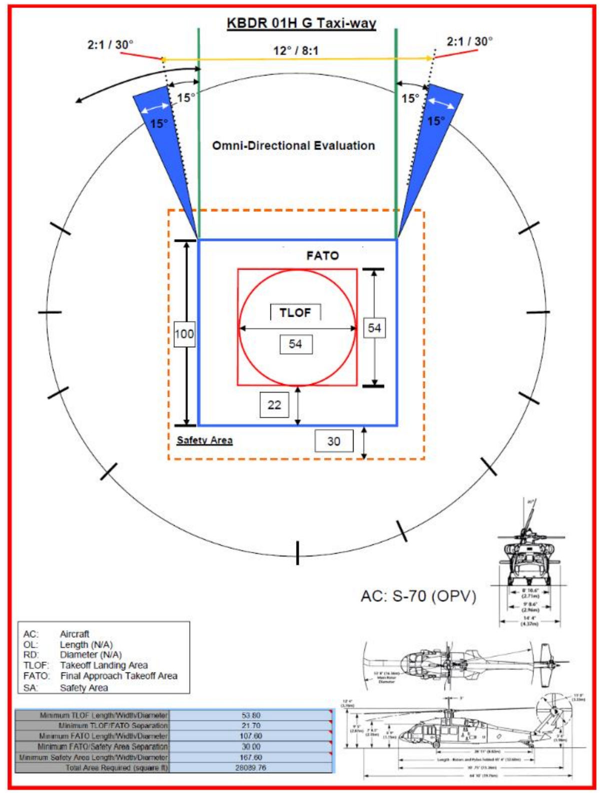

Fig. A-3 KBDR Landing Site Evaluation Worksheet.

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