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UAM Instrument Flight Procedure Design and Evaluation in the Joby Flight Simulator

National Campaign Joby Activity Team

Abstract

NASA’s Advanced Air Mobility (AAM) National Campaign (NC) partnered with Joby Aviation to test and evaluate different developmental candidate Urban Air Mobility (UAM) Instrument Flight Procedure (IFP) designs including new departure, enroute, approach and missed approach architectures using Joby’s high-fidelity engineering aircraft simulator. In conjunction with the simulator testing, this effort also evaluated related aspects such as charting, coding, and adherence to flight planning criteria. The test objectives were to assess the safety, efficiency, passenger comfort and noise of the different variations of the developmental IFPs. Safety-related measures include clearance from terrain and vertical obstructions, procedure flyability, and flight path conformance. Efficiency-related measures included time required, airspace volume required, and battery energy required. Passenger comfort and ride quality measures include roll/pitch angles, roll/pitch attitude change rates, and airspeeds prior to aggressive maneuvers, subjective pilot/passenger responses and acceleration forces. The noise impacts of the different IFPs will be interpolated/extrapolated using data from the simulator fed into a separate Joby acoustic software-based tool. Overall, several tradeoffs were identified and characterized between the different variations of the developmental IFP profiles. No single version of the developmental IFP structure scored highest across all measures listed above; rather, different IFP variations proved optimal for different measures, confirming that the best IFP depends on which specific measures are prioritized for a given aircraft, location and operation.

Revision History

Rev	Date	Sections Affected	Description of Change	Who
0	2/24/2023	NA	Original	NC Joby Activity Team

Authors	
David Zahn NASA Ames Research Center	**Andrew Guion** NASA Armstrong Flight Research Center
Ryan Naru Joby Aviation	**Sarah Eggum** Federal Aviation Administration, Leidos
Contributors	
Brad Snelling NASA Armstrong Flight Research Center, American Systems Corporation	**Ledger West** NASA Ames Research Center, Mosaic ATM
Robert Hamilton Federal Aviation Administration, AJV-A443	**Tim Bagnall** NASA Ames Research Center, Mosaic ATM
Sean Barbee Federal Aviation Administration, AJV-A442	**Jerry Wilwerding** NASA Ames Research Center, Mosaic ATM
Tom Burton Federal Aviation Administration, AJV-A443	**Daiven Patel** NASA Ames Research Center, Mosaic ATM
Sean Clarke NASA Armstrong Flight Research Center	**Kyle Copeland, Ph.D.** Federal Aviation Administration, AAM-631
Lane Ramirez Federal Aviation Administration, AFS-430	**Susan Jay, Ph.D.** Federal Aviation Administration, AAM-631
Bernard *‘Dov’* Adelstein, Ph.D. NASA Ames Research Center	**Brad Drake** Federal Aviation Administration, AUS-440
Research / Test Pilots	
Wayne *‘Ringo’* Ringelberg NASA Armstrong Flight Research Center	**Aaron Poidevin** Joby Aviation
Scott *‘Jelly’* Howe NASA Armstrong Flight Research Center	**Peter *‘Wizzer’* Wilson** Joby Aviation
Gerrit *‘BLNG’* Everson NASA Armstrong Flight Research Center	**Sean *‘Garmin’* Doyle** Joby Aviation
David *‘Dizzy’* Zahn NASA Ames Research Center	**Ryan *‘Zombie’* Naru** Joby Aviation
VSIL Simulator Test Support	
David Oda Joby Aviation	**Denise Bellamy** Joby Aviation
Bradley Stemm Joby Aviation	**Scot Hathaway** Joby Aviation
Chaitanya Neelamraju Joby Aviation	**Gary Anglin** Joby Aviation
Zach Reeder Joby Aviation	**Erik Lassen** Joby Aviation

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1 Introduction

The current level of safety and efficiency in today's National Airspace System (NAS) is supported by Instrument Flight Procedures (IFP) which define specific departure, enroute, and approach routes with adequate terrain and obstacle clearance. This standardization benefits operators and air traffic controllers. The Advanced Air Mobility (AAM) infrastructure may require equivalent IFPs for unique aircraft performance, shorter route structure, and traffic density. An experimental IFP was developed which combines the departure, enroute, and approach segments into a single procedure called "deproach". Several deproach IFPs were tested in the Joby S4 engineering simulator [1] and evaluated against measures of performance related to safety, efficiency, and passenger comfort. This working paper reports preliminary findings, conclusions, recommendations, and thoughts for future research.

1.1 UAM/eVTOL IFR-like Procedures

Instrument Flight Procedures (IFPs) are predetermined sets of maneuvers with specified protection from obstacles for safe operations and orderly traffic flow. IFPs offer benefits of standardization, obstacle clearance, noise abatement, and traffic separation. Different IFPs exist for different aircraft performance categories. Terminal IFPs are designed exclusively in accordance with very detailed standardized methods and criteria Terminal Instrument Procedures (TERPS) considering factors such as airport airspace, infrastructure, nav facilities, obstacles, weather info and communications. Terminal IFPs are tailored to different airports with considerations for prevailing winds, geography, terrain, noise, obstacles, and traffic flow. Neither Instrument Flight Procedures (IFP)s nor IFP design/evaluation criteria (TERPS) currently exist for emerging needs like electric Vertical Take-off and Landing (eVTOL) aircraft, Urban Air Mobility (UAM) operations, or vertiports. The goal of this work is to progress toward development of design criteria (TERPS) for UAM/eVTOL IFR-like procedures of the FAA 8260 series orders. [2]

The hypothesis that underpins this research activity is that numerous potential benefits will be realized if IFR-like structured constructs and standardized instrument flight procedures are applied to future UAM and eVTOL aircraft operations. IFR-like structures for UAM will not only enable flight in IMC but also provide better standardization, predictability, consistency, and levels of safety not guaranteed by Visual Flight Rules (VFR)-like operations. IFR-like structures will enable much greater capacity for higher volumes of aircraft operations. FAA 8260 series orders prescribe very specific and detailed standardized methods for designing and evaluating IFPs for fixed wing and helicopter aircraft; the goal for this research is to contribute toward development of equivalent IFP design and evaluation criteria for eVTOL aircraft conducting UAM operations.

Currently, many thousands of IFPs exist for existing types of legacy aircraft and typical operations but these IFPs are inadequate for future UAM operations for several reasons. Instrument departures & arrivals to/from the ground do not exist for rotorcraft. Fixed wing IFPs require large volumes of airspace which would be incompatible with envisioned urban operations and airspace constraints. IFPs are currently very expensive to develop due to a high degree of manual evaluation required in the design process, and the current design process is not upwardly scalable for the anticipated number of vertiports.

1.2 Benefit to the Public

The expected benefits of this research may include validation of a safe and scalable airspace architecture model that will enable the UAM business use case. The measures of performance will help inform future UAM criteria, policy, and regulations to standardize airspace evaluation and procedure development and may help avoid overtaxing FAA resources. The research aims to lay out methods to evaluate novel IFP designs for precision approaches suited for eVTOL characteristics. Eventually, tests like these may contribute to validation of candidate instrument flight procedures, which integrate a precision approach with a descent and deceleration profile to a point in space on the ground, in contrast to current helicopter approaches which end at a Visual Descent Point (VDP) and require a visual or VFR transition to the ground. In the future, this research could be extended to explore a conservation of airspace model and coding construct that includes departure, enroute and approach coding with waypoint restrictions covering speed, altitude, and navigation and battery requirements. This research recommends a balanced approach to weigh flight path profile tradeoffs between passenger comfort, efficiency, ambient noise and urban airspace constraints to maximize public acceptance for a scalable UAM airspace architecture.

2 Pathfinder Research

2.1 Scalability

National Campaign (NC) candidate UAM procedure design test objectives are organized to evaluate how scalable the IFPs are across the two axes: phase of IFR flight and four categories of metrics. The four phases of IFR flight are departure, enroute, missed approach and final approach. Scalability is the evaluation criteria for the candidate IFPs and includes measurements to characterize safety, efficiency, passenger comfort and acoustics. Safety-related measures include clearance from terrain and vertical obstructions, procedure flyability, and flight path conformance. Efficiency-related measures include time required, airspace volume required, and battery energy required. Passenger comfort and ride quality measures include roll/pitch angles, roll/pitch attitude change rates, airspeeds prior to aggressive maneuvers, subjective pilot/passenger responses and acceleration forces. The Joby simulator did not directly provide noise data for the different IFP designs, but the noise impacts of the different IFPs were interpolated/extrapolated using data from the simulator fed into a separate Joby acoustic software-based tool. The expected acoustic signatures of the different IFP designs will be characterized after the sim testing to enable comparisons of different airspeed, altitude, and transition mode profiles. The NC Research Focus areas are illustrated below in Figure 1.

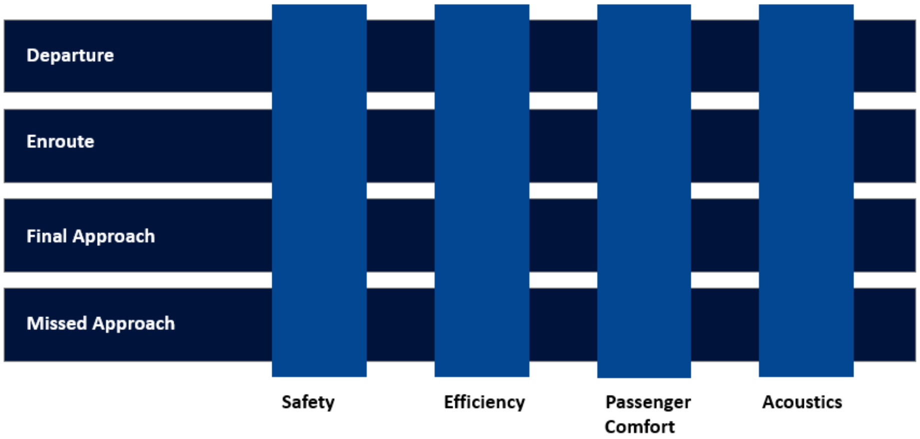


Figure 1. National Campaign simulation pillars

Safety

Safety for this pathfinder research is defined using existing instrument flight procedure policy, criteria, regulations, and standards governing the respective areas of departure, enroute, and approach for Performance Based Navigation (PBN). [3] Safety-related measures include clearance from terrain and vertical obstructions, procedure flyability, and flight path conformance. Due to certain UAM flight profiles existing outside of current regulations, the NC procedure team used the same ratios of safety outlined in the FAA Order 8260 series that include evaluations and obstacle clearance surfaces, enroute tracking, required navigation performance, and primary/secondary areas of operations. The NC procedures team also strived to maintain the same ratios of safety in spacing, sequencing, and separation representative of operations in the urban environment as seen in Figure 2 below. [4] The test results are meant to explore the UAM use case and highlight focus areas that will need additional research to make the UAM operational use case a reality.

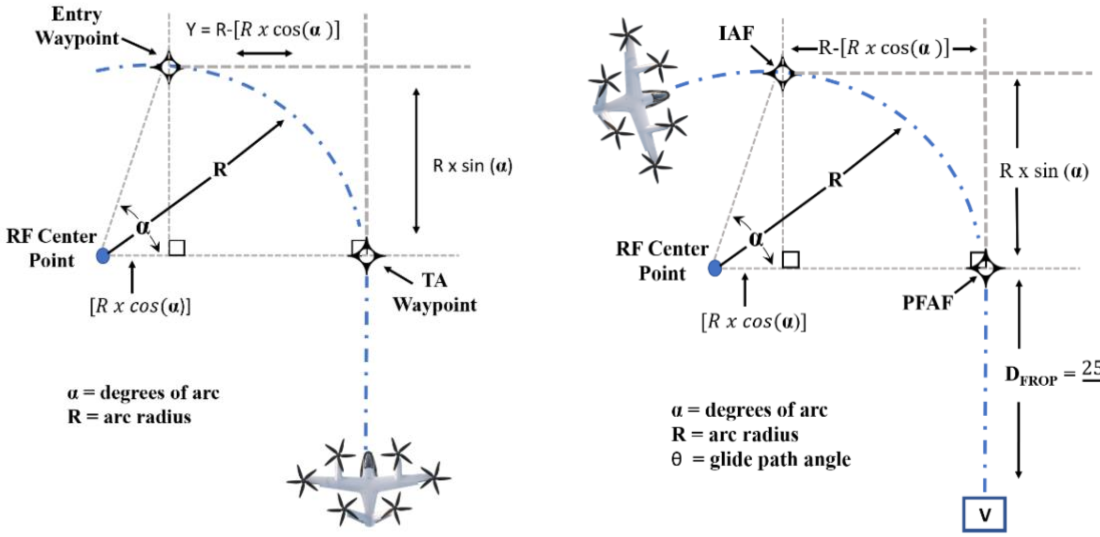


Figure 2. Departure/approach TF-RF construction

Efficiency

Once procedural safety has been established, the candidate procedures are measured for efficiency. Procedure efficiency is baselined by analyzing and comparing different Joby S4 vehicle configurations exercising the vertical axis in take-off and landing utilizing electric propulsion. Efficiency-related measures include time required, airspace volume required, and battery energy/temperature required. Currently no government or industry standards are in place to measure conformance in these areas. The NC procedure team set out to explore the optimization of the departure and approach profiles to balance battery energetics/temperature, time, and airspace volume. The measure of efficiency for airspace volume required are derived by comparing current departure and approach procedures with an equivalent level of safety for new precision operations. The measure of efficiency for the S4 battery energetics is derived by directly comparing kwh required for different airspeeds at steeper climb or approach gradients with departure and approaches representative of the urban environment. [5] Figure 3 (below) displays a CFD simulation of a single propeller and nacelle at an advance ratio of μ = 0.09 and angle of attack αp = 95◦, showing Q criterion isosurfaces colored by vorticity, followed by resultant power requirements for the Joby S4 (below). Efficiency was derived from the current Joby S4 torque and battery performance models.

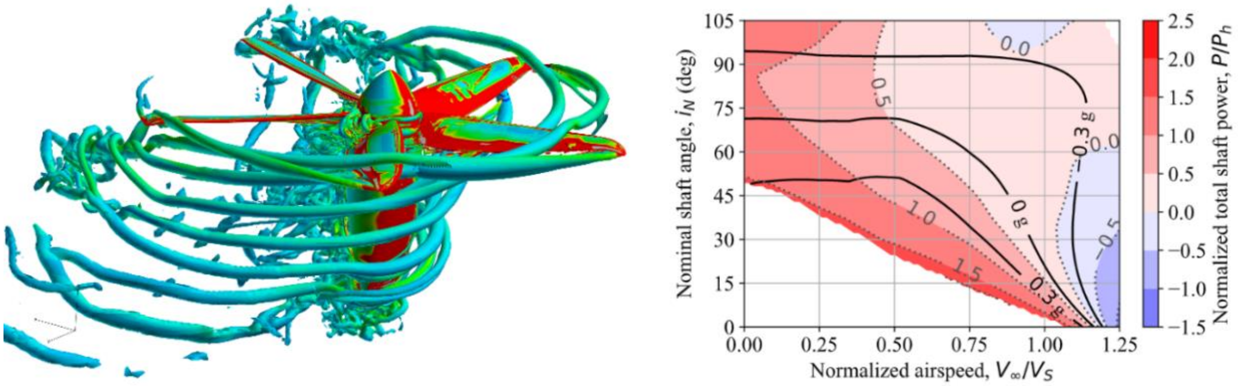


Figure 3. CFD simulation of S4 single propeller (left) S4 power requirements at α = 12◦ (right) [1]

Passenger Comfort

Pathfinder passenger comfort is derived from combinations of acceleration: linear and rotational (angular) acceleration. Vibration and response to turbulence are important aspects of passenger comfort, but for the limited considerations available through the study, linear and rotational accelerations were considered. Linear acceleration reflects a change of speed in a straight line. This type of acceleration normally occurs during take-off, landing, or in-level flight when a power setting is changed. Rotational acceleration, results from a simultaneous change in both speed and direction, which happens in climbing and descending turns. At a high-level, the body axis orientations are color-coded in the pitch, roll, and yaw axis respectively in the Figure 4 below. [6]

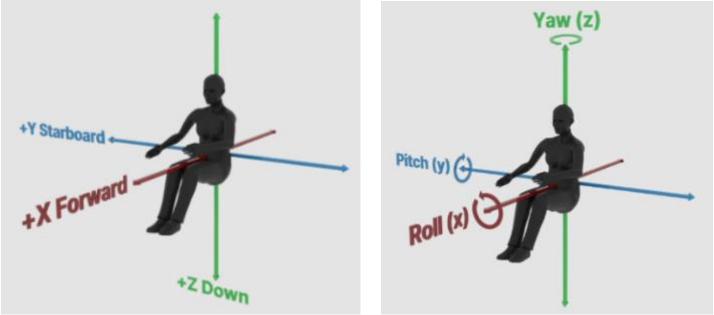


Figure 4. Body axis orientation (left) Rotational accelerations (right)
Credit: Joby Aviation

Currently no regulations, criteria, or industry standards exist for eVTOL passenger comfort. Due to the lack of information, the NC team used equivalent levels of acceptable passenger comfort in the vertical and lateral axis for commercial transportation proxies. Passenger comfort and ride quality measures include roll/pitch angles, roll/pitch attitude change rates, and accelerations prior to aggressive maneuvers, and subjective pilot/passenger responses. As a pathfinder test, equivalent levels of ride quality and comfort were researched to create a baseline to compare the candidate UAM procedure comfort as in Figure 5 below. The assumed passenger comfort metric for the vertical axis, takeoffs, and landings were compared using an acceptable level of comfort in common elevator operations. This is considered extremely conservative because the elevator metric is derived from a standing passenger while UAM operations will have seatbelt-restrained passengers who may be willing to tolerate higher g-levels because they will not be or feel at risk of falling over. [7] Additionally, data was compared to sustained translational acceleration limits for seated passengers by NASA [8]: G_x 137 m/s^2, G_y 19.6, G_z 19.6 > 0.5 sec. The vertical motion for slowly varying oscillatory rates was compared against motion sickness guidance provided in ISO standard 2631-1 Annex D. [9] The derived cross-coupled rotational rates from the Joby 4 flights are compared to levels in NASA Standard 3001 Volume 2 Revision C Section 6.5.2.2 (2.0 rad/sec^2) as the procedure transited the applicable flight profile to the assumed passenger comfort baseline. (See Appendix D)

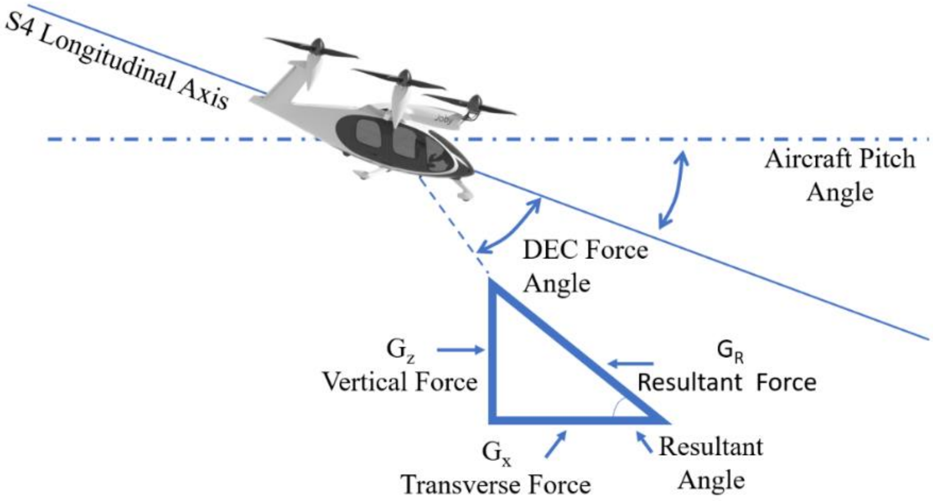


Figure 5. Resultant passenger comfort

Acoustics

Noise impacts may be interpolated/extrapolated from data obtained in previous 2021 Joby-NASA acoustic flight tests. The expected acoustic signatures of the different IFP designs can be characterized in association with sim test results to enable comparisons of different airspeed, altitude, and transition mode profiles. The Joby team developed an advanced acoustic model tool in conjunction with NASA that generates hemispheric data, as seen in Figure 6 below, which projects representative decibel exposure through each flight segment. [10]

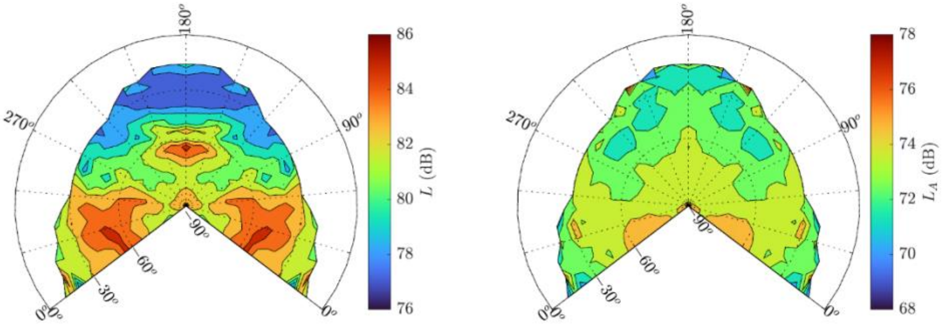


Figure 6. S4 hemispheric data for 60 kt constant airspeed level flyover
Credit: Joby Aviation

Joby's software-based noise tool "AAM" was developed to predict overall or instantaneous sound propagation for flight scenarios. It can animate a fly-over and generate POI time histories, broad-band or narrow-band, accounting for non-linear propagation and atmospheric absorption. The tool requires comprehensive 3D source data for tilt, velocity, pitch, Angle of Attack (AoA), etc., which could in the future be provided from the simulator data. Output metrics include maximum A-weighted sound level (Lmax), Sound Exposure Level (overall, C-, A-weighted) (SEL), Perceived Noise Level (PNL), Tone-Corrected Perceived Noise Level (PNLT), Effective Perceived Noise Level (EPNL), Day-Night Average Sound Level (DNL), and Community Noise Equivalent Level (CNEL).

Joby was able to validate and improve computational modeling of their aircraft acoustics leveraging experimental data from the acoustic flight test of the Joby preproduction prototype aircraft during the National Campaign Development Test (NC-DT). Those previous flight tests consisted of flyovers from 50 to 110 knots and the data was used to generate acoustic hemispheres. The flight test had more than 100 test points that were flown at 31 unique conditions. This included numerous different approaches and departures. More details of the flight test are documented in the final report and subsequent publication at the 28th AIAA/CEAS Aeroacoustics Conference [10].

The aircraft is modeled using the NASA unsteady Reynolds-Averaged Navier-Stokes code OVERFLOW 2.3e. The flow solution implements Delayed Detached Eddy Simulation (DDES) with a fifth order HLLE+ upwind scheme and the SSOR algorithm. Laminar-turbulent transition is predicted via the Amplification Factor Transport (AFT) Transition model. The predicted surface flow variables are then exported as triq triangulation files for the airframe and propeller blades. The averaged flight test measured angle of attack, ruddervator angle, propeller tilt, propeller pitch, and propeller RPM are used to initialize the case. Then, each case is trimmed for lift and pitching moment by adjusting the aircraft angle of attack and propeller pitch. The unsteady surface pressures are converted into PSU-WOPWOP 3.4 format to conduct impermeable surface acoustics simulations. The semi-empirical Brooks, Pope, & Marcolini model is used for broadband noise prediction as in Figure 7.

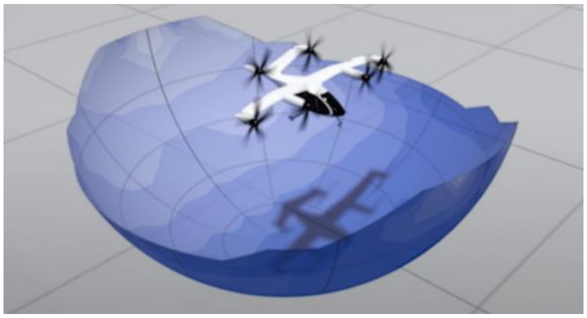


Figure 7. Acoustic evaluation sample data
Credit: Joby Aviation

An approach or departure can also be simulated using computed hemispheres representing several points in the trajectory. The hemispheres together with the measured flight path data are then provided to the Advanced Acoustic Model from the U.S Department of Transportation's Volpe Center. The results from the computational toolchain are being validated using the measured data from NC-DT test for flyovers, approaches, and departures in Figure 8. This process could be used together with data from the flight simulator to evaluate noise associated with different IFPs in the future.

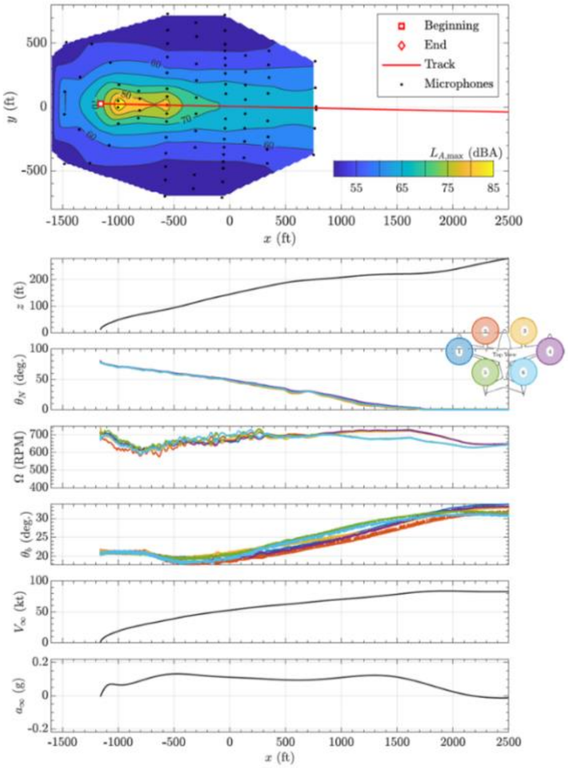


Figure 8. LA max ground noise contour for a departure test point from the NC-DT test campaign.
Flight direction is left to right. [10] Credit: Joby Aviation

2.2 Research Setup

2.2.1 Research Objectives

The objectives and measures of the IFP test plan are broken down into a structure of general test objectives (GTOs), specific test objectives (STOs) and measures of performance (MOPs) in Table 2 below. These GTOs, STOs and MOPs have direct traceability to the overarching subproject-level NC Objective #2 and can be summarized by the overall test activity objective in Table 1.

Table 1. High-Level Objectives

RESEARCH HIGH-LEVEL OBJECTIVES	
Overarching NC Objective	**NC #2 - Develop Flight Procedure Guidelines** Develop preliminary guidelines for flight procedures and related airspace design criteria.
Overall Test Activity Objective	Assess the scalability of candidate Instrument Flight Procedures (IFPs) for UAM eVTOL aircraft to contribute to standardized methods for designing and evaluating UAM eVTOL IFPs akin to FAA Order 8260 series for fixed wing and helicopter aircraft.

Table 2. Simulator Test Objectives

RESEARCH OBJECTIVES		
GTO 1	**‘Deproach’ Instrument flight procedures design criteria** Evaluate suitability and operational safety of candidate UAM/eVTOL IFP ‘deproach’ design criteria, across different climb gradients including fast acceleration, optimized climb, and precision climb; different final and missed approach segments at steeper 5°, 8° and 12° glide paths; and with and without available automation features.	
STO 1	**Terminal Infrastructure** Validate potential/proposed requirements for obstacle clearance surfaces and vertiport landing area dimensions for eVTOL IFR operations.	
MOP 1.01	Experimental ‘deproach’ IFP development in TARGETS and OEA execution for area that corresponds to deproach radii for 5°, 8° & 12° glidepath angles	
MOP 1.02	Characterize landing area scatter to partially validate potential TLOF, FATO & SA dimensions	
STO 2	**Coding & Approach Plates** Validate usability and simplicity of candidate ‘deproach’ IFP coding (ARINC 424) and Instrument Approach Plate for UAM eVTOL use case.	
MOP 2.01	UAM candidate IFP code creation and ground validation via FIAPA	
MOP 2.02	eVTOL flight management system data ingestion	
MOP 2.03	Correct display of nav guidance on PFD and route on MFD	
MOP 2.04	Manual IFP execution using paper instrument approach plate	
MOP 2.05	Assess code complexity (number of legs) for deproach versus standard IFPs (sum total of MA, departure, arrival), normalized for number of departure & arrival azimuths	
MOP 2.06	Assess ability to easily duplicate deproach code at disparate locations/vertiports, versus conventional IFP development	
STO 3	**Departure** Validate and qualitatively assess candidate departure procedures with various climb gradients representing fast acceleration, optimized vertical profile and a precision climb gradient including departure from hover taxi, departure from rolling taxi, and vertical takeoff, using both pilot and ‘pilot-assist’ augmentation departures. Sim tests will include assessment of vehicle performance criteria and environmental constraints.	
MOP 3.01	Safety	Navigation data verification for desired path
MOP 3.02	Safety	Aircraft departure climb path
MOP 3.03	Safety	Qualitative pilot assessment of procedure flyability, safety and design
MOP 3.04	Safety	Vertical FTE (3σ)
MOP 3.05	Safety	Lateral FTE (2σ)
MOP 3.06	Efficiency	Energy required

MOP 3.07	Efficiency	Battery temperature increase
MOP 3.08	Efficiency	Minimization of airspace volume
MOP 3.09	Efficiency	Minimization of departure time duration
MOP 3.10	Pax Comfort	Linear acceleration
MOP 3.11	Pax Comfort	Rotational acceleration
STO 4	**Enroute/Holding** Validate candidate enroute procedures_and flight plan conformance using both pilot and pilot assist augmentation flown routes across different altitude, airspeed, transition and intercept designs.	
MOP 4.01	Safety	Navigation data verification for desired path
MOP 4.03	Safety	Qualitative pilot assessment of procedure flyability, safety and design
MOP 4.04	Safety	Vertical FTE
MOP 4.05	Safety	Lateral FTE
MOP 4.10	Pax Comfort	Linear acceleration
MOP 4.11	Pax Comfort	Rotational acceleration
STO 5	**Final Approach** Validate and qualitatively assess candidate final approach procedures using both pilot- and autopilot / ‘pilot-assist’ -flown approaches across different altitudes, airspeeds, descent gradients, decelerations, transition rates, intercept angles and glide path angles (5°, 8°, 12°). Sim tests will include assessment at max speeds, worst -case winds and temperature limits.	
MOP 5.01	Safety	Navigation data verification for desired path
MOP 5.02	Safety	Aircraft final approach path
MOP 5.03	Safety	Qualitative pilot assessment of procedure flyability, safety and design
MOP 5.04	Safety	Vertical FTE (3σ)
MOP 5.05	Safety	Lateral FTE (2σ)
MOP 5.06	Efficiency	Energy required
MOP 5.07	Efficiency	Battery temperature increase
MOP 5.08	Efficiency	Minimization of airspace volume
MOP 5.09	Efficiency	Minimization of approach time duration
MOP 5.10	Pax Comfort	Linear acceleration
MOP 5.11	Pax Comfort	Rotational acceleration
STO 6	**Missed Approach** Validate and qualitatively assess different candidate missed approach procedures for terminal area operations. Simulation tests will include assessment of vehicle performance criteria and environmental constraints, including final and missed approach segments at steeper vertical profiles of 5°, 8° and 12°.	
MOP 6.01	Safety	Navigation data verification for desired path
MOP 6.03	Safety	Qualitative pilot assessment of procedure flyability, safety and design
MOP 6.06	Efficiency	Energy required
MOP 6.07	Efficiency	Battery temperature increase
MOP 6.08	Efficiency	Minimization of airspace volume
MOP 6.09	Efficiency	Minimization of missed approach time duration
MOP 6.10	Pax Comfort	Linear acceleration
MOP 6.11	Pax Comfort	Rotational acceleration
MOP 6.12	Safety	Glidepath Decoupling Point Deviation
MOP 6.13	Safety	Distance of Height Loss (2σ)
MOP 6.14	Safety	Flat Surface Length
MOP 6.15	Safety	Departure Intercept Point

2.3 Simulator Description

The Joby S4 Simulator was utilized through Joby’s Vehicle Software Integration Lab (VSIL) in Marina, CA. The S4 aircraft is intended to be operated under 14 CFR Part 91 and Part 135 by Joby or a subsidiary company; the S4 is not intended to be marketed to individual owners/operators.

The S4 will be certified for operating under day and night Visual Flight Rules (VFR); the S4 will not initially be certified for flight in instrument meteorological conditions or for operating under Instrument Flight Rules (IFR). The S4 will not be certified for aerobatics, ditching, or flight in icing conditions. In normal and abnormal operations, the S4 will be operationally limited to thrust-borne and semi-thrust-borne takeoffs and landings. See Figure 9.

Figure 9. Overhead view of Joby S4 model
Credit: Joby Aviation

The S4 vehicle is an all-electric, carbon-composite airplane capable of vertical and rolling takeoffs and landings. The S4 seats one pilot and four passengers with a maximum takeoff weight of 4,800 pound-mass (lbm) and operates at speeds up to 163 Knots Equivalent Airspeed (KEAS) Never Exceed Airspeed (VNE) and altitudes up to 15,000 feet MSL.

The S4 uses a completely electric, advanced Integrated Flight and Propulsion Control System (IFPCS) using Fly-By-Wire (FBW) flight controls with unified control laws, flight control augmentation, and envelope protection to provide safe, easy handling and low pilot workload.

The S4 has six propulsion stations, each with an Electric Propulsion Unit (EPU), tilt mechanism, and five-bladed variable pitch propeller. The propulsion stations are fully integrated into the IFPCS and are used to provide lift and maneuvering in flight. Four propulsion stations are mounted on the wing and two are mounted on the tips of the V-tail. The propulsion stations tilt down/forward and up/backward to transition the S4 between thrust-borne and wing-borne flight. See Figure 10.

For energy storage and distribution, the S4 uses four separately appointed, actively managed airframe battery packs housed in the wing roots and inboard nacelles.

The airplane is unpressurized, has four cabin doors, and has fixed tricycle-style landing gear.

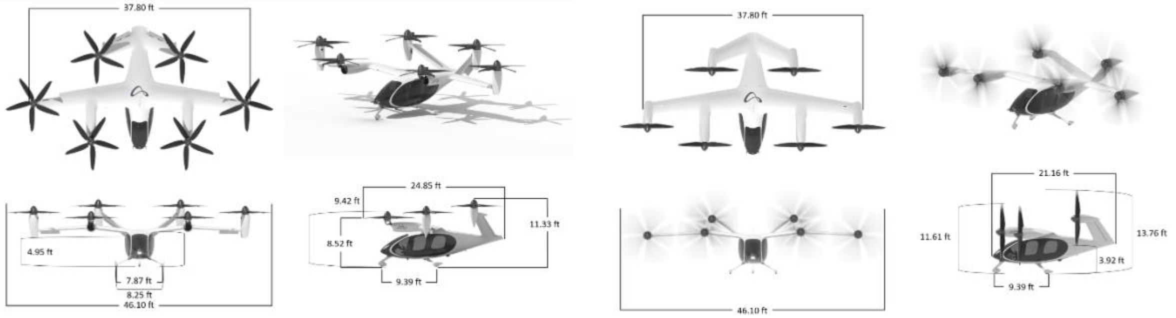


Figure 10. S4 hover configuration (left) cruise configuration (right)
Credit: Joby Aviation

The VSIL is one of Joby's primary platforms for testing flight-critical software on target hardware. The VSIL is located at Joby's flight test headquarters at Marina Municipal Airport Building 524.

Joby uses the term Integrated Vehicle Simulator (IVS) to describe the software tool developed in-house to simulate the entire S4 system. The IVS is a platform that the software verification team relies on heavily to enable the verification of requirements. It also allows Joby's Flight Test team to test and evaluate the performance of the airplane before conducting full scale flights.

Often called the "simulator," this tool uses modern containerization technology known as Docker to represent each Line Replaceable Unit (LRU) on the airframe with a single logical application "container." These LRU representations are essentially Linux ports of the software that run on the embedded systems on the airplane.

Code running in the container is identical to the code running in the airplane, with exception of code that communicates with the operating system, hardware interface, and physical models. The physical models are containerized in "host simulations." Each container is attached to a virtual network in a topology that mimics the airplane, thus exposing redundancy, network performance and other factors.

This combination allows a user of IVS to run a closed-loop flight simulation across one or more computers at a desk. Testers can isolate individual containers, or groups of containers, to focus on testing LRU software or physical models in smaller subsets. Testers can also substitute real hardware or hardware emulation for the software containers, which is advantageous in many situations.

Hardware Emulation

It is not always feasible to have the full set of electronics for each LRU. For example, the Battery Control and Distribution Module and Quad Inverters have extensive high-speed electronics beyond the LRU itself, and there are personal safety concerns with these systems. Testing performed with individual LRUs of this type is typically low-level testing in which the lack of the full electronic environment does not impact the test results.

To support hardware emulation, the Joby System-on-a-Chip (SoC) environment with the same processor cards as the LRUs on the plane is used. This means that the same software and Field-Programmable Gate Array (FPGA) image as those on the S4 airplane are used for this testing.

For motor control algorithms, Joby uses closed-loop simulation of the design models and a high-fidelity motor and power electronics plant model for formal testing of the software and algorithms. The fidelity of the motor and power electronics plant models will be verified by comparing the inverter and motor control desktop simulation results against the actual dynamometer testing data and the prototype flight test data collected at all the operating conditions specified in the HLRs.

For battery algorithms, Joby will use closed-loop simulation of the design models and a high-fidelity battery pack plant model for formal testing of the software and algorithms. The fidelity of the battery pack plant model is verified by comparing against the actual battery cell/pack testing data and the prototype flight test data collected at all the operating conditions specified in the HLRs. Further, Joby validates simulation results from the battery algorithms against measurements in battery pack and cell pack tests as well as prototype flight tests.

Closed Loop Flight Simulation

For the NASA NC-1 activity, a closed-loop simulation using the VSIL “Pilot Sim” was used. The Pilot sim is designed for flight test, human factors, software development and software verification for flight testing. It is designed to be as close to target hardware as possible. Although it contains no moving flight control actuators, electric propulsion units or high voltage batteries, the software aspects and the electronics that run the software are highly representative of the aircraft.

The physical configuration of the VSIL pilot sim cockpit is intended to conform to the most recent cockpit design of the S4 2.1 aircraft. This includes seat height and position, position of switches, position of avionics, and position of inceptors. The flight deck has a dimensionally accurate flight deck panel, glare shield and inceptor arms. The cockpit features an airplane quality seat with full adjustment control to position the pilot at an eye reference point. A partial fuselage mockup provides representative inner and outer mold lines as in Figure 11.

Figure 11. S4 VSIL (left) preliminary S4 flight deck avionics layout (right)
Credit: Joby Aviation

The VSIL Pilot Simulator contains two identical Mission Display Computers (MDCs) interfaced with Garmin displays. The system includes video, RDC ethernet, and ARINC-429. These MDCs shall act as the interface between Joby’s Powered Network and Garmin hardware.

The VSIL pilot simulator features the G3000 integrated flight deck avionics system. The G3000 includes:

- Two GDU 1250W 12-inch Displays
    - Bezel softkeys provide pilot control of display features
- GTC 575 Touchscreen Controller
    - Primary user input into the flight deck avionics. Provides control over pane management, flight planning, map viewing, data entry, and more.
- GCU 275 PFD Controller
    - Provides selection of altitude, heading and course bugs, as well as barometric altitude correction, backup control of COM/NAV radios and flight planning, and moving map range selection.

Telemetry, Data Infrastructure, and Data Analytics

The VSIL Pilot Sim uses the standard Joby software platform for data acquisition, the High-Resolution Recorder (HRR). For the purposes of the NC-1 exercise, supplemental data logging software has been developed to capture data messages of interest to be recorded into a conveniently shared and utilized CSV file.

Out-the-Window Visualization

Out-the-window visualization is somewhat limited in the VSIL Pilot Sim. Three large LCD displays are used to project the external environment. This visualization system limits the pilot's ability to "look down" during vertical landings but is useful throughout the rest of the flight envelope. See Figure 12.

3-D Environment

X-Plane is used for the generation of the external 3-D environment. A Joby-developed X-Plane plugin sends GPS information to the simulation to update the host simulation containers. X-Plane is not needed to run simulations in the VSIL; however, terrain position information relative to the aircraft position is provided from X-plane to support Garmin functionality.

Figure 12. VSIL display screen
Credit: Joby Aviation

2.4 Research Execution

The Joby S4 aircraft engineering simulator was used to evaluate variations of experimental IFPs constructed in the FAA's Terminal Area Route Generation Evaluation and Traffic Simulation (TARGETS) software. The test IFPs combined departure, enroute, approach, and missed approach segments into a single procedure called "deproach." The departure and approach segments of the deproach use a traffic pattern-like wheel centered over the vertiport, with a variably sized ring to account for aircraft terminal airspeed, desired climb/descent angle, and sectors of usable departure/approach airspace tailored for each vertiport

Joby Aviation and National Campaign partnered to test and evaluate different developmental candidate UAM instrument flight procedure designs including new departure, enroute, approach and missed approach architectures as a deproach concept. In conjunction with the simulator testing, this effort also evaluated related aspects such as charting, coding, and adherence to flight planning criteria.

Data were collected using eight pilots on a total of 100 test runs. Each pilot flew each test point once to assess criteria across each phase of flight. Joby transferred post-flight data logs securely to National Campaign. From there data was processed, computed for metrics, and developed into data products and findings. The simulator flight phase one events occurred over a five-day span with two sorties per day and flight phase two events occurred over a two-day span with two sorties per day (Figure 13).

Figure 13. Key events schedule overview

2.5 Data Methodology

The activity data was provided by Joby Aviation to NASA National Campaign through the Advanced Air Mobility Space Act Agreement for the research partnership. Simulator data was logged from the events by Joby Aviation, uploaded from the VSIL system and provisioned to the government liaison for transfer to a secure NASA Box account. The simulator data is marked CUI//SP-PROPIN and is protected for proprietary qualities. Secure and permissioned access was granted by the NC data science team. The data was then uploaded, cleaned, parsed and analyzed.

Data consists of three files from the S4 VSIL modeled systems: Angular Navigation, Battery and Kinematic files. Upon post-processing, files constituted over 3,200,000 rows of data with over 100 raw and applied columns of attributes. The first step in the data process included ingestion of raw data files. Proper metadata tags and secondary data and information (such as waypoints, informative airspace constructs, etc.) were applied to the data to enable proper slicing, metric generation and to enhance the informative qualities of the analysis. Data files were merged via a UTC Time in Microseconds attribute and a forward fill application was applied to account for the discrepancy in sampling rates among the system files. Data transformations were applied to convert measures to desired units (e.g., metric to English system). Data was renamed where appropriate for clarity (yaw to heading). Key computations were applied to the data (linear distances, numeric range, interpolations, and scaling).

Data was then systematically parsed from flight sortie (a loop of test points) down to individual test points that were appointed by proximity to start and end waypoints for each test. To support research for the deproach model, data was truncated where aircraft joins (departure), maintains (enroute), concludes (final approach) or rejoins (missed approach) the deproach wheel at pattern altitude. Additional computations and calculations were applied to the data where appropriate to extract the desired measure for each metric (cross products, divide for zero gravity, etc.).

The activity data was then explored, statistics were applied, and data visualizations, charts and products were created to communicate the research findings. Data and the ensuing report scope and details were reviewed by both Joby and NASA for mutually agreed levels of detail for public release.

3 Deproach Infrastructure

3.1 Candidate Deproach Procedures

The candidate terminal airspace construct, termed 'deproach,' can be easily adjusted, flexed or retracted at time of design for a specific vertiport location to account for airspeed, obstacles and winds to enable on-demand departure and approach procedures as seen in Figure 14 below. [11] The departure and approach radii are defined by vehicle performance and the altitude will account for any controlling obstacle(s). The usable portion of the 'deproach' cone may be easily limited to certain sectors (pie slices) of the cone, or certain sectors (pie slices) could be easily removed based on outcomes of a streamlined obstacle evaluation and airspace analysis process when the 'deproach' is first designed for a given vertiport location.

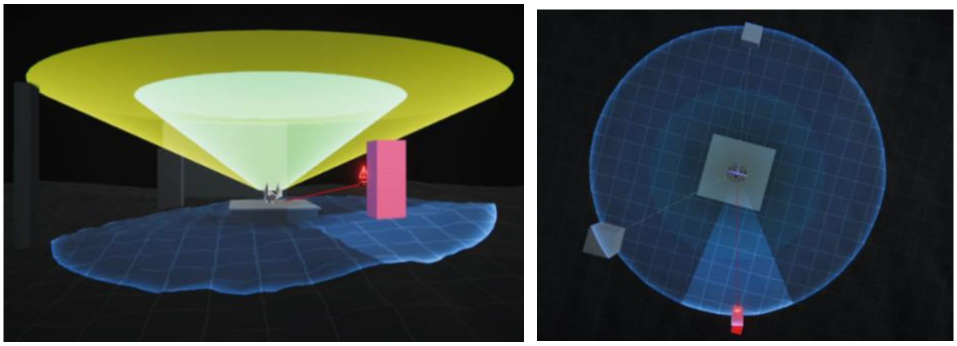


Figure 14. Candidate 'deproach' terminal airspace construct profile (left) and overhead (right)

A first step in the design process is to evaluate obstacle clearance. Detailed obstacle clearance surface requirements exist for legacy aircraft and terminal IFPs but not for UAM/eVTOL. An Obstacle Evaluation Assessment Area (OEAA) is established from any landing surface outbound towards an approach path. This assessment area is used to evaluate terrain, vertical obstructions and airspace penetrations. Once the outer dimensions of the assessment area are established and vertical obstructions are populated within the evaluation plane, the vertical component is evaluated against the minimum climb gradient required for a departure or against a rise over run obstacle clearance slope from the landing surface. Executing this process for the candidate deproach IFP will enable an omni-directional evaluation, which would provide scalability and increased operational flexibility for UAM. Due to the inherent simplicity, repeatability and the versatile nature of the candidate deproach IFP, vertiport evaluations and procedure development will be greatly streamlined in contrast to current fixed wing terminal IFPs, which are highly complex and highly variable/unique from one to another. [12] The ‘deproach’ provides standardization and a streamlined UAM IFP architecture usable at any location. An eVTOL deproach IFP would provide precision for instrument departures and arrivals to and from the ground, which does not currently exist for rotorcraft. Currently, instrument procedures are uniquely customized for each airport runway and individually tailored to the runway centerline using manually intensive evaluation criteria.

The IFP procedures are aligned to Joby S4 performance and operational parameters to include optimized customer experience profiles. The concept airspace architecture was designed around 5°, 8°, and 12° flight profiles with fictitious obstacles that were strategically placed to generate steeper ingress and egress gradients for the departure, enroute, final approach, and missed profiles.

3.2 Deproach Requisites

3.2.1 Vertiport Infrastructure

The deproach model was used to evaluate, construct, and code the different procedure segments at Marina Municipal Airport (KOAR), Marina, CA for a designated vertiport. The Marina Municipal Airport was used as part of the partnership with Joby Aviation, and representative of real world UAM operations in NAS with realistic terrain, vertical obstruction, and airspace restrictions. Figure 15 below is the Marina, CA with the deproach evaluation polygon ring and final approach ingress/egress trapezoid boundaries.

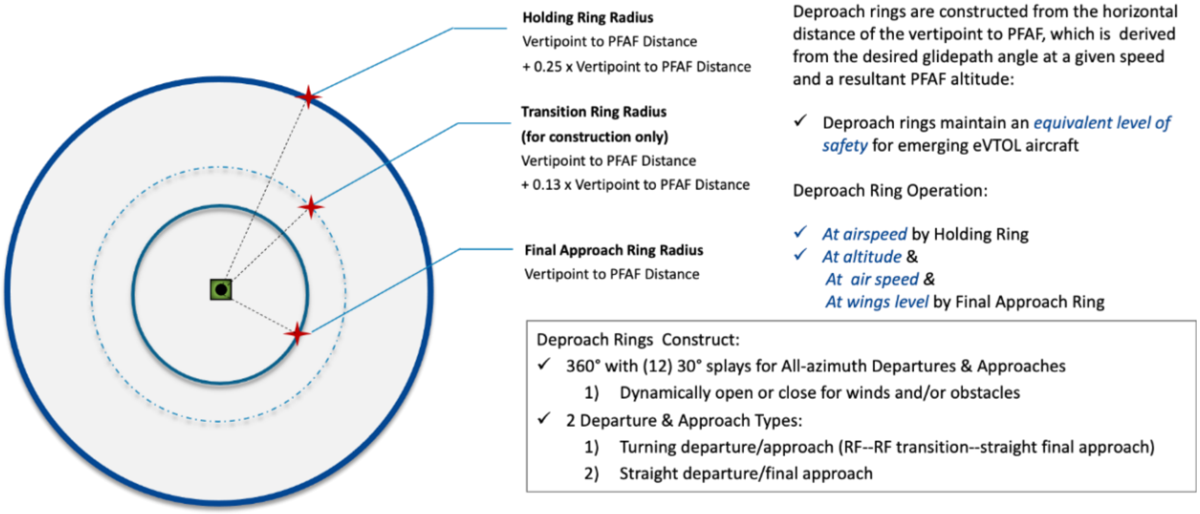
Figure 15. ‘Deproach’ terminal airspace construct applied to KOAR

3.2.2 Terminal Procedure Design

The NAS consists of an inventory of approximately 20,000 approach, arrival, departure, and enroute IFPs. This inventory of conventional and PBN procedures must be continuously evaluated as IFPs are added or canceled, nav aids are implemented or discontinued, new obstacles are identified, airspace is redesigned, and regulations evolve. The TARGETS system is the FAA's enterprise solution for that mission. The TARGETS tool was developed by MITRE and sponsored by the FAA. It has capabilities for design, analysis, and operational assessment of air traffic procedures and airspace. TARGETS incorporates data visualization with design elements to enable procedure designers to run simulations. The data output is formatted to support operational, certification, and charting needs. FAA partners collaborated as part of this effort to develop versions of the experimental deproach IFPs using current existing types of waypoints and legs, using the standard TARGETS software for IFP development, and explored wake turbulence concepts with Aircraft Vortex Spacing System (AVOSS) 3.2 Wake Model.

Deproach Design Process

The deproach concept centered around a vertiport and the design consists of a series of Track to Fix (TF) and Radius Fix (RF) segments. [4] TARGETS is limited in its computer aided design abilities, which consist of “projections” that are used to build straight TF segments. However, the user can create complete circles around a fix, or around the endpoint of a projection. TARGETS is also able to create arcs about a fix, or projection endpoint, by creating boundary radials to define the beginning and end of any given arc. These functions are used to design RF segments. Both types of segments are built to RNP 0.10. Figure 16 below provides additional description.



Holding Ring Radius
Vertipoint to PFAF Distance
+ 0.25 x Vertipoint to PFAF Distance

Transition Ring Radius
(for construction only)
Vertipoint to PFAF Distance
+ 0.13 x Vertipoint to PFAF Distance

Final Approach Ring Radius
Vertipoint to PFAF Distance

Deproach rings are constructed from the horizontal distance of the vertipoint to PFAF, which is derived from the desired glidepath angle at a given speed and a resultant PFAF altitude:

- ✓ Deproach rings maintain an *equivalent level of safety* for emerging eVTOL aircraft

Deproach Ring Operation:

- ✓ *At airspeed* by Holding Ring
- ✓ *At altitude* &
  At air speed &
  At wings level by Final Approach Ring

Deproach Rings Construct:
- ✓ 360° with (12) 30° splays for All-azimuth Departures & Approaches
  1) Dynamically open or close for winds and/or obstacles
- ✓ 2 Departure & Approach Types:
  1) Turning departure/approach (RF--RF transition--straight final approach)
  2) Straight departure/final approach

Figure 16. Candidate deproach IFP overhead design

Figure 17 below features the TARGETS construction of a 5-degree ring with 7,143 ft radius, 8-degree ring with 4,889.50 ft radius, and 12-degree radius of 2938.45 ft. Since the landing surface 01H does not exist in the FAA AIRNAV database, a User Defined (UD) point was used to establish the range rings at KOAR.

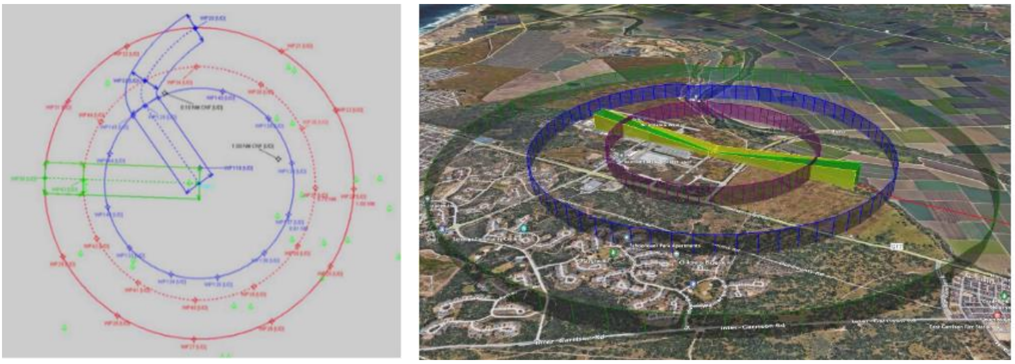


Figure 17. TARGETS development (left) Varying range rings (right)

Building TF segments

Once the desired ground track is determined, the beginning and end of the segment are defined by waypoints (WP). The WPs are then connected to define the aircraft ground track. Two projections are created perpendicular to the segment's ground track to form the baselines at each fix. Adhering to established Performance Based Navigation (PBN) concepts, the segment ½ width (either side of the ground track) is 2 x RNP 0.10, or 0.20 NM. [3] The total width for both TF and RF segments is 0.4 NM. The perpendicular base lines at each fix are extended 0.2 NM (segment ½ width), and then connected with lines that are parallel to the ground track. This forms the boundaries of the obstacle identification surface for a TF segment as seen in Figure 18.

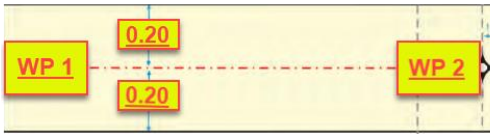


Figure 18. 8260.58 RNP 0.1 track-to-fix waypoint criteria

Building RF segments

Once WP2 (beginning of segment) and WP3 (end of segment) are defined, the ground tracks for the preceding and succeeding segments are determined. Lines perpendicular to the ground tracks are created at WP2 and WP3; these are defined as R (green line with arrow in the diagram below). The perpendicular lines extend from each WP towards the inside of the turn. These lines extend until they form an intersection. The Computer Navigation Fix (CNF) is placed at this intersection as seen in Figure 19. Using the CNF as the center point, three arcs are created around the CNF to form the inside turn boundary, ground track, and outside turn boundary. The ½ width of the RF segment is the same as the TF leg (2 x RNP 0.10 = RNP 0.20). The radius of the inside turn boundary is determined by subtracting 0.20 NM from the distance from the segment WP to the CNF. For example, using a hypothetical distance of 2.0 NM from WP2 to the CNF, the radius used to define the inside turn boundary would be 2.0 – 0.20 = 1.8 NM. The same methodology is used to define the outside turn boundary, except the segment ½ width (0.20 NM) is added to the distance from the segment WP to the CNF; 2.0 + 0.20 = 2.20 NM. In this scenario the ground track would be defined at 2.0 NM from the CNF. The inside turn boundary arcs and outside turn boundary arcs are extended to points that are 0.10 NM beyond WP2 and WP3 (points are measured on segment ground track) to connect to the RF segment to the preceding and succeeding segments. The Deproach concept is based on PBN concepts, and instructions for how to build TF and RF segments can be found in FAA Order 8260.58B. [3]

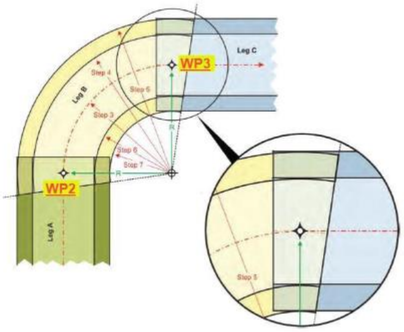


Figure 19. 8260.58 RNP 0.1 radius-to-fix waypoint criteria

Tailoring Procedures

Currently there are three primary types of instrument design procedures: a departure leaving a location, the enroute transition going from point A to B, and the approach landing at a new location. Each one of these procedures has its own criteria and is designed, documented, coded, and charted separately. All require large amounts of airspace and coordination, taking months from the start of the process to completion.

The current RNAV procedure to runway 29 at KOAR (Figure 20) was identified as an adequate baseline to compare the candidate UAM procedures against. It is the most current RNAV procedure at the airport and it is also aligned on the 287 heading to the runway. To adequately compare the procedure, approach plate, and coding, the procedure file was used to reconstruct RNAV 29 at KOAR and the candidate UAM procedure was overlayed adjacent to the pertinent segments. The detailed segmental breakdown of the procedure will be illustrated in follow-on sections to provide a direct comparison to the experimental procedures.

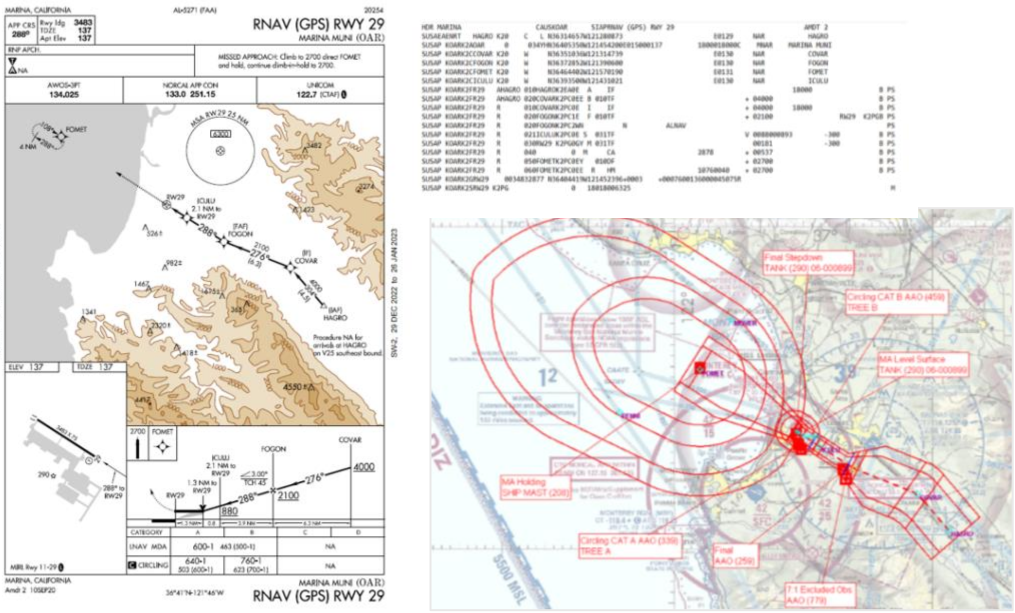
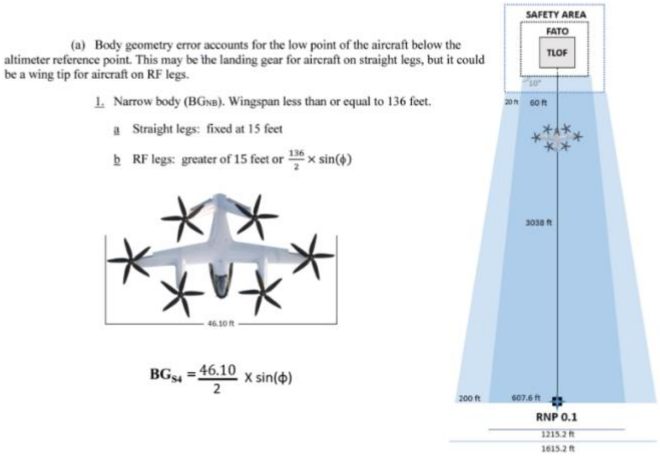


Figure 20. Existing KOAR RNAV 29 approach plate (left) TARGETS code and build (right)

Utilizing the candidate vertiport dimensions, a target RNP value of 0.1 was created at the final approach fix/final roll out point to create the trapezoidal boundaries of the final approach. Because total flight technical error was assumed at zero for the simulator activity, the S4 wingspan was used to accommodate a centerline bias error based on the wide body geometry of the S4. [4] The final roll out point had a clearance of 1615.2 ft that allowed for a tightening alignment accounting for the final decent and deceleration profile to 120 ft as seen in Figure 21 below. The splaying assumed less corrections required in final segment alignment by a pilot or with use of an autopilot. The resulting final approach trap allots the 46.10 ft S4 vehicle 35x its wingspan (including secondary areas) at >80 kts and tappers down to 2.6x the vehicles wingspan at less <30 kts.



(a) Body geometry error accounts for the low point of the aircraft below the altimeter reference point. This may be the landing gear for aircraft on straight legs, but it could be a wing tip for aircraft on RF legs.

1. Narrow body (BG_{NB}). Wingspan less than or equal to 136 feet.
   - a Straight legs: fixed at 15 feet
   - b RF legs: greater of 15 feet or $\frac{136}{2} \times \sin(\phi)$

$$BG_{S4} = \frac{46.10}{2} \times \sin(\phi)$$

Figure 21. Candidate RNP 0.1 for landing surfaces
Diagram (not to scale)

Missed Approach Segment

The missed approach segment was evaluated by analyzing the path deviation, height loss, flat surface distance, and departure intercept point; see **Error! Reference source not found.**. These parameters exist today in traditional TERPS criteria; however, no criteria currently exist for the unique flight characteristics of descending/decelerating and high angle approaches. To explore the possibility of using a procedure that exercises the vertical land component, the NC team slightly modified existing criteria and attempted to show equivalent or higher safety for the Joby S4 use-case.

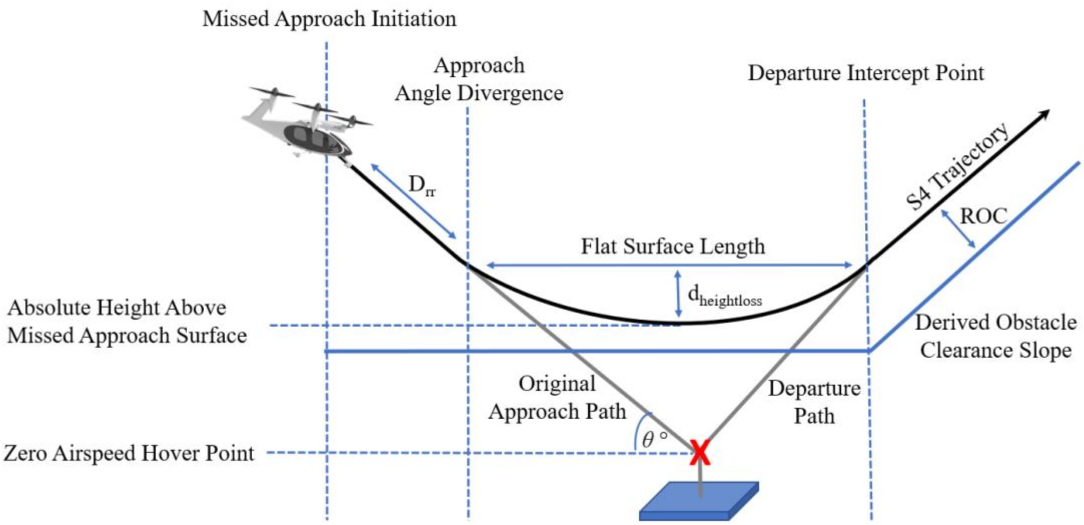


Figure 22. Missed approach breakdown

3.2.3 Coding and Validation

IFPs are coded using the ARINC-424 standard format. This format is readable by all commercial flight management systems and includes structures for all procedure elements and types. ARINC-424 is an industry standard, not necessarily driven by FAA regulations. The FAA has strict regulations defining requirements for procedures including spacing, obstacle clearance, required navigational precision (RNP), and many other constraints. These regulations have been developed over decades of manned flight operations and have driven the design of the ARINC-424 standard, as well as many software tools used by the FAA to design, code, and publish instrument flight procedures.

Every segment of every IFR departure, enroute segment, arrival and approach is a specific type of leg. Each leg is coded using a two-letter identifier that is entered as code (ARINC 424 legs) in the nav database, and IFPs are sequences of those legs. There are 23 ARINC 424 leg types that have been created to be digested and used by the FMS. The legs are also known as “path terminators” because they describe the path or action to be taken on that leg and show where that path will end so the next leg can begin. Flight plans are entered in the FMS by chaining procedures from the nav database together as seen in Figure 23.

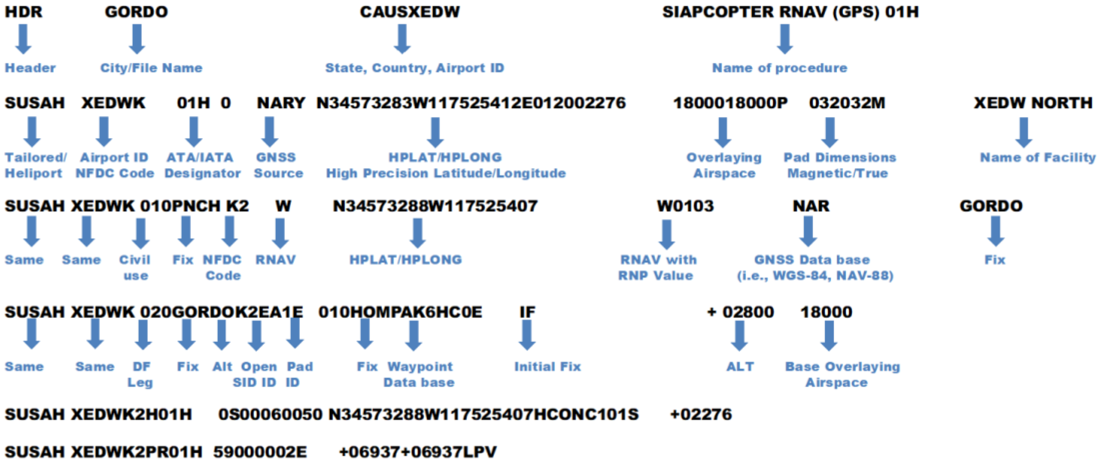
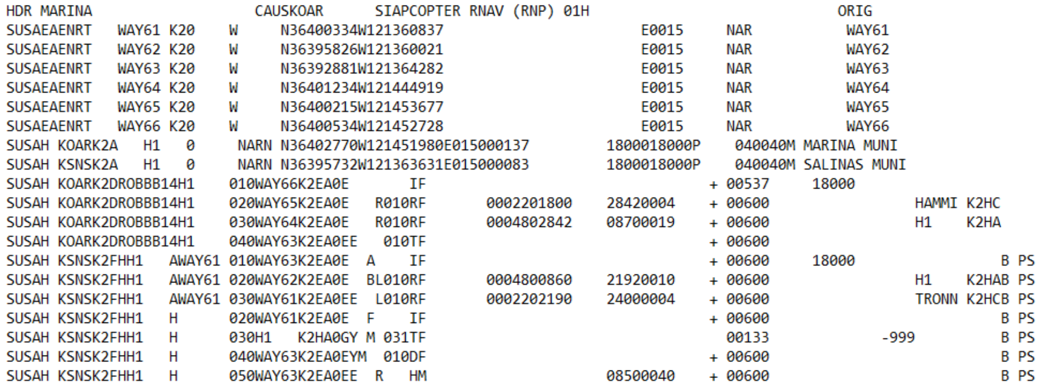


Figure 23. FAS data ARINC 424 coding

Coding Process for Deproach

For the Joby simulator test, the nav data was combined with current individual procedural criteria of Standard Instrument Departure (SID) procedures, enroute transitions, and approaches that create the candidate deproach. At first, each segment was comprised of three separate procedures requiring independent ARINC 424 coding for commercial use, but through trial and error the research team was able to develop a way to manually combine and code all three procedures into one. Current FAA tools aren’t designed to develop a deproach, and current TERPS criteria allow do not allow for it. The single coded procedure was able to be completely flown by the FAA coding computer system from start to finish with no changeovers nor a need to select different procedure types at different times throughout the flight. As seen in Figure 24 below, the deproach coding was manually generated for end-to-end operations from Marina (KOAR) to Salinas (KSNS). The single coded procedures featured successfully proved that a departure, enroute, final approach and missed could be generated for the UAM use case with the same level of precision as current IFR operations (RNP 0.1).



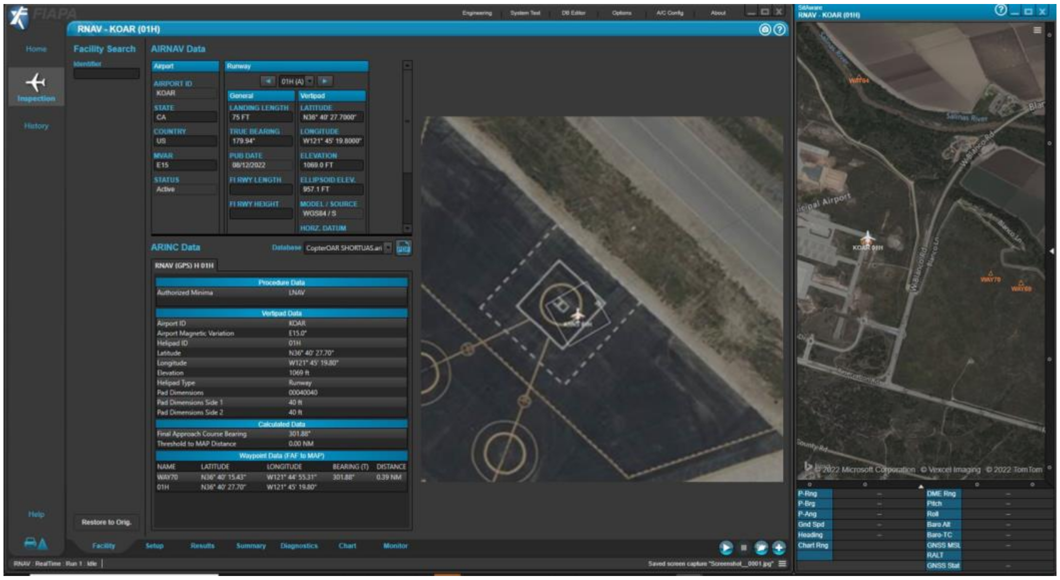
```
HDR MARINA                   CAUSKOAR      SIAPCOPTER RNAV (RNP) 01H                             ORIG
SUSAEAENRT   WAY61 K20    W     N36400334W121360837                       E0015     NAR           WAY61
SUSAEAENRT   WAY62 K20    W     N36395826W121360021                       E0015     NAR           WAY62
SUSAEAENRT   WAY63 K20    W     N36392881W121364282                       E0015     NAR           WAY63
SUSAEAENRT   WAY64 K20    W     N36401234W121444919                       E0015     NAR           WAY64
SUSAEAENRT   WAY65 K20    W     N36400215W121453677                       E0015     NAR           WAY65
SUSAEAENRT   WAY66 K20    W     N36400534W121452728                       E0015     NAR           WAY66
SUSAH KOARK2A   H1   0     NARN N36402770W121451980E015000137         1800018000P    040040M MARINA MUNI
SUSAH KSNSK2A   H1   0     NARN N36395732W121363631E015000083         1800018000P    040040M SALINAS MUNI
SUSAH KOARK2DROBBB14H1    010WAY66K2EA0E       IF                                 + 00537     18000
SUSAH KOARK2DROBBB14H1    020WAY65K2EA0E   R010RF       0002201800    28420004    + 00600                 HAMMI K2HC
SUSAH KOARK2DROBBB14H1    030WAY64K2EA0E   R010RF       0004802842    08700019    + 00600                 H1    K2HA
SUSAH KOARK2DROBBB14H1    040WAY63K2EA0EE   010TF                                 + 00600
SUSAH KSNSK2FHH1   AWAY61 010WAY63K2EA0E  A    IF                                 + 00600     18000                 B PS
SUSAH KSNSK2FHH1   AWAY61 020WAY62K2EA0E  BL010RF       0004800860    21920010    + 00600                 H1    K2HAB PS
SUSAH KSNSK2FHH1   AWAY61 030WAY61K2EA0EE  L010RF       0002202190    24000004    + 00600                 TRONN K2HCB PS
SUSAH KSNSK2FHH1   H      020WAY61K2EA0E  F    IF                                 + 00600                           B PS
SUSAH KSNSK2FHH1   H      030H1   K2HA0GY M 031TF                                   00133             -999          B PS
SUSAH KSNSK2FHH1   H      040WAY63K2EA0EYM  010DF                                 + 00600                           B PS
SUSAH KSNSK2FHH1   H      050WAY63K2EA0EE  R   HM                     08500040    + 00600                           B PS
```

Figure 24. KOAR 01H deproach ARINC 424 coding

Flight Inspection Validation

The code and airspace constructs created in TARGETS by FAA AJV- were validated by FAA Flight Operations Flight Check via Flight Inspection Airborne Processing Application (FIAPA) software desktop in simulation by FAA AJF as seen in Figure 25. For the test, the files were named “CopterOARSNANORTH UAS.ari” due to FIAPA requirement as of today to proceed file name with ‘Copter’ for Point in Space (PinS) approach ingestion. As featured below, the landing surface ID was modified from “H1” to “01H” to conform with AIRNAV Helipad Naming conventions. Additionally, the modified Heliport (HA) records were updated to follow ARINC specification 424-21. The resulting landing surface and spatial data validation were added to the Helipad (HH) record database.

Follow-on research and software testing will be needed to explore the utility of procedural data validation for the AAM use case. As FIAPA plays a critical role in current IFP validation, an equivalent level of safety will need to be investigated to maintain or exceed the precision required for current commercial (Part 121) compensation for hire operations. FIAPA, or a like system, will need to be modified to allow for point-to-point RNAV inspections. The future validation framework will either need an AAM mode to translate criteria or have a dedicated platform for the AAM profiles outside of criteria. An enhanced situational awareness tool or viewer will be needed to display greater details in terrain and vertical obstructions in the urban environment. A flight inspection aircraft will need to be selected, and once inspection aircraft is identified, an interface will need to be installed for current or any new equipment that is needed to execute procedure validation, purchase or lease the latest ARINC Specification (424-23), and document any new requirements that are found outside of the findings of this isolated test.



AIRNAV Data

Airport

AIRPORT ID: KOAR
STATE: CA
COUNTRY: US
MVAR: E15
STATUS: Active

Runway: 01H (A)

General

LANDING LENGTH: 75 FT
TRUE BEARING: 179.94°
PUB DATE: 08/12/2022
FI RWY LENGTH:
FI RWY HEIGHT:

Vertipad

LATITUDE: N36° 40' 27.7000"
LONGITUDE: W121° 45' 19.8000"
ELEVATION: 1069.0 FT
ELLIPSOID ELEV.: 957.1 FT
MODEL / SOURCE: WGS84 / S
HORZ. DATUM:

ARINC Data

Database: CopterOAR SHORTUAS.arl

RNAV (GPS) H 01H

Procedure Data	
Authorized Minima	LNAV

Vertipad Data	
Airport ID	KOAR
Airport Magnetic Variation	E15.0°
Helipad ID	01H
Latitude	N36° 40' 27.70"
Longitude	W121° 45' 19.80"
Elevation	1069 ft
Helipad Type	Runway
Pad Dimensions	00040040
Pad Dimensions Side 1	40 ft
Pad Dimensions Side 2	40 ft

Calculated Data	
Final Approach Course Bearing	301.88°
Threshold to MAP Distance	0.00 NM

Waypoint Data (FAF to MAP)

NAME	LATITUDE	LONGITUDE	BEARING (T)	DISTANCE
WAY70	N36° 40' 15.43"	W121° 44' 55.31"	301.88°	0.39 NM
01H	N36° 40' 27.70"	W121° 45' 19.80"		

Figure 25. Marina KOAR deproach model FIAPA validation

Significant Differences of Deproach IFP from Standard IFPs

Several aspects of the deproach IFP are novel from existing criteria and operations. For instance, glideslopes are currently programmed for fixed wing up to 7.5° (24% of value for the glideslope clearance, OCS is 76% against terrain). In contrast, this research involved candidate UAM eVTOL glideslopes of 5°, 8° & 12°. Also, current helicopter procedures only bring the aircraft to a point in space, followed by VFR to the ground. [13] However, this research intends to eventually build towards showing that the deproach IFP could enable UAM/EVTOL operations to conduct precision IFR approaches down to the surface.

3.2.4 Research Support Material Designs

Departure/Approach Plate Design

Once an airspace has been evaluated and risks are mitigated to an acceptable level for operation, two products are made. The first instrument procedure product is ARINC 424 coding that is designed for machine (FMS) consumption. The second instrument procedure product is the approach/departure plate that is designed for human (pilot) consumption. The NC procedure team designed and developed candidate AAM procedure plates designed to manage low altitude, closely spaced departure/approach location. The approach and departure plate information flow use the same format but with the following adaptation: the pilot briefing/header section includes negative symbology to indicate the departure and non-negative symbology to indicate an approach. Figures 26 - 29 below break down the approach plate design highlighting the main differences between traditional procedure plate design and the research plates designed for the Joby S4 UAM use case.

Approach Plate

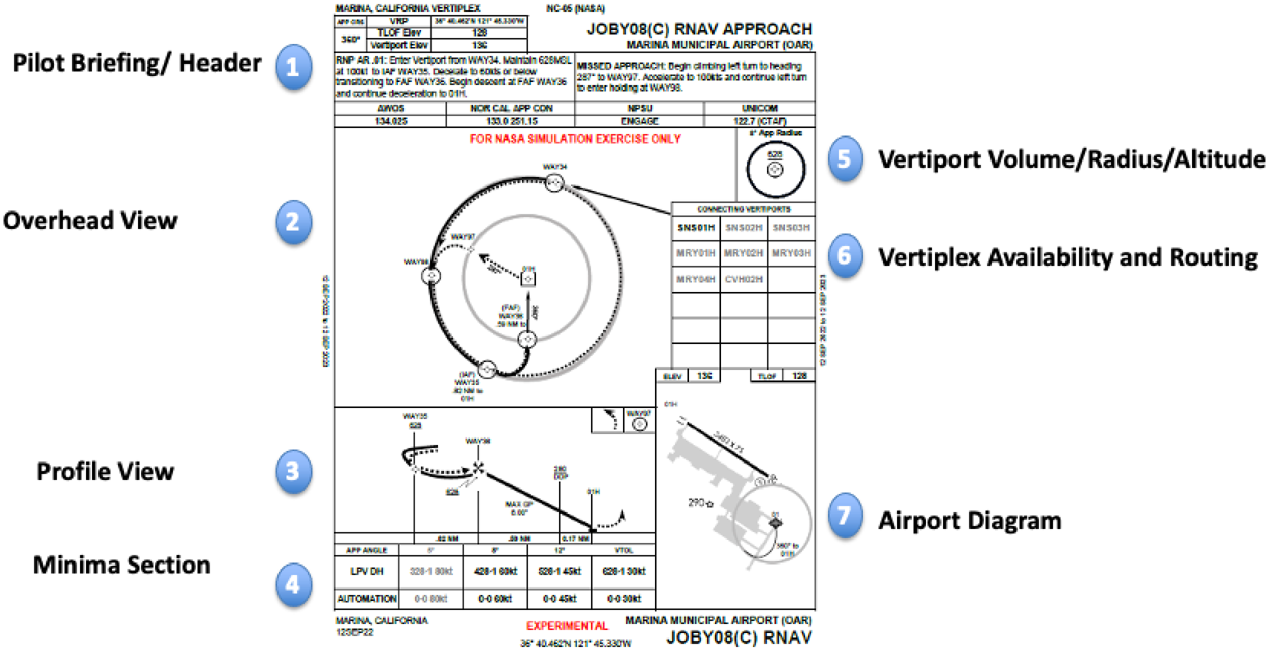
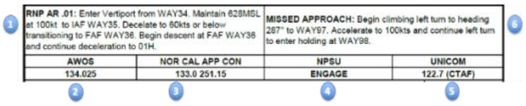


Figure 26. Approach Plate

Pilot Briefing

#	Description
①	Name of Vertiport or Vertiplex
②	Approach Course in line with predominate wind, traffic, airspace or obstruction
③	Vertiport Reference Point (center of Vertipad and RF leg) with elevations in feet
④	National Campaign Publication Card # (example 5) and organization (NASA)
⑤	Name of Approach, "C" for curved to final, "S" for straight in on final



RNP AR .01: Enter Vertiport from WAY34. Maintain 628MSL at 100kt to IAF WAY35. Decelate to 60kts or below transitioning to FAF WAY36. Begin descent at FAF WAY36 and continue deceleration to 01H.

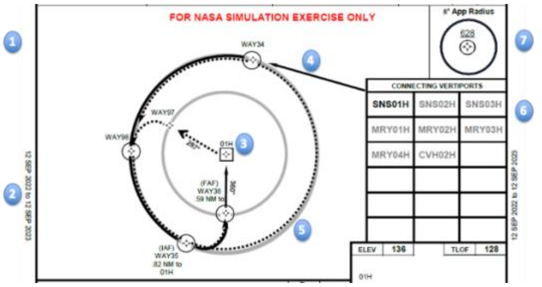
MISSED APPROACH: Begin climbing left turn to heading 287° to WAY97. Accelerate to 100kts and continue left turn to enter holding at WAY98.

AWOS	NOR CAL APP CON	NPSU	UNICOM
134.025	133.0 251.15	ENGAGE	122.7 (CTAF)

#	Description
①	Textual description of the approach procedure and RNP Value
②	Weather reporting (example AWOS) frequency or overlay display
③	Traditional ATC or controlling airspace call sign and frequency
④	Engage surrogate PSU or supplemental service provider (not used for this sim)
⑤	CTAF, UNICOM, or Vertiport frequency
⑥	Textual description of the missed approach sequence

Figure 27. Approach plate pilot briefing section

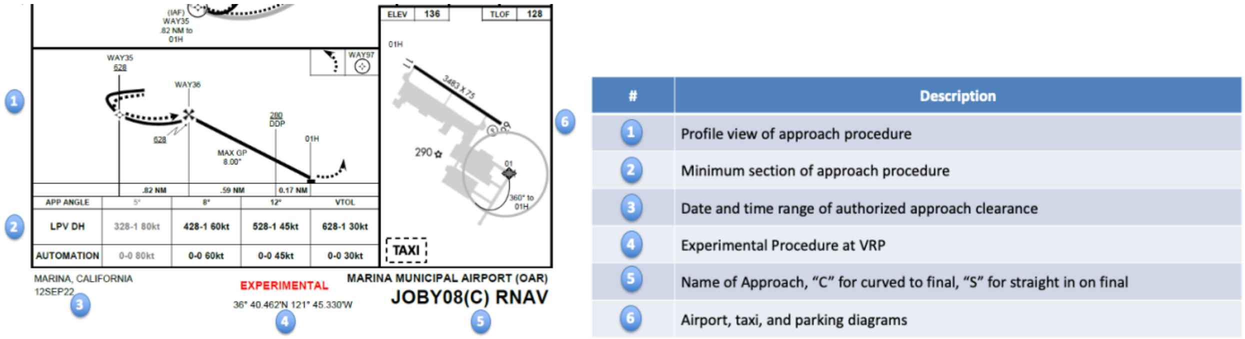
Overhead View



#	Description
①	Lateral or "overhead" view of approach procedure
②	Date and time range of authorized approach clearance
③	VRP and landing service
④	Nominal flight path maker and vertiport entry point (solid black line)
⑤	Off-nominal or contingent flight path marker (dashed black line)
⑥	Connecting vertiports in the Vertiplex structure
⑦	Approach radius, glide path angle, and altitude restriction

Figure 28. Approach plate overhead view

Profile View & Minima Section



APP ANGLE	5°	8°	12°	VTOL
LPV DH	328-1 80kt	428-1 60kt	528-1 45kt	628-1 30kt
AUTOMATION	0-0 80kt	0-0 60kt	0-0 45kt	0-0 30kt

#	Description
①	Profile view of approach procedure
②	Minimum section of approach procedure
③	Date and time range of authorized approach clearance
④	Experimental Procedure at VRP
⑤	Name of Approach, "C" for curved to final, "S" for straight in on final
⑥	Airport, taxi, and parking diagrams

Figure 29. Approach plate profile view & minima section

The approach procedures were designed to the Joby S4 vehicle configuration and every approach plate tailored to the assumed passenger comfort metrics outlined in the test. As depicted in Figure 30 below, the maneuver to enter the candidate UAM terminal area and turn to final were designed at airspeeds and distances to maintain a less than 30-degree angle of bank.

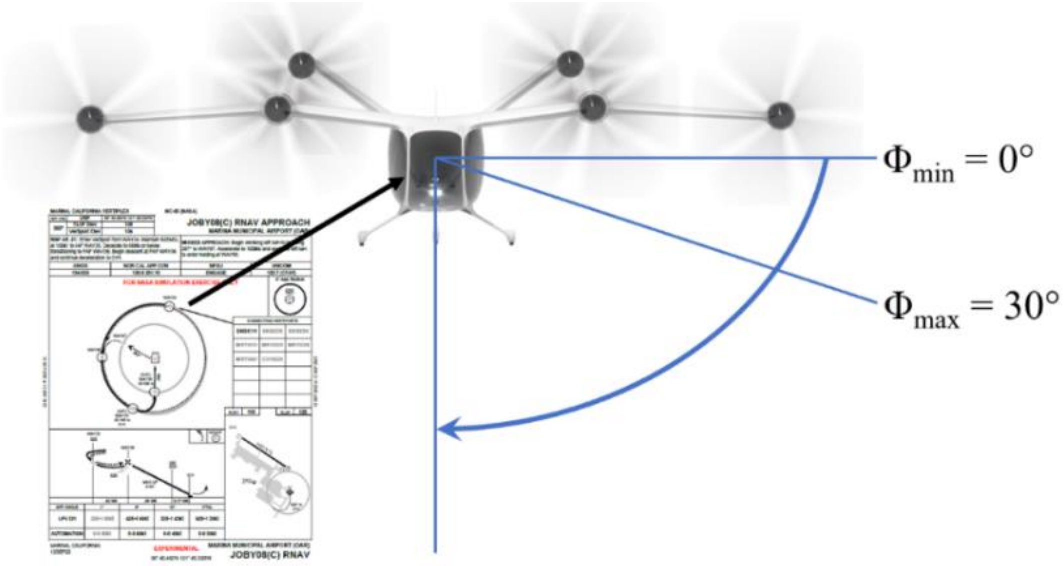


Figure 30. Approach plate bank angle max

Once the Joby S4 vehicle enters the terminal and is aligned with the final approach path, the procedure is designed for the aircraft to maintain all maneuvering as depicted in Figure 31 below. The design parameters include the descent, deceleration, missed approach and climb out to maintain plus or minus 30-degree bank angle, plus or minus 10 degrees from the required pitch attitude, and plus or minus 5 degrees from the assigned heading.

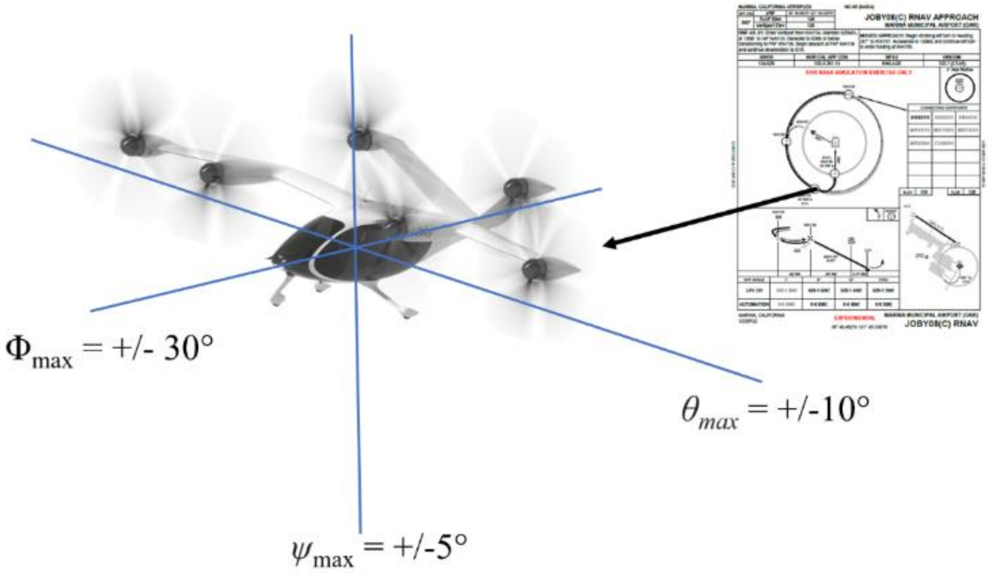


Figure 31. Approach plate pitch, roll & yaw design max

Procedures Automation Rating Matrix

The Procedure Automation Rating Matrix (PARM) was created by trial and error with the help of NASA and Joby Aviation test pilots at the Joby Aviation high fidelity engineering simulator in Marina, California. See Figure 32. The PARM is not a modification of the unidimensional Bedford Workload Scale (BWS) or the Modified Cooper-Harper rating scale (MCH) explicitly assessing pilot workload or aircraft handling for traditional or legacy pilot/aircraft interactions, but rather evaluates instrument flight procedures. The NC airspace procedure research and development required a tool that would provide direct feedback for the following:

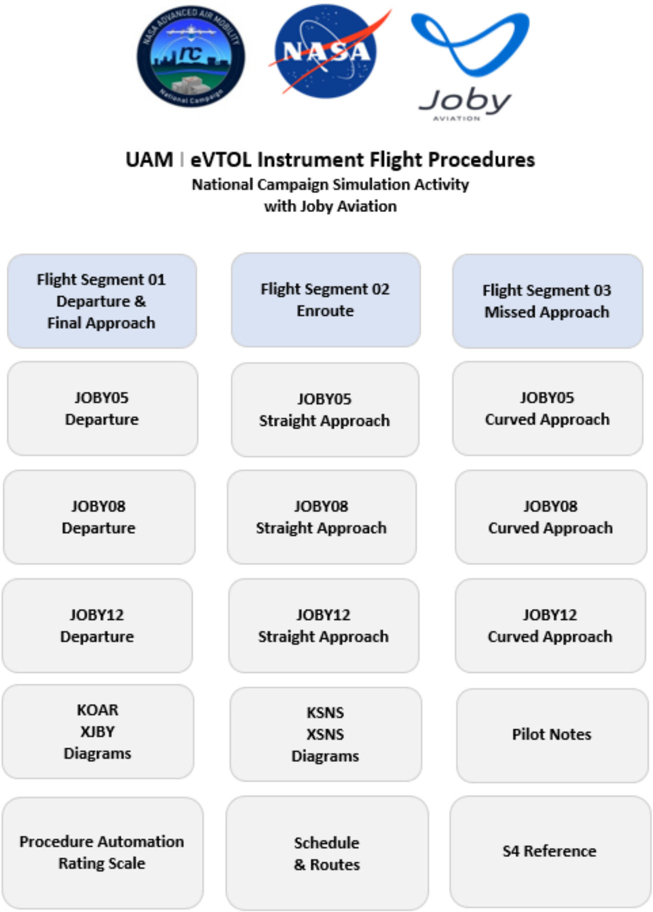
- Provision of preflight procedural information to the pilot or operator (e.g., airspace management construct such as Provider of Services for UAM (PSU)
- Execution of flight information with any pilot/operator interface that includes in cockpit manual control, remote operation, or automation with any combination thereof (e.g., new and novel approach plate design or multi-function display)
- An indication for the adequacy of training required to achieve safe and scalable integration of any procedural operational concepts (e.g., commercial, instrument, or fundamentals of instruction (FOI) recommendations)

The NC procedure team developed a structure with four main categories, ten ranks and a format that presents question "gateways" in the familiar binary decision tree that test pilots are familiar with from the BWS and MCH. The four main categories rank whether (1) it was possible to validate and accept the proposed procedure, (2) the procedural workload was tolerable, (3) there were acceptable depreciation levels of pilot situational awareness, and (4) indicate the projected level of training for median pilot proficiency. Additional criteria for the tool included complexity and timing for the PARM evaluation. For more information, reference NC Working Paper Series publication AAM-NC-112-001.

Figure 32. Procedure Automation Rating Matrix

Joby S4 Digital Mission Packet

The NC procedure team developed a Digital Mission Packet that was distributed to the pilots via tablet and was utilized during the test via kneeboard. See Figure 33. The DMP was built in excel with hyperlinks to the flight segments used to coordinate the simulator test. The NC developed the DMP to give the pilot and test conductor an expedient way to reference a traditional kneeboard packet as well as maintain the ability to quickly navigate to supporting documentation or schedule navigation material during the test. The test points and methodology were outlined and updated per day or per pilot iteration. Minimal familiarization training was required for the pilots, with the greatest emphasis being on the PARM worksheet and the S4 vehicle operation and limitations tab. The primary use of the DMP was the ability for the pilot and test conductor to transition between the departure and missed approach plates for the respective departure, final approach, and missed approach parameters. The image below highlights the home page interface that was developed for the Joby Simulator Test.



UAM | eVTOL Instrument Flight Procedures
National Campaign Simulation Activity
with Joby Aviation

Flight Segment 01 Departure & Final Approach	Flight Segment 02 Enroute	Flight Segment 03 Missed Approach
JOBY05 Departure	JOBY05 Straight Approach	JOBY05 Curved Approach
JOBY08 Departure	JOBY08 Straight Approach	JOBY08 Curved Approach
JOBY12 Departure	JOBY12 Straight Approach	JOBY12 Curved Approach
KOAR XJBY Diagrams	KSNS XSNS Diagrams	Pilot Notes
Procedure Automation Rating Scale	Schedule & Routes	S4 Reference

Figure 33. Digital mission packet home page

4 Summary of Research Results

4.1 Activity Achievements

The deproach IFP concept was used to join departure, approach and missed approach procedures using an omni-directional traffic pattern-like wheel centered over a vertiport. The deproach construct is sized for the aircraft terminal area speed and desired climb/descent angle, and sectors of usable departure/approach headings tailored for each vertiport. The FAA was successfully able to create the deproach IFP using work arounds in the TARGETS software, conduct an obstacle evaluation for the 01H vertipad at Marina, generate the corresponding ARINC 424 code, and validate the code using the FIAPA desktop software. The deproach-defining waypoint latitudes and longitudes were manually input into the S4 simulator's G3000. Different variations of the deproach IFP were tested using the Joby engineering aircraft simulator. Each procedure was flown without flight guidance to develop a comparative baseline for the roadmap from pilot flight to enhanced automation. The following achievements were accomplished for the IFP design and evaluation research activity:

Infrastructure

- Constructed concept IFP vertiport evaluation worksheet (See Appendix B)
- Developed novel approach and departure plates for AAM IFPs (See Appendix C)
- Performed sUAS 2020 LiDAR exploratory survey of KOAR Marina 01H (future work)
- Built KOAR 01H vertiport in the AIRNAV database with X identifier
- Created the Procedure Automation Rating Matrix for IFP evaluation

Safety

- Explored Wake Turbulence model tool AVOSS for AAM operations at Marina KOAR
- Successfully built concept approach/departure/missed segments in TARGETS software
- Tailored ARINC 424 coding for concept deproach procedures
- Successfully validated concept procedure coding in FIAPA software

Efficiency

- Analyzed Joby S4 battery model data for concept procedure work
- Confirmed conservation of airspace model impact with current KOAR RNAV RWY 29

Passenger Comfort

- Explored assumed passenger comfort target levels based on Joby S4 procedure data
- Successfully ran Joby S4 acceleration data in CGEM Linear Acceleration Model

Acoustics

- Leveraged NC-Joby acoustic data applied for deproach operations
- Explored Joby AAM Acoustics Tool for projected environmental noise of procedures

4.2 Summary of Tradeoff Findings

No single version of the developmental IFP structure scored highest across all measures (see blue highlights in Table 3); rather, different IFP variations proved optimal for different measures, confirming that the best IFP depends on which specific measures are prioritized for a given aircraft, location and operation.

Table 3. Research Findings

Parameters				Safety			Efficiency			Passenger Comfort		Pilot Rating
Test	*Technique*	*Angle*	*Max Speed*	*Glidepath (deg)*	*Vert. Deviations (ft)*	*Lat. Deviations (ft)*	*Duration (sec)*	*Total Energy by Procedure (kWh)*	*Battery Temperature Delta (°C)*	*Linear Acceleration Jerk Rate X-Y-Z (m/sec^2)*	*Rotational Accelerations (rad/sec^2)*	*Procedure Automation Rating Matrix (low/1- high/10)*
Departure	Vertical Takeoff Accelerate to Assigned Speed	5°	45 kts	On glidepath	Least Deviation	Least Deviation	Slowest Duration	Least Efficient	Most	Most Comfortable	Most Comfortable	Highest Rating
			60 kts	On glidepath	Moderate	Moderate	Moderate	Moderate Efficiency	Moderate	Comfortable	Within Limits	Acceptable for Pilot Training
			80 kts	Best conformance	Most Deviation	Most	Shortest Duration	Most Efficient	Least Thermal	Comfortable	Within Limits	Acceptable for Pilot Training
		8°	45 kts	Best conformance	Least Deviation	Least Deviation	Slowest Duration	Least Efficient	Most	Most Comfortable	Most Comfortable	Acceptable for Pilot Training
			60 kts	On glidepath	Moderate	Moderate	Moderate	Moderate Efficiency	Moderate	Comfortable	Within Limits	Highest Rating
			80 kts	On glidepath	Most Deviation	Most	Shortest Duration	Most Efficient	Least Thermal	Comfortable	Within Limits	Acceptable for Pilot Training
		12°	45 kts	On glidepath	Least Deviation	Most	Slowest Duration	Least Efficient	Least Thermal	Most Comfortable	Most Comfortable	Highest Rating
			60 kts	Best conformance	Moderate	Moderate	Moderate	Moderate Efficiency	Moderate	Comfortable	Within Limits	Workload/Situational Awareness
			80 kts	On glidepath	Most Deviation	Least Deviation	Shortest Duration	Most Efficient	Most	Comfortable	Within Limits	Workload/Situational Awareness
Enroute	Tailwind Entry	12°	100 kts	NA	NA	NA	Moderate	Moderate Efficiency	Least Thermal	Comfortable	Within Limits	Acceptable for Pilot Training
	Headwind Entry		100 kts	NA	NA	NA	Shortest Duration	Most Efficient	Moderate	Comfortable	Within Limits	Highest Rating
Final Approach	FAF Decel	5°	80 kts	Best conformance	Moderate	Moderate	Moderate	Moderate Efficiency	Moderate	Comfortable	Within Limits	Workload/Situational Awareness
	Delayed Decel			On glidepath	Least Deviation	Least Deviation	Shortest Duration	Most Efficient	Least Thermal	More Comfortable	More Comfortable	Highest Rating
	FAF Decel	8°	60 kts	Best conformance	Least Deviation	Least Deviation	Shortest Duration	Moderate Efficiency	Moderate	More Comfortable	More Comfortable	Highest Rating (tie)
	Delayed Decel			On glidepath	Moderate	Moderate	Moderate	Most Efficient	Least Thermal	Comfortable	Within Limits	Highest Rating (tie)
	FAF Decel	12°	45 kts	Best conformance	Least Deviation	Least Deviation	Shortest Duration	Most Efficient	Least Thermal	Comfortable	More Comfortable (tie)	Workload/Situational Awareness
	Delayed Decel			On glidepath	Moderate	Moderate	Moderate	Moderate Efficiency	Moderate	More Comfortable	More Comfortable (tie)	Highest Rating
					Height Loss (ft)	*Flat Surface Length (ft)*						
Missed Approach	FAF Decel On-Course	5°	80 kts	NA	Moderate	Moderate	Moderate	Least Efficiency	Most	More Comfortable	Within Limits	Highest Rating
	Delayed Decel On-Course			NA	Most	Minimal Surface	Longest Duration	Moderate Efficiency	Moderate	Comfortable	More Comfortable	Acceptable for Pilot Training
	FAF Decel Coordinated Turn			NA	Minimal Loss	Most Surface	Shortest Duration	Most Efficient	Least Thermal	Comfortable	Within Limits	Acceptable for Pilot Training
	Delayed Decel Coordinated Turn			NA	Moderate	More Surface	Moderate	Moderate Efficiency	Moderate	More Comfortable	More Comfortable	Acceptable for Pilot Training
	FAF Decel On-Course	8°	60 kts	NA	Minimal Loss	More Surface	Moderate	Moderate Efficiency	Moderate	More Comfortable	Within Limits	Highest Rating
	Delayed Decel On-Course			NA	Most	Most Surface	Shortest Duration	Most Efficient	Least Thermal	Comfortable	More Comfortable	Acceptable for Pilot Training
	FAF Decel Coordinated Turn			NA	Moderate	Minimal Surface	Longest Duration	Least Efficiency	Most	More Comfortable	More Comfortable	Acceptable for Pilot Training
	Delayed Decel Coordinated Turn			NA	Moderate	Moderate	Moderate	Moderate Efficiency	Moderate	Comfortable	Comfortable	Acceptable for Pilot Training
	FAF Decel On-Course	12°	45 kts	NA	Moderate	Most Surface	Shortest Duration	Most Efficient (tie)	Least Thermal	More Comfortable	More Comfortable (tie)	Workload/Situational Awareness
	Delayed Decel On-Course			NA	Moderate	Moderate	Moderate	Moderate Efficiency	Moderate	Comfortable	More Comfortable (tie)	Highest Rating
	FAF Decel Coordinated Turn			NA	Most	Minimal Surface	Longest Duration	Least Efficiency	Most	Comfortable	Within Limits	Workload/Situational Awareness
	Delayed Decel Coordinated Turn			NA	Minimal Loss	More Surface	Moderate	Most Efficient (tie)	Moderate	More Comfortable	More Comfortable	Workload/Situational Awareness

4.3 Recommendations of Change

Due to the exploratory and pathfinder nature of the simulator test activity, additional research will be required in many areas before any candidate AAM airspace constructs can be implemented. The following sections will highlight areas of advisement that can provide detailed data and dialogue from subject matter experts within government and industry. These recommendations follow the Federal Advisory Committee Act (FACA) defined as any committee, board, commission, council, conference, panel, task force, working group or Administrative Procedure Act as applicable to FAA. (Title 5 U.S.C. Appendix 2), (Title 49 U.S.C section 106(p)(5)).

Advisory and Rulemaking Committees

Due to the nature of reduced separation criteria that was used in this test to explore the viability of confined airspace operations for the UAM use case, an Aviation Rulemaking Advisory Committee (ARAC) under the Federal Advisory Committee Act (FACA) or Aviation Rulemaking Committee (ARC) is suggested to elicit the advice, recommendations, and concerns that would determine the suitability of the candidate operations. The following recommendation committees and focus areas are examples and non-exhaustive:

> *Obstacle Evaluation Assessment (OEA):* Required Obstacle Clearance Slope (OCS) for UAM operations utilizing PBN procedure criteria.
>
> *Flight Inspection Validation:* Focused on the spatial data validation software using RNAV departure and approaches for candidate AAM profiles.
>
> *Categorical Exclusion (CATEX):* Define acceptable levels of visible and acoustic pollution to evaluate candidate urban environment instrument flight procedures.

Safety Working Group

Safety system working groups are a useful tool the FAA has to assess new operation, and technology integration. Safety working groups are assigned to improve safety and efficiency for air carrier operation. The SWG’s are designed to discuss issues and prioritize recommendations set forth in the SWG’s charter.

> *Separation Standards:* Discuss separation standards with reduced RNP values derived from Performance Based Navigation (PBN) UAM operations.
>
> *Descending/Decelerating Approach:* Determine the appropriate level of safety and next steps needed to further research the applicability of a vertically guided Point in Space (PinS) approach to the ground with a deceleration component terminating at zero airspeed.

Human Factors Working Group

Human factors working groups are focused on the physiological aspects of flight integration of new and novel concepts. Although there are several lines of business that have human factor researchers within the FAA, the Civil Aeromedical Institute (CAMI) is the primary line of business that fields most research requests for human factor research. Due to the intersection of air traffic control, pilot, and dispatch operator roles being redefined with the UAM use case, additional research will be needed in the development of procedures design, execution, and operational management of them.

> *Reduced Visibility of Missed Approach:* Explore the required ceilings and visibility, reaction time, latency, and bias errors needed to support steeper approaches with a deceleration component.
>
> *UAM Departure / Approach Plate Design:* Evaluate the applicability and utility of candidate UAM departure and approach plates designed for UAM procedures, utilizing dynamic or electric charting and publication.

4.4 Follow-on Research Opportunities

The following are potential activities or areas of interest that can be explored with Joby, FAA, academia or other industry and governmental partnerships. These research questions and potential next steps include:

- Assess the code complexity (number of legs) for the deproach versus standard IFPs (ref. previous MOP 2.05), normalized for the number of departure and arrival azimuths. The assessment should include quantifying if the number of deproach legs is less than the number for standard fixed wing IFPs.
- Determine if the deproach code can be more easily duplicated at disparate locations and vertiports (ref. previous MOP 2.08) relative to conventional IFP development.
- Assess the noise impacts of various candidate UAM IFPs, potentially leveraging Joby's acoustic software models
- The AAM system will need to ensure wake turbulence from other aircraft have no adverse impact on safety. A significant increase in the IFP spatial density is an area of concern which simulator testing could support when adequate encounter models are developed.
- The S4 deproach IFP simulator data could be potentially leveraged and input into a higher fidelity full motion simulator such as the Virtual Motion Simulator at Ames to further assess the deproach IFP's flyability and ride quality.
- Additional passenger comfort and ride quality analysis should be conducted to compare the data collected against existing candidate sets of requirements. Further discussion should assess what sets of requirements might be most appropriate/applicable.
- The NC team should refine and streamline the methodology to calculate lateral displacement of the aircraft from the desired path in turns, in order to derive these values more efficiently in the future.
- Iteration on the deproach IFP construct should eliminate past ambiguity on waypoint types (flyby vs. flyover).
- Further research should investigate how flight procedure validation could be accomplished for UAM/eVTOL IFPs. Use and/or modification of existing software, tools, and processes should be investigated, as well as potential opportunities for new methods.

- The current adequacy or need/desire for potential changes to the ARINC 424 specification to accommodate UAM/eVTOL IFPs should be assessed.
- Acoustic Evaluation: All aircraft data to characterize environmental noise along the deproach were collected and could be reduced if desired.
- Human Factors: Future acceleration data may be valuable to analyze due to the unique vertical profiles, body angles and acceleration/decelerations. Care should be taken when developing simulator profiles for the purpose of passenger comfort due to the limitations of a simulated environment (e.g., no human evaluation possible, limited turbulence modeling, etc.).

Planning is currently underway with subject matter experts from NASA, FAA, DoD (Air Force Research Laboratory - Agility Prime) and Joby.

Appendix A: Abbreviations, Acronyms & New Terms

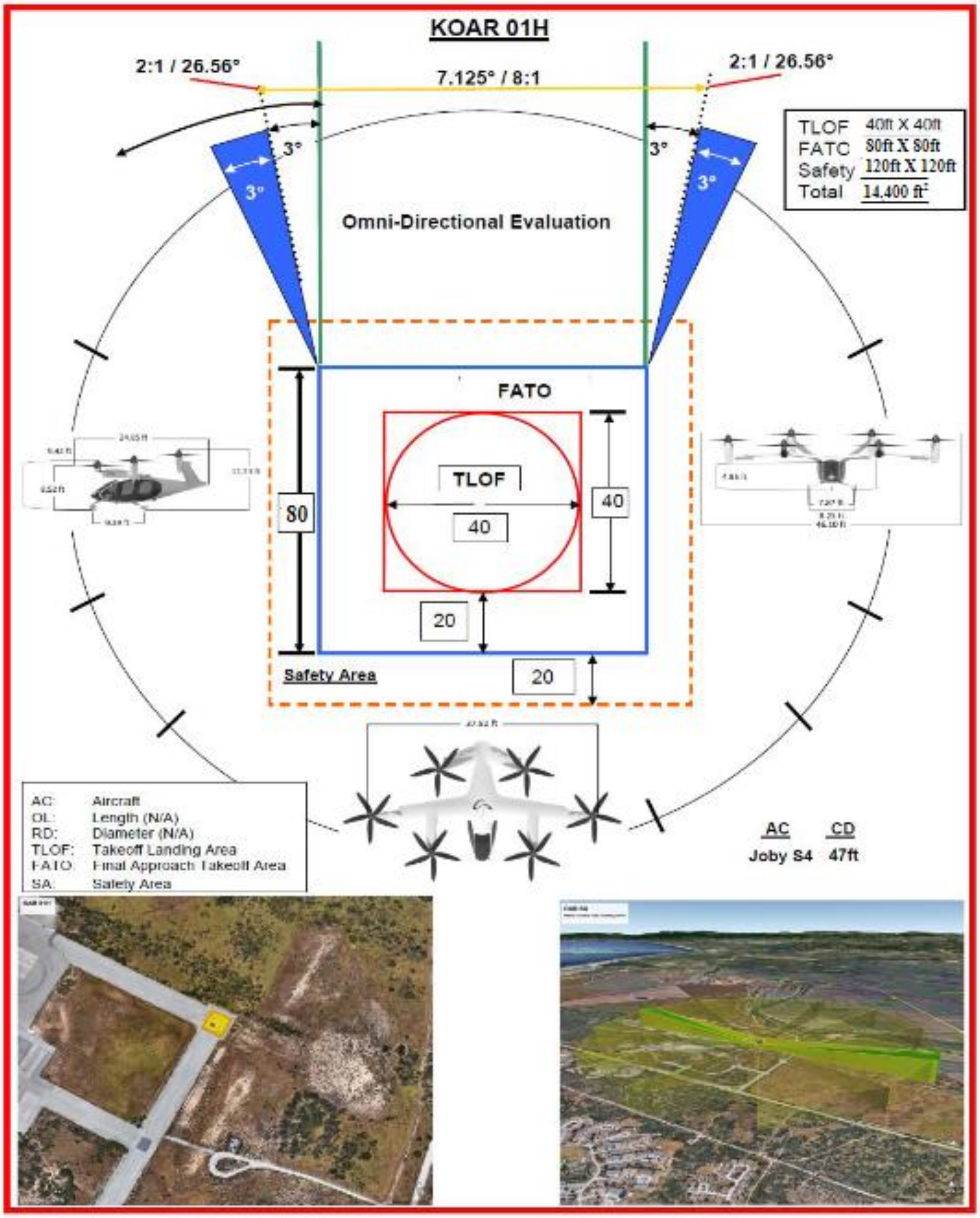
This appendix contains acronyms that are used throughout this document. * New Term

Table 4. Abbreviations, Acronyms and New Terms

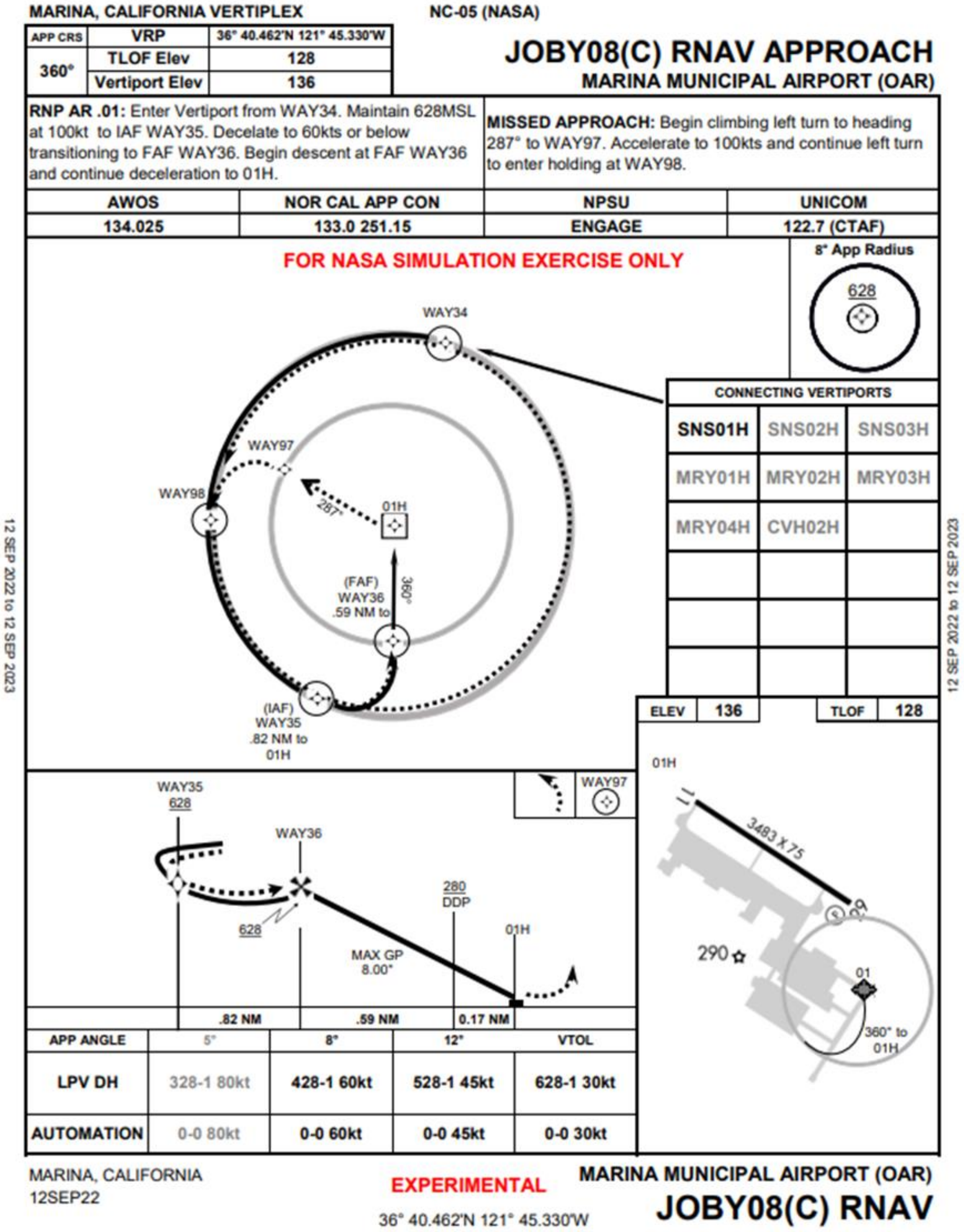
ACRONYM	TERM
AAM	Advanced Air Mobility
AC	Advisory Circular
AGL	Above Ground Level
AIRNAV	Airport Navigation database
AoA	Angle of Attack
ATS	Air Traffic Services
ARINC	Aeronautical Radio, Incorporated
AVOSS	Aircraft Vortex Spacing System
BWS	Bedford Workload Scale
CCHP	Continuously Computed Hover Point
CNEL	Community Noise Equivalent Level
CNF	Computer Navigation Fix
CRM	Collision Risk Model
CSV	Comma Separated Value
CWT	Consolidated Wake Turbulence
deproach*	UAM Departure & Approach Airspace Architecture
DIP*	Departure Intercept Point
DNL	Day-Night Average Sound Level
DTED	Digital Terrain Elevation Data
EPNL	Effective Perceived Noise Level
eVTOL	Electric Vertical Take-Off and Landing
FAA	Federal Aviation Administration
FATO	Final Approach and Takeoff Area
FIAPA	Flight Inspection Airborne Processing Application
FMS	Flight Monitoring System
GNC	Guidance Navigation and Control
GPS	Global Positioning System
GTO	General Test Objective
HRR	High Resolution Recorder
HSI	Horizontal Situation Indicator
IAP	Instrument Approach Plate
IFP	Instrument Flight Procedures
IFPA	Instrument Flight Procedures Automation
IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions
IVS	Integrated Vehicle Simulator
LCD	Liquid Crystal Display
Lmax	Maximum Sound Level

LRU	Line Replaceable Unit
MCH	Modified Cooper-Harper rating scale
MOP	Measure of Performance
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NAVAIDS	Navigational Aids
NC	National Campaign
NC-DT	National Campaign Developmental Testing
NM	Nautical Mile
OCS	Obstacle Clearance Slope
OEA	Obstacle Evaluation Assessment
OEAA	Obstacle Evaluation Assessment Area
OE / AAA	Obstruction Evaluation/ Airport Airspace Analysis
PARM*	Procedure Automation Rating Matrix
PBN	Performance Based Navigation
PFAF	Precision Final Approach Fix
PFD	Primary Flight Display
PNL	Perceived Noise Level
PNLT	Tone-Corrected Perceived Noise Level
POI	Point of Interest
RF	Radius-to-Fix
RNAV	Area Navigation
RNP AR	Required Navigation Performance Authorization Required
ROC	Required Obstacle Clearance
SA	Safety Area
SEL	Sound Exposure Level
SID	Standard Instrument Departure
STO	Specific Test Objective
TARGETS	Terminal Area Route Generation Evaluation and Traffic Simulation
TERPS	Terminal Instrument Procedures
TF	Track-to-Fix
TLOF	Touchdown and Liftoff
TRC	Transformative Rate Command
TSE	Total System Error
UAM	Urban Air Mobility
UAS	Unmanned Aircraft System
UTC	Coordinated Universal Time
VDP	Visual Descent Point
VFR	Visual Flight Rules
VRP*	Vertiport Reference Point
VMC	Visual Meteorological Conditions
VSIL	Vehicle Software Integration Lab
WP	Waypoint

Appendix B: Vertiport Evaluation Worksheet



Appendix C: Approach & Departure Plates



MARINA, CALIFORNIA VERTIPLEX

NC-05 (NASA)

APP CRS	VRP	36° 40.462'N 121° 45.330'W
360°	TLOF Elev	128
	Vertiport Elev	136

JOBY08(C) RNAV APPROACH

MARINA MUNICIPAL AIRPORT (OAR)

RNP AR .01: Enter Vertiport from WAY34. Maintain 628MSL at 100kt to IAF WAY35. Decelate to 60kts or below transitioning to FAF WAY36. Begin descent at FAF WAY36 and continue deceleration to 01H.

MISSED APPROACH: Begin climbing left turn to heading 287° to WAY97. Accelerate to 100kts and continue left turn to enter holding at WAY98.

AWOS	NOR CAL APP CON	NPSU	UNICOM
134.025	133.0 251.15	ENGAGE	122.7 (CTAF)

FOR NASA SIMULATION EXERCISE ONLY

12 SEP 2022 to 12 SEP 2023

CONNECTING VERTIPORTS		
SNS01H	SNS02H	SNS03H
MRY01H	MRY02H	MRY03H
MRY04H	CVH02H	

ELEV	136	TLOF	128

APP ANGLE	5°	8°	12°	VTOL
LPV DH	328-1 80kt	428-1 60kt	528-1 45kt	628-1 30kt
AUTOMATION	0-0 80kt	0-0 60kt	0-0 45kt	0-0 30kt

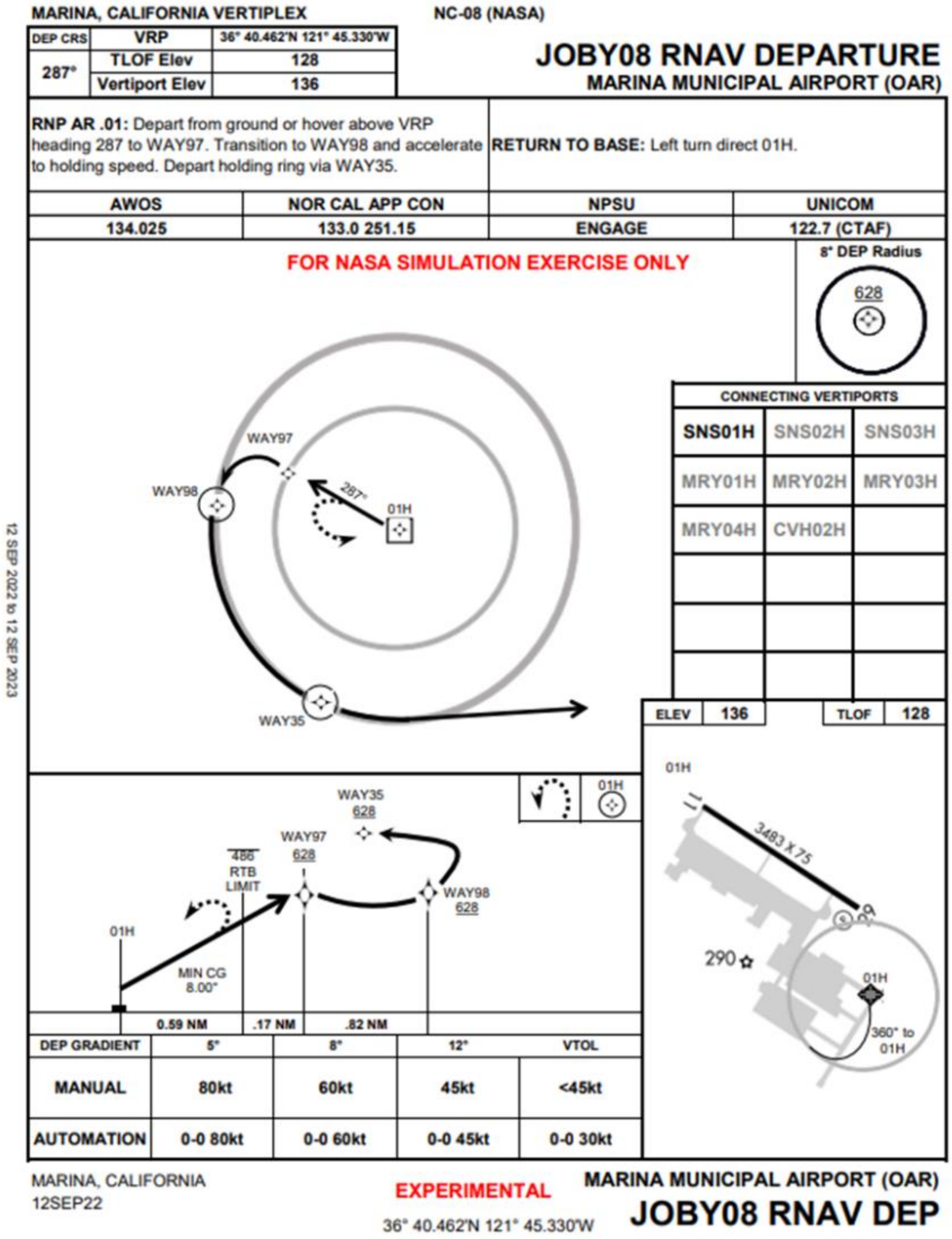
MARINA, CALIFORNIA
12SEP22

EXPERIMENTAL

36° 40.462'N 121° 45.330'W

MARINA MUNICIPAL AIRPORT (OAR)

JOBY08(C) RNAV



MARINA, CALIFORNIA VERTIPLEX **NC-08 (NASA)**

DEP CRS	VRP	36° 40.462'N 121° 45.330'W
287°	TLOF Elev	128
	Vertiport Elev	136

JOBY08 RNAV DEPARTURE

MARINA MUNICIPAL AIRPORT (OAR)

RNP AR .01: Depart from ground or hover above VRP heading 287 to WAY97. Transition to WAY98 and accelerate to holding speed. Depart holding ring via WAY35.

RETURN TO BASE: Left turn direct 01H.

AWOS	NOR CAL APP CON	NPSU	UNICOM
134.025	133.0 251.15	ENGAGE	122.7 (CTAF)

FOR NASA SIMULATION EXERCISE ONLY

8° DEP Radius

628

CONNECTING VERTIPORTS		
SNS01H	SNS02H	SNS03H
MRY01H	MRY02H	MRY03H
MRY04H	CVH02H	

ELEV	136	TLOF	128

	0.59 NM	.17 NM	.82 NM

DEP GRADIENT	5°	8°	12°	VTOL
MANUAL	80kt	60kt	45kt	<45kt
AUTOMATION	0-0 80kt	0-0 60kt	0-0 45kt	0-0 30kt

12 SEP 2022 to 12 SEP 2023

12 SEP 2022 to 12 SEP 2023

MARINA, CALIFORNIA
12SEP22

EXPERIMENTAL

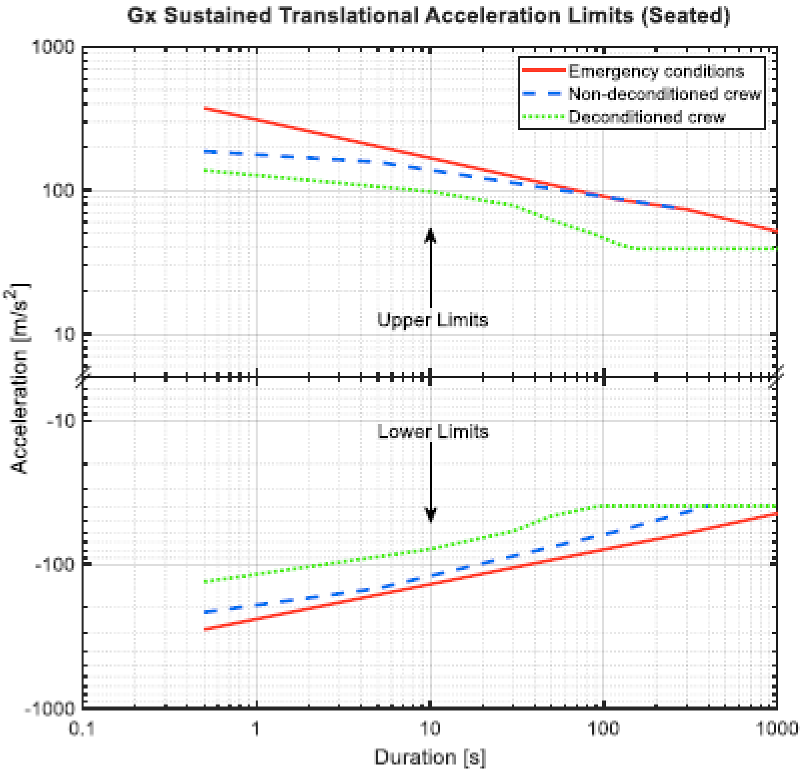
36° 40.462'N 121° 45.330'W

MARINA MUNICIPAL AIRPORT (OAR)

JOBY08 RNAV DEP

Appendix D: Sustained Translational Acceleration Limits

NASA-STD-3001, VOLUME 2, REVISION C



Acceleration limits for emergency conditions (seated)

Upper limit	Duration [s]	0.5	120	300	1200
	Acceleration [m/s^2]	373	86.3	73.5	49.0
Lower limit	Duration [s]	0.5	120	300	1200
	Acceleration [m/s^2]	-284	-75.5	-60.8	-42.2

Acceleration limits for non-deconditioned crew (seated)

Upper limit	Duration [s]	0.5	5	300	
	Acceleration [m/s^2]	186	157	73.5	
Lower limit	Duration [s]	0.5	5	120	400
	Acceleration [m/s^2]	-216	-147	-58.8	-39.2

Acceleration limits for deconditioned crew (seated)

Upper limit	Duration [s]	0.5	10	30	50	90	120	150	10000
	Acceleration [m/s^2]	137	98.1	78.5	61.8	49.0	42.2	39.2	39.2
Lower limit	Duration [s]	0.5	10	30	50	90	100	10000	
	Acceleration [m/s^2]	-132	-78.5	-58.8	-46.1	-39.7	-39.2	-39.2	

Figure 4—Gx Sustained Translational Acceleration Limits (Seated)

Appendix E: KOAR 01H Wake Turbulence Exploration

As part of the pathfinder research for UAM IFP construction, FAA believes wake turbulence needs to be evaluated for operations in and around airports. For the Joby simulator activity, the NC collaborated with the FAA to explore the impact of a single runway on an adjacent vertiport. Because no current modeling exists for UAM vertiport operations, a simulation of simultaneous approaches to parallel runways was used to develop an estimated wake vortex risk of time and lateral distance. Experimental exploration was run with the Aircraft Vortex Spacing System (AVOSS) 3.2 Wake Model (legacy version).

Typical Collision Risk Model (CRM) error distributions, crosswind and appropriate fleet mix were applied to the simulation. A fast time stochastic simulation of arrivals using CRM Instrument CAT I with 50ft TCH was used to generate a wake vortex during a 15kt unfavorable crosswind. Two test vehicles were run against the KOAR 01H vertiport simulation: an Airbus A380 (an atypical aircraft for the 3,200 ft runway) and a Gulfstream GLF4. The results featured below in Figures 20 & 21 are an example of how wake turbulence can be used as part of future UAM IFP evaluation criteria.

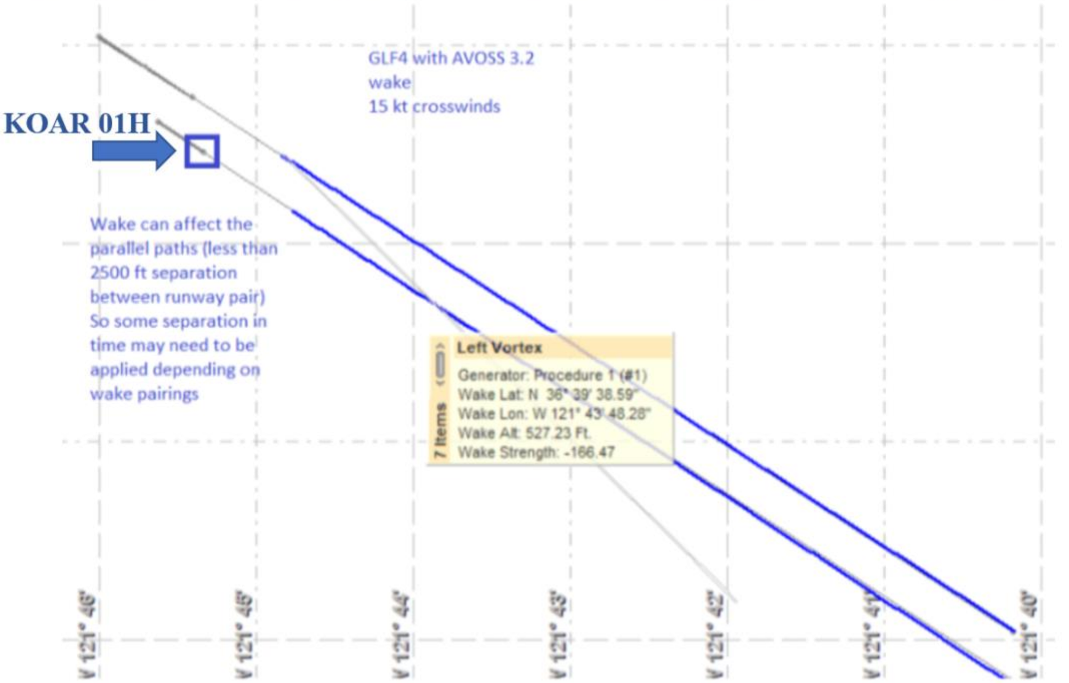
The following conclusions were derived from the KOAR simulation exercise:

- Wake will affect UAM IFP operations of parallel approach/departure paths in unfavorable crosswind conditions (less than 2,500 ft. separation between runway pairs).
- Separation timing requirements will be dependent upon a UAM wake pairing matrix.
- For the notional experimental purpose of this test, a worst-case aircraft flight generating AVOSS 3.2 wake with 15 kt crosswind persisted for more than 2 minutes.
- UAM operational performance and flight technical error is unknown to derive an equivalent CRM.

Further exploration will be required to answer the following questions:

- Which wake strengths are necessary to cause flight control issues or other hazards to flight/stability/control for UAM vehicles?
- Are there sufficient representative classes for wake encounters?
- What is the worst-case representative aircraft/atmospheric conditions [xx] for UAM?
- Is Consolidated Wake Turbulence (CWT) 7110.126B sufficient to protect UAM class aircraft?
- Does CWT assume both aircraft are moving and stable in inertial flight?
- What is the cutoff vortex strength used for CWT risk?
- Are helicopter targets treated differently than fixed wing targets?

Gulfstream IV on parallel final with Joby S4 PinS Approach



GLF4 with AVOSS 3.2 wake
15 kt crosswinds

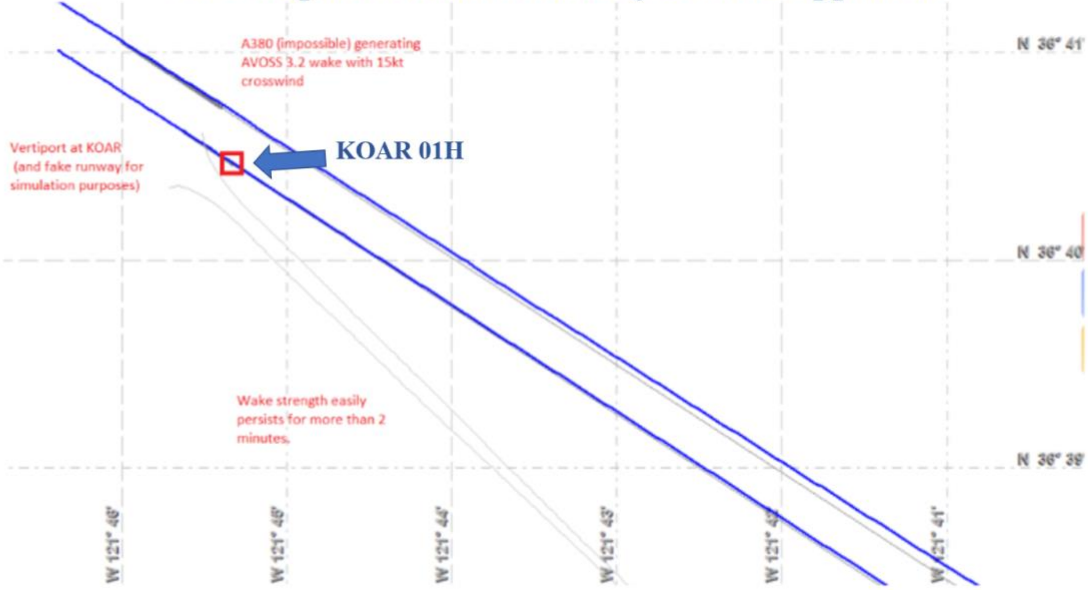
KOAR 01H

Wake can affect the parallel paths (less than 2500 ft separation between runway pair) So some separation in time may need to be applied depending on wake pairings

Left Vortex

Generator: Procedure 1 (#1)
Wake Lat: N 36° 39' 38.59"
Wake Lon: W 121° 43' 48.28"
Wake Alt: 527.23 Ft.
Wake Strength: -166.47

A380 on parallel final with Joby S4 PinS Approach



A380 (impossible) generating AVOSS 3.2 wake with 15kt crosswind

Vertiport at KOAR (and fake runway for simulation purposes)

KOAR 01H

Wake strength easily persists for more than 2 minutes.

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