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High Density Vertiplex Flight Test Report Advanced Onboard Automation

Robert G. Mcswain
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January 2023

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Acronyms

4G	Fourth Generation
AAM	Advanced Air Mobility
ADS-B	Automatic Dependent Surveillance – Broadcast
AGAM	Automated Geofence Avoidance Maneuver
AELM	Automated Emergency Landing Maneuver
AOA	Advanced Onboard Automation
AOL	Airspace Operations Laboratory
AP	Approach Point
ARC	NASA Ames Research Center
ATAM	Automatic Traffic Avoidance Maneuver
ATMS	Air Traffic Management Station
ATP	Approach Taxi Point
AVAL	Autonomous Vehicle Applications Laboratory
BVLOS	Beyond Visual Line of Sight
C2	Command and Control
C3	Command, Control, and Communications
CERTAIN	City Environment for Range Testing of Autonomous Integrated Navigation
CPA	Closest Point of Approach
EVLOS	Extended Visual Line of Sight
FLARM	Flight Alarm
FPA	Flight Path Assessment
GCS	Ground Control Station
GHz	Gigahertz
GPS	Global Position System
FM	Fleet Manager
HDV	High Density Vertiplex
HF	Human Factors
ICAROUS	Integrated Architecture for Reliable Operations of Unmanned Systems
INS	Inertial Navigation System
ISM	Industrial, Scientific and Medical Radio Frequencies
LandIR	Landing and Impact Research Facility
LaRC	NASA Langley Research Center
LTE	Long Term Evolution
MHz	Megahertz
PAO	Prototype Assessment Operations
PIC	Pilot In Command
ROAM	Remote Operations for Autonomous Missions
RTL	Return To Launch
S2D	Safe To Ditch Contingency Management
sUAS	small Uncrewed Aircraft System
SWP	Schedule Work Package
UAM	Urban Air Mobility
UML	UAM Maturity Level
VAS	Vertiport Automation System
V2V	Vehicle 2 Vehicle
VHF	Very High Frequency
VLOS	Visual Line Of Sight

Introduction

NASA's Advanced Air Mobility (AAM) Project has established a line of research within its portfolio referred to as the High Density Vertiplex (HDV) sub-project [1]. Overall, the HDV sub-project endeavors to perform rapid prototyping and assessment of an Urban Air Mobility (UAM) Ecosystem to help inform future research investments with a particular focus on vertiport operations and their associated elements. Within HDV's UAM Ecosystem prototyping, representative elements of: 1) Onboard autonomous systems, 2) Ground control and fleet management systems, 3) airspace management systems and 4) Vertiport automation systems are included. The technical work within the HDV sub-project was designed to follow an iterative, phased approach, with the first phase designated as the Advanced Onboard Automation (AOA) schedule work package (SWP). A key focus area of the HDV sub-project is the development and integration of vertiport automation systems (VAS). However, only very basic functionality for the VAS was included within the AOA schedule work package due to the initial scope being the implementation of the foundational capabilities needed to integrate and test with the VAS as part of the envisioned ecosystem. Although the HDV sub-project had many objectives for the AOA phase, this report will focus on the flight testing conducted to support Human Factors (HF) [2] [3] research related to vertiport Prototype Assessment Operations (PAO). This flight activity was designated HDV AOA Flight Test, which started February 2022 and ended April 2022.

The flight testing conducted within HDV AOA focused on three components: 1) Vertiport PAO; 2) Automated unpiloted aircraft maneuvers; 3) Remote command and control of unpiloted aircraft. The vertiport PAO component focused on scenarios that would drive nominal and off-nominal aircraft operations within an airspace with multiple vertiports. The automated unpiloted aircraft maneuvers component focused on exploring onboard aircraft systems capabilities that could support off-nominal events during operations. The remote command and control of unpiloted aircraft component focused on evaluating unpiloted aircraft flight crew roles and responsibilities, control interfaces and the associated data links needed to operate a fleet of aircraft within a UAM Ecosystem.

This work supports the development of future aviation operational concepts based on an Urban Air Mobility Maturity Level (UML) 4 environment [4]. This future airspace can be envisioned in Figure *1*. It is assumed that this airspace will include hundreds of simultaneous aircraft operations within the airspace, therefore scalable operations are essential for enabling this future airspace to become a reality.

Figure 1: Advanced Air Mobility Concept Art

System Description

Aviation systems are complex. Therefore, the system descriptions in this report will focus on high level sub-systems used to execute the HDV AOA Flight Test. The sub-systems that will be described include: Research aircraft systems; Research facility systems; and Command, Control, and Communications (C3) systems. Each of these sub-systems have many technical details that are outside the scope of this report. The intent of this document is to provide a high level system context that supported the flight testing documented in this report.

Research Aircraft

The research aircraft system was built around a small Uncrewed Aircraft System (sUAS) to support high density air operations for the flight activity. These sUAS were intended as surrogate aircraft for the larger vehicles envisioned in future UAM operations in order to test onboard systems in a live environment. Based on project scope and resources, the required number of aircraft needed in flight for the flight test was three. This provided an initial look at conducting low-risk multi-aircraft flight operations to demonstrate data link performance and automation software behavior. Each sUAS was equipped with three command links: 2.4 GHz ISM, 915 MHz ISM and 4G LTE Cellular Bands. These communication interfaces can be seen in Figure 2, which are connected to the aircraft flight control system. The flight control system would be responsible for navigating the aircraft based on remote operator command inputs from the command links, and also would use automated trajectory guidance from the automation computer system during off-nominal test events. It is intended that the auto-pilot sub-system would be included in the flight control system. During flight testing an open-source hardware/software auto-pilot was used to support integration and testing. During nominal operations the situational awareness data generated by the automation computer system can be relayed to the flight control system and therefore remote operators. During flight testing traffic broadcast systems were used to provide the automation computer system with traffic detection capabilities. Vehicle 2 Vehicle (V2V) systems used during testing included: Automatic Dependent Surveillance Broadcast (ADS-B) input (1090/978 MHz), Flight Alarm (FLARM) input and output. (915 Mhz ISM). The automation computer relied on an Inertial Navigation System (INS) which provided it with an independent source of vehicle data (Attitude, Position, Velocity, etc….). To support landing automation, a camera was included to provide a visual sensor to support the detection of ground hazards during approach and landing.

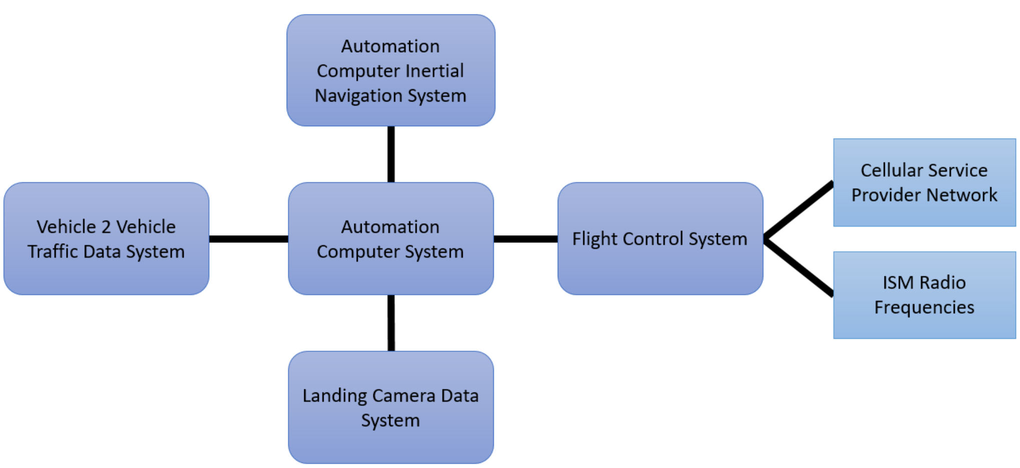

Figure 2: Aircraft Systems High Level Diagram

In total there were three GPS receivers, 3 Command and Control (C2) transceivers, one V2V receiver and one V2V transceiver was integrated and used during three aircraft operations during HDV AOA Flight Testing. An image of a research aircraft is shown in Figure 3.

Figure 3: Research sUAS Aircraft N557NU In Flight

During three aircraft operations, aircraft were launched and recovered from a co-located take off and landing area which was designated a vertiport. This can be seen in Figure 4 where the first of three aircraft is taking off and preparing to depart the vertiport.

Figure 4: Three Research Aircraft During Multi-Aircraft Operations

Research Facilities

To support aircraft systems, several ground systems were required on the flight range which enabled the Command Control and Communications (C3) required to support flight operations. In Figure 5 we can see the flight range research facilities used to support the flight test. This flight range is identified as the City Environment for Range Testing of Autonomous Integrated Navigation (CERTAIN) located at NASA Langley Research Center (LaRC). In this figure we can see ground transceivers for 915 MHz C2 located next to a covered awning that is used as a staging area for pre-flight procedures. Although difficult to see, there is also equipment located at the CERTAIN trailer which allows vertiport camera streams and air traffic control tower radio communications.

Figure 5: Flight Range Research Facilities

A take off and landing area with flight crews for the multi-aircraft operations can be seen in Figure 6. Although the research was focused on remote operations within a high density vertiport airspace, the flight crew that supported these remote operations were on site to prepare aircraft for take off, and supervise the flights within Visual Line Of Sight (VLOS). The field crews enabled a safety net to establish new operational roles and responsibilities for remote fleet operations.

Figure 6: Flight Crew Supervising Remote Operations

The new operational roles and responsibilities included remote operators of the aircraft which utilized a facility designated Remote Operations for Autonomous Missions (ROAM). This remote operations room can be seen in Figure 7. Each remote operator had a control station which included a Ground Control Station (GCS) and an Air Traffic Management Station (ATMS). The GCS was used to issue commands and interact with the aircraft, while the ATMS allowed the remote operator to interact with the fleet and vertiport managers.

Figure 7: ROAM Remote Operation during Multi-Aircraft Operations

The fleet manager utilized the facility designated as the Airspace Operations Laboratory (AOL) located at NASA Ames Research Center (ARC) to supervise overall fleet operations and assign flight plans for aircraft during flight operations. This facility can be seen in Figure 8, which is where flight plans based on vertiport and routes were assigned to remote operators and their associated aircraft. The fleet manager had to coordinate with the vertiport manager to establish an approved departure and arrival time, and associated take off and landing pads.

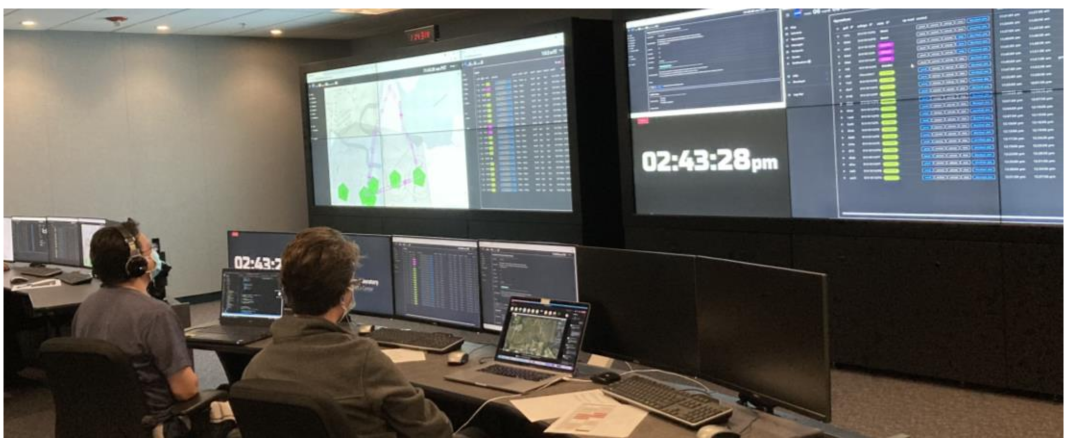

Figure 8: AOL Fleet Management during Multi-Aircraft Operations

The vertiport manager established the status of the vertiport to include availability of take off and landing pads, and approach and departure schedules. This role utilized the facility designated as the Autonomous Vehicle Applications Laboratory (AVAL), which can be seen in Figure 9.

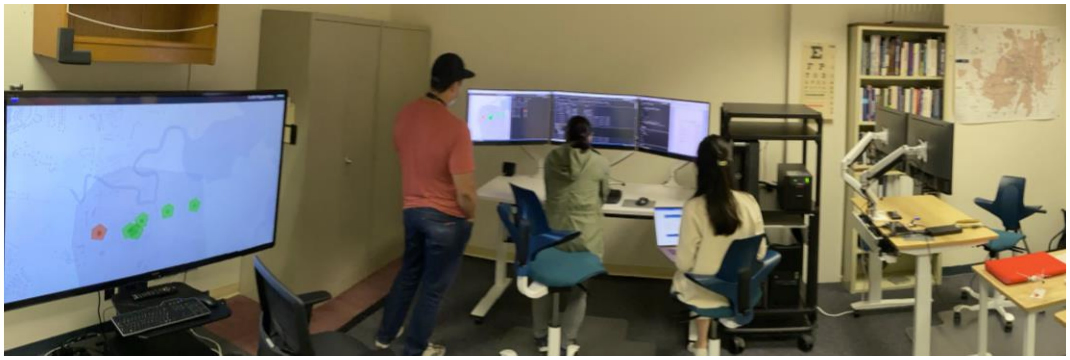

Figure 9: AVAL Vertiport Management during Multi-Aircraft Operations

Command Control and Communications

Three control links were established to allow a remote operator to control the aircraft, while the flight crew in the field could supervise. These link interfaces can be seen in Figure 10, with two of them being line of sight with the field-based flight crew. The remote operator used a cloud based remote connection utilizing a cellular network service provider to access the aircraft remotely. The two GCS control links provided the following information:

- Real-Time Command and Control
- Real-Time Aircraft V2V Air Traffic Positions
- Pre-Flight and In-Flight Flight Plan
- Real-Time Vehicle Systems Status
- Pre-Flight Vehicle Auto-Pilot Settings
- Real-Time Mission Computer Status

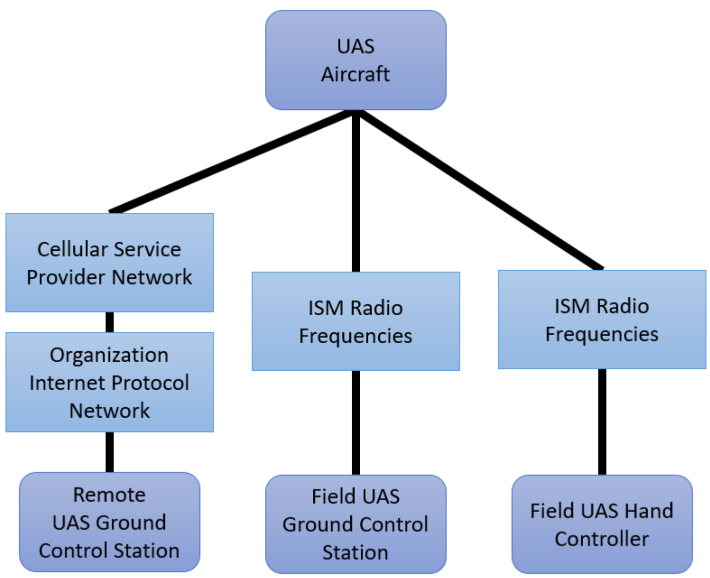

Figure 10: High Level C2 System Diagram

Data communications were established to support traffic data exchanges associated with fleet and vertiport management across the research facilities. A high level diagram can be seen in Figure 11, showing how each facility had to communicate through an organizational network. The aircraft data was filtered and sent to the vertiport and fleet managers to be used in their respective roles. Data for fleet and vertiport managers being transmitted included:

- Real-Time Flight Route Air Traffic Volumes
- Real-Time Vertiport Status

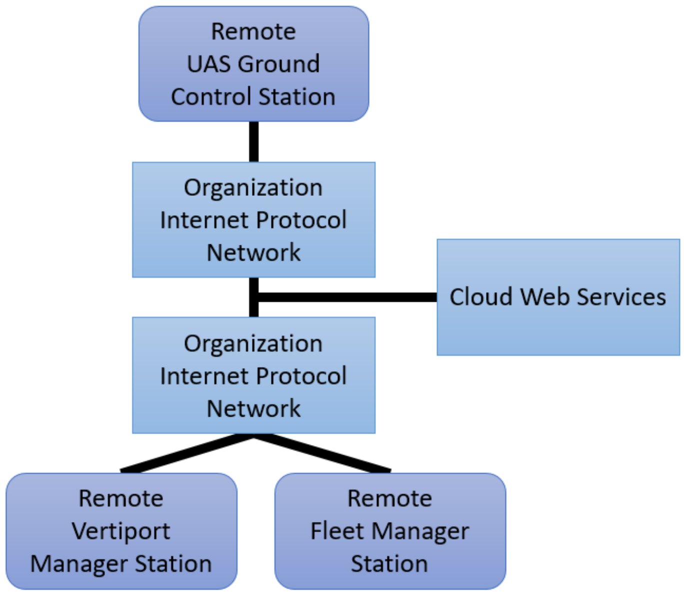

Figure 11: High Level Traffic Management Data System Diagram

Another component of data included sensors that were installed on the flight range and provided additional airspace and environmental awareness. In Figure 12 this can be seen as the infrastructure sensors which were installed and connected to the organizational network at CERTAIN. This type of data included:

- Real-Time Vertiport V2V Air Traffic Positions
- Real-Time Vertiport Vertipad Video
- Real-Time Vertiport Radio Frequency Spectrum Status
- Real-Time Vertiport and Flight Route Weather Status

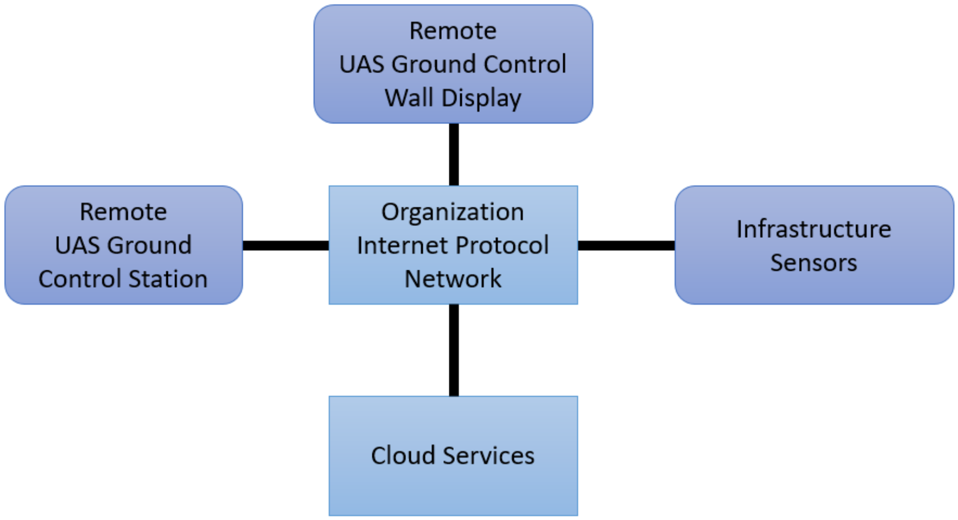

Figure 12: High Level Remote Operator Data System Diagram

In addition to digital communications, voice communications between the various roles and responsibilities occurred on both telecommunications and through face to face conversations. A high level view of these interfaces can be seen in Figure 13. The co-located roles were able to conduct face to face conversations. Field personnel communicated with tower utilizing Very High Frequency (VHF) radios, and aircraft Pilot In Command (PIC) communicated with remote operators utilizing a cellular phone. A virtual teleconference system was used to establish voice and video across the various research facilities.

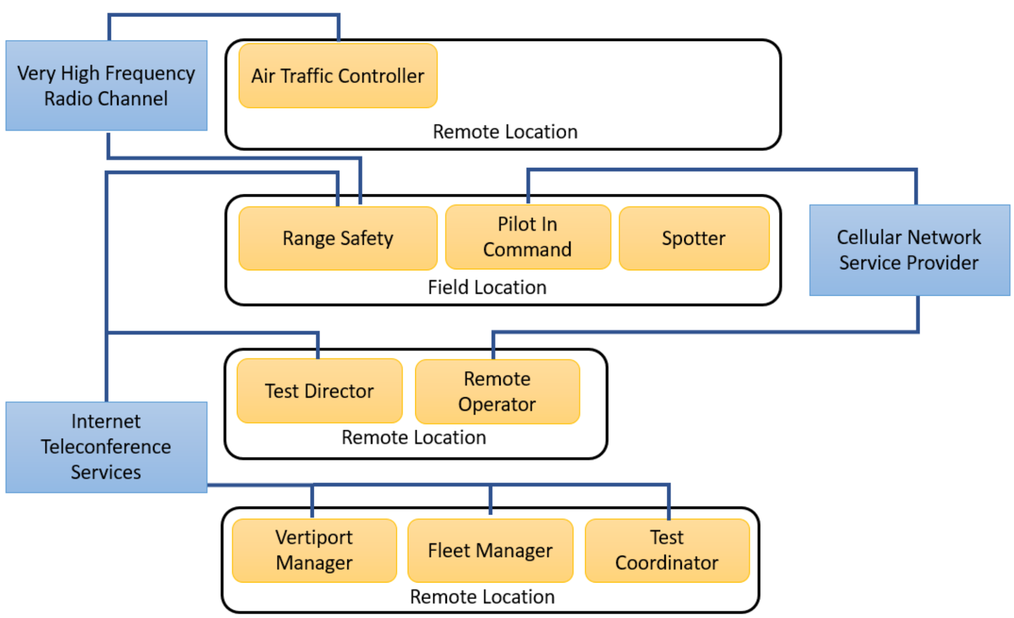

Figure 13: Voice Communications System Diagram

Vertiport Prototype Assessment Operations (PAO)

The HDV team developed several scenarios to establish nominal and off-nominal test procedures to be used for Human Factors (HF) testing. These scenarios were designed and tested within the HDV AOA Simulation HF Test to support the development of the roles and responsibilities of various positions being proposed within the vertiport environment. The three major roles considered during the scenario development were: Remote Ground Control Station Operator, Fleet Manager, and Vertiport Manager. All scenarios that were flight tested are shown in Table **1**.

Table 1: Advanced Onboard Automation Flight Test Summary

Tests Completed	Scenario Identification	Scenario Name	Scenario Description
17	**1**	**Nominal Flight**	**Flight executed per flight plan**.
10	**2A**	**Tactical Ownship Conflict Conformant**	**Flight path deviation needed to address minor traffic incursion.**
6	**2B**	**Tactical Ownship Conflict Non-Conformant**	**Flight path deviation needed to address traffic incursion.**
10	**3A**	**Emergency Re-Route S2D Manual**	**Flight path deviation to Vertistop needed to address vehicle health issue, manually triggered.**
3	**3B**	**Emergency Re-route S2D Manual**	**Flight path deviation to Vertiport needed to address vehicle health issues, manually triggered.**
6	**4A**	**Re-Route for Non-Emergency Reasons**	**Flight path deviation needed to address vertiport closure, manually triggered.**
2	**5A**	**Geofence Encounter**	**Flight path deviation needed to address geofence encounter.**

In this report data analysis and figures were generated using the following tools: Microsoft Power Point, Google Earth Pro, Matlab, Matlab UAV Toolbox, Microsoft Excel, Microsoft Snipping Tool, and PX4 pyulog.

Nominal Flight Scenario

The nominal flight scenario was the initial scenario that defined the expected flight profiles and procedures for departing and arriving from a vertiport. This scenario was to be the foundation on which additional scenarios would use to establish initial conditions to setup for an off-nominal event. The flight profile can be seen in Figure 14 which shows the operational area as an orange line, the flight path as the green line, and the take off and landing area as the green hexagon point. The take-off and landing points nomenclature is defined by the geographic area, vertiport numeric reference, and the vertipad numeric reference. Therefore the nominal scenario would take off and land from Langley Research Center Vertiport 1 Vertipad 1 in this example.

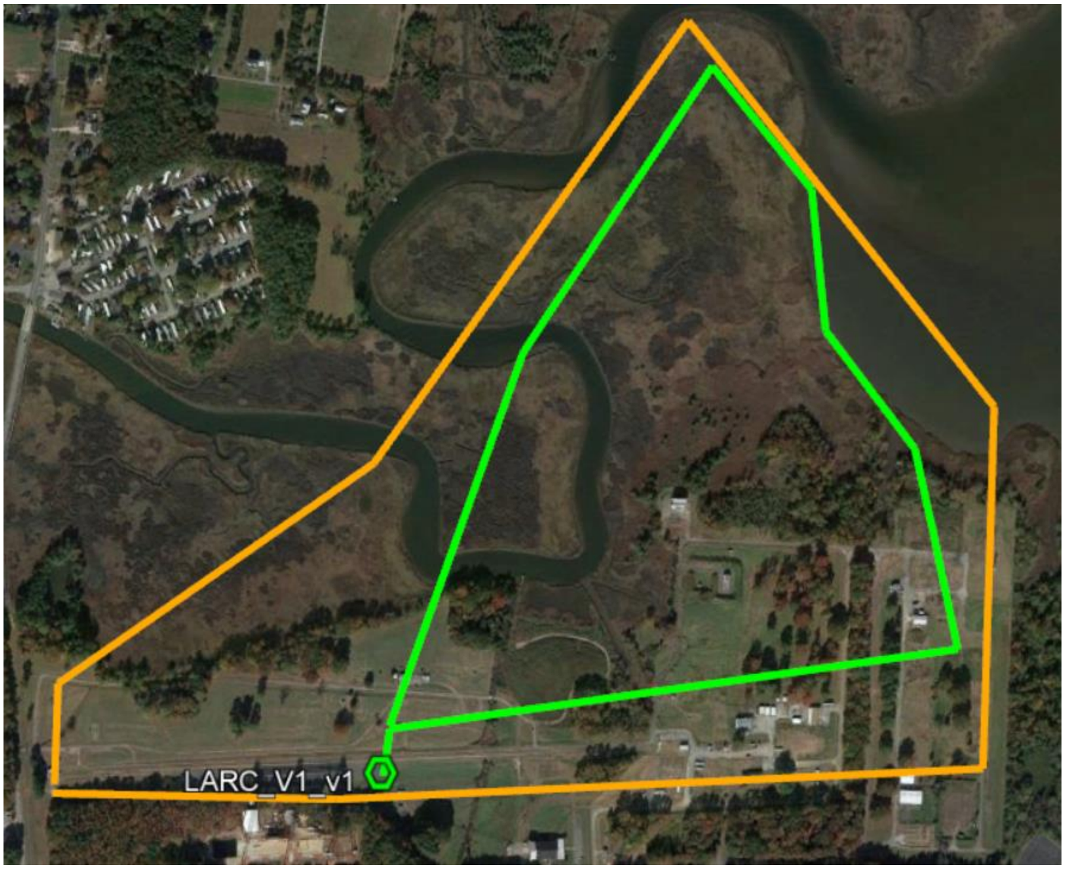

Figure 14: Nominal Scenario Flight Profile

Although the scenarios were initially developed with a single take-off and landing location, additional locations were needed to support multiple aircraft operations. During three aircraft operations LARC_V1_v1, LARC_V1_v2 and LARC_V1_v3 were used. These vertipad locations are shown in Figure 15 and were established with 100ft lateral separation to permit ground crews to access their aircraft on the vertipad while other aircraft were departing or arriving from the vertiport.

Figure 15: Langley Research Center Vertiport 1 Vertipads

To accompany the additional take-off and landing locations, taxi phases of the flight profile were added to prevent aircraft from over flying ground crews during pre-flight or post-flight procedures. This can be seen in Figure 16 as the blue square points. The taxi phase also reduced ground speeds of the aircraft providing more reaction time for ground crews and remote operators when in close proximity to other aircraft and ground crews.

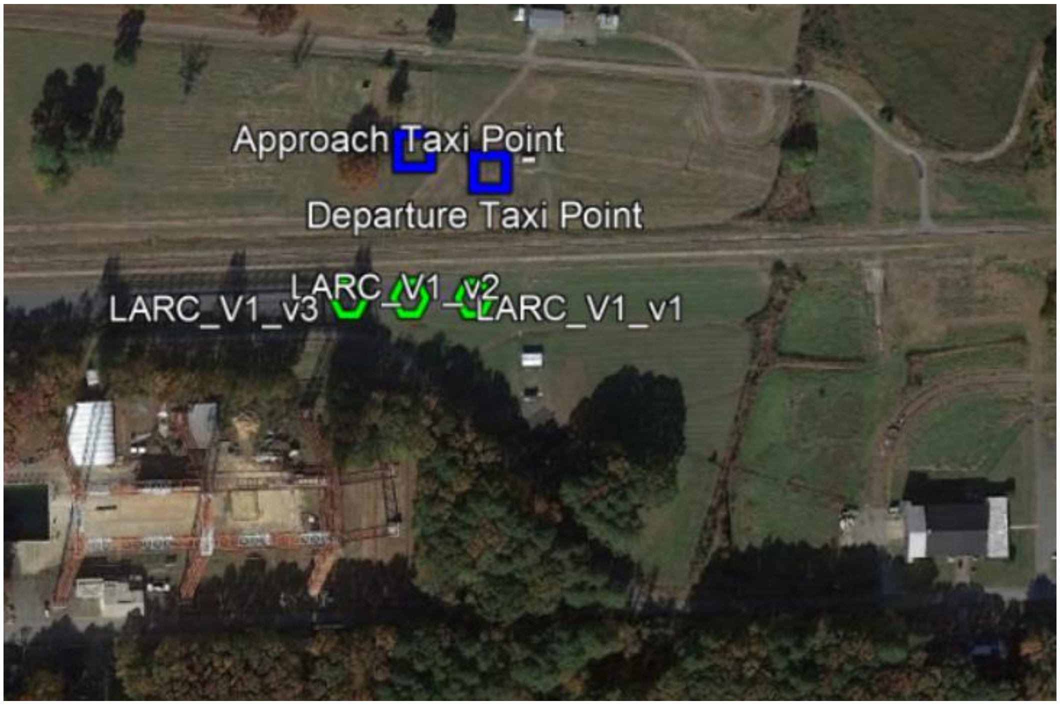

Figure 16: Vertiport 1 Departure and Approach Taxi Points

The flight profile for the nominal scenario included a climb and descent segment for both departure and arrival. This established the approach and departure points which are shown as blue square points in Figure 17. The final approach segment used a 10 degree glide slope. The departure segment used a 7 degree climb out angle.

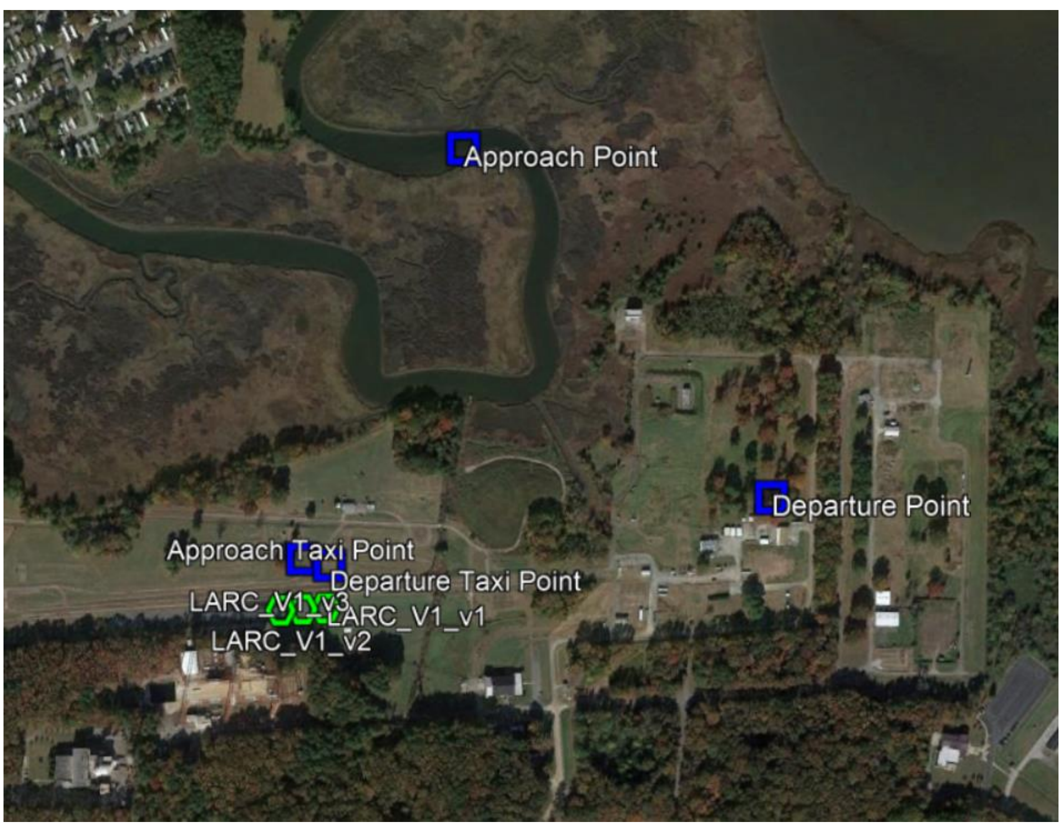

Figure 17: Vertiport 1 Approach and Departure Points

The remaining flight profile components of the nominal scenario included mission waypoints that defined the route for the aircraft. The waypoints are shown as green square points in the Figure 18.

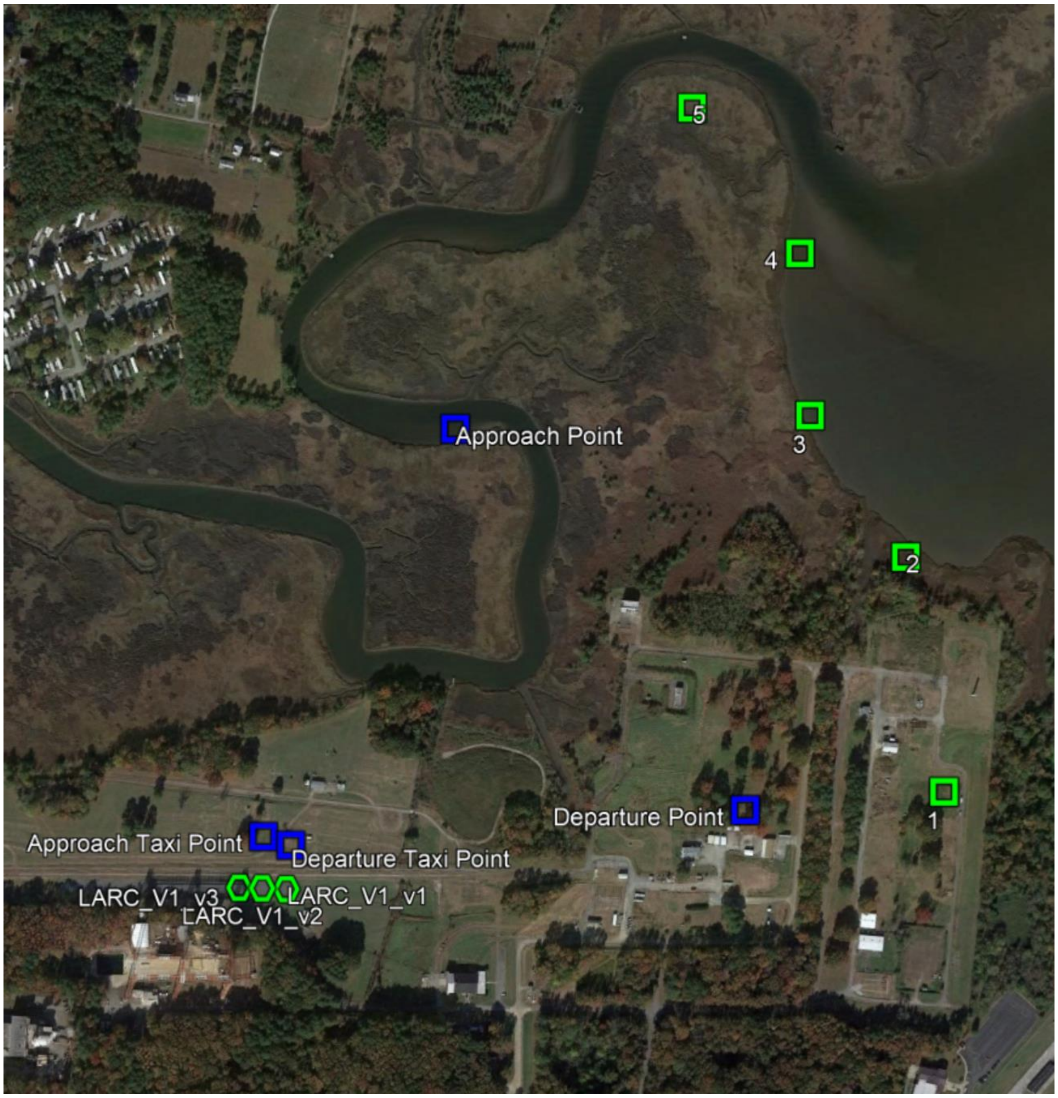

Figure 18: Nominal Scenario Route Waypoints

Nominal Flight Testing

The first flights conducted on the HDV project for HF data collection purposes were done with single aircraft operations. Over the course of the flight test campaign the crew experience and aircraft equipment were built up to support multiple aircraft operations. A total of 17 nominal scenario test runs were completed over the course of the HDV AOA flight test, which is summarized in Table 2. Of these 11 test runs, 6 met all data collections expectations. For this scenario the various types of data included: eXtensible Traffic Management (xTM) [5] data collected, Multi Aircraft Control System (MACS) simulated aircraft data, HF data collected from participants, Remote Operations for Autonomous Missions (ROAM) Ground Control System (GCS) data collected. Through testing, a significant amount of data was generated. The purpose of labeling the test runs is to provide a reference for the best test runs for analysis.

Table 2: Nominal Scenario Flight Test Operations for Scenario 1.

Date	Test Run	Scenario	Aircraft	Satisfactory Data
20220201	1	1	N557NU	Partial
20220201	2	1	N557NU	Partial
20220203	1	1	N557NU	Partial
20220203	2	1	N557NU	Partial
20220203	4	1	N557NU	Full
20220208	1	1	N557NU	Full
20220208	3	1	N557NU	Full
20220421	1	1/1/1	N559NU/N557NU/N556NU	Partial
20220429	1	1/1/1	N559NU/N557NU/N556NU	Full
20220429	2	1/1/4A	N559NU/N557NU/N556NU	Full
20220429	3	1/1/4A	N559NU/N557NU/N556NU	Full

It is worth noting that during all test runs there was both live aircraft operations and simulated aircraft operations. This provided the test environment with both real world constraints and the ability to scale traffic at the vertiport. All test runs had a departure and arrival operational tempo of 20 flights per hour. The schedule of the vertiport flights showing this can be seen in Figure 19. The time between departures at the vertiport was 3 minutes.

Figure 19: Vertiport 1 Flight Schedule during Test Run 3 on April 29th

During testing, the runs began with simulated operations while the live aircraft crew were conducting the pre-flight procedures. The flight crew would notify the vertiport scheduler they were ready for take-off, allowing them to be assigned a departure slot on the schedule. After take-off, the flight crew activated their flight operation and it was observed on the traffic management display shown in Figure 20. The green pentagon shapes in the figure represent vertiports, and the circular boundaries around them represent their associated airspace volumes [6]. The routes between vertiports can be seen as gray lines. The aircraft are shown as four rotor icons. The aircraft assigned volumes are shown, with magenta indicating conformance.

Figure 20: Vertiplex Traffic Management Display during Test Run 3 on April 29th

The live aircraft were launched consecutively during multi-aircraft testing, supporting higher fidelity operations within the live/virtual test environment. To highlight this, images from the live aircraft have been overlaid on the traffic management map display which can be seen in Figure 21.

Figure 21: Onboard View during Test Run 3 on April 29th

All of the nominal scenario test runs were nearly identical with the exception of the take off and landing location. This difference is shown in Figure 22 where the only variation is between the three vertiports. During testing, the aircraft landed at the same location they departed from. This was done to utilize the fail-safe feature designated Return To Launch (RTL) in the event of a lost communications link event during testing.

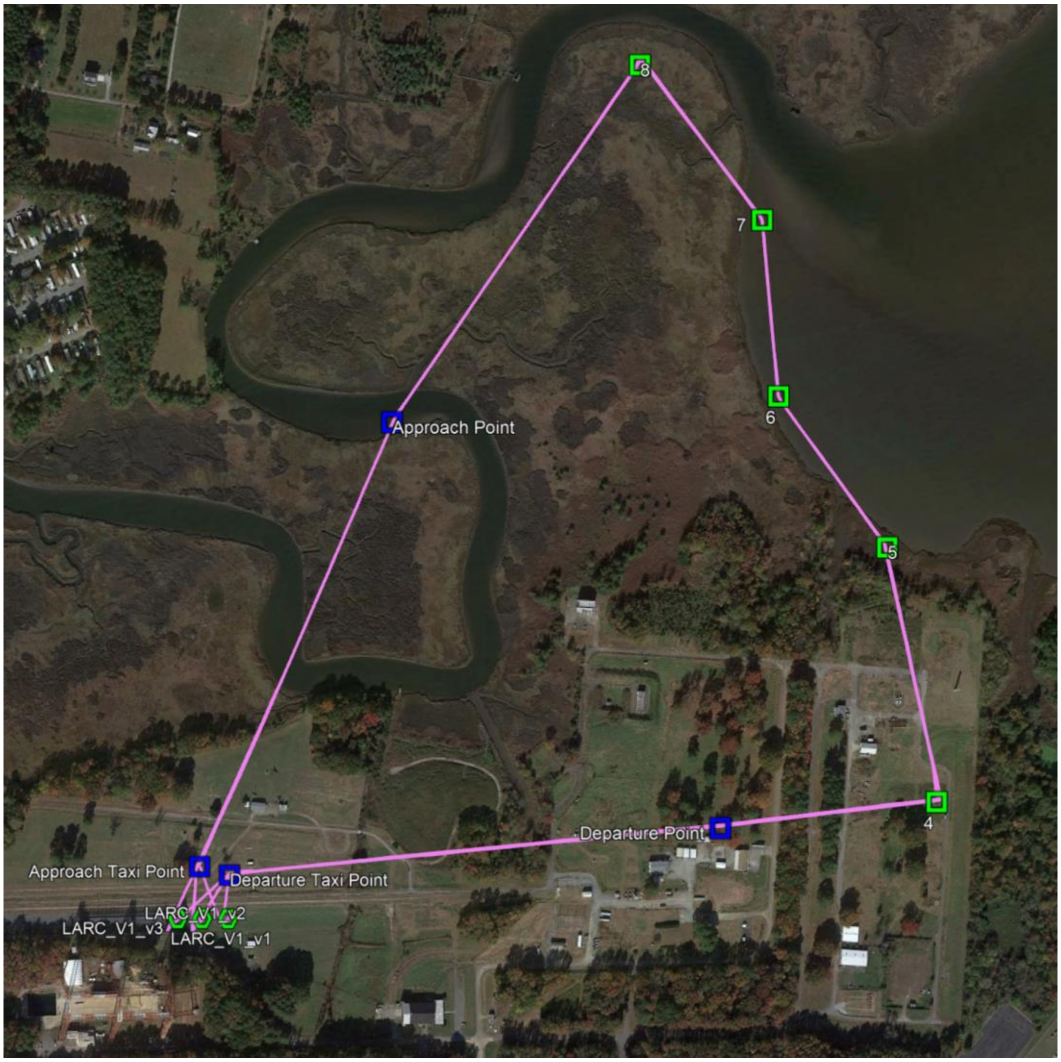

Figure 22: All Nominal Flight Test Run Flight Tracks

Low-Conflict Multi-Aircraft Scenarios

Since the scenarios were defined relative to a single aircraft, the low-conflict multi-aircraft scenarios included scenarios 2A and 3A. The scenarios also required two live aircraft to support Vehicle 2 Vehicle (V2V) communications needed for the aircraft systems to take automated actions. The Tactical Ownship Conflict Conformant (2A) scenario involved the aircraft making an Automated Traffic Conflict Maneuver (ATAM) adjustment to its flight path, allowing the aircraft to maintain well clear of the off-nominal traffic while maintaining conformance with the assigned airspace volume. This can be seen as the magenta line in Figure 23 between the Approach Point (AP) and the Approach Taxi Point (ATP). The Emergency Re-Route S2D Manual (3A) scenario had the aircraft make an Automated Emergency Landing Maneuver (AELM) to a Vertistop when initiated by the remote operator. The Vertistop can be seen as a green hexagon in the figure. The emergency landing maneuver can be seen as the magenta line between the Departure Point and the Mission Point 1. The Vertistop is a landing site with minimal infrastructure planned for use in, for example, off-nominal conditions when the vehicle is in an emergency condition and unable to fly all the way to its scheduled vertiport. A 500ft radius around the Vertistop is shown as a blue line which relates to the well clear settings for the onboard automation system responsible for making the tactical maneuver to maintain well clear while on approach.

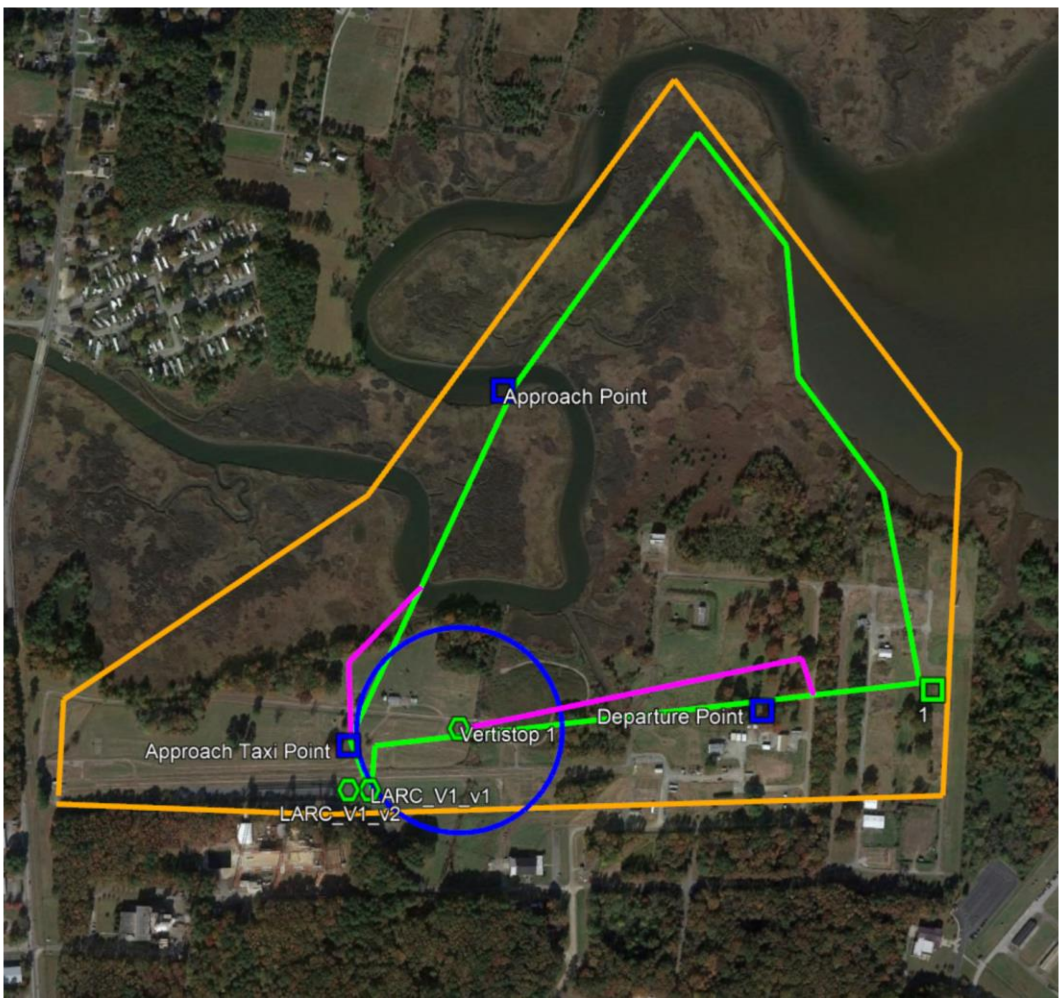

Figure 23: Low-Conflict Multi-Aircraft Scenarios Flight Profiles

During the automated maneuver, the pilot was notified of the automatic traffic avoidance maneuver as shown in Figure 24. The circle around the aircraft shows the headings that will ensure separation between the ownship aircraft and surrounding traffic. The green arc indicates headings that will keep the traffic greater than 500ft lateral from ownship. The red arc indicates headings that will lead to trajectories with other air traffic within 500ft lateral of ownship. In the figure, the traffic below (south of) ownship was displayed as a gray circle with a black aircraft icon. The ownship aircraft is displayed as a blue circle with a quadcopter icon. The aircraft heading is shown as a red arrow on the ownship icon, and the heading resolution arcs are around the ownship icon as well. The traffic avoidance system status can be seen on the right side of the display, showing a current traffic status in the upper rectangular icon and system ready state on the lower rectangular icon. There is also an icon stating that the automated traffic avoidance is active which can be seen above the traffic avoidance system status icon.

Figure 24: ATAM Display on the remote GCS in ROAM

During the emergency landing, onboard systems scanned the landing site as seen in Figure 25. This information is used to check if the emergency landing site has hazards prior to initiating the landing above the ditch site. In this figure, geographic reference tracks for an automotive vehicle driving along the road during an approach are shown. If the detected hazards are within the landing site, the system can either hold off on landing or divert to another viable emergency landing site. If this vehicle was detected in the vertiport 1 vertipad 1 landing site during the emergency landing, it could divert to the vertistop to the northeast. The detection capability is shown in this figure, and the logic is being developed for the intended vertiport concept of operations. In the figure, the blue dots represent the location where the onboard system calculated the position from an optical camera input, inertial measurement sensors providing camera attitude and GPS position providing geographic camera position. The orange dots show the geographic location of the road the vehicle was driving on. The faded geographic map image was overlaid to help provide insight into estimate accuracies of the calculated truck position from the onboard system.

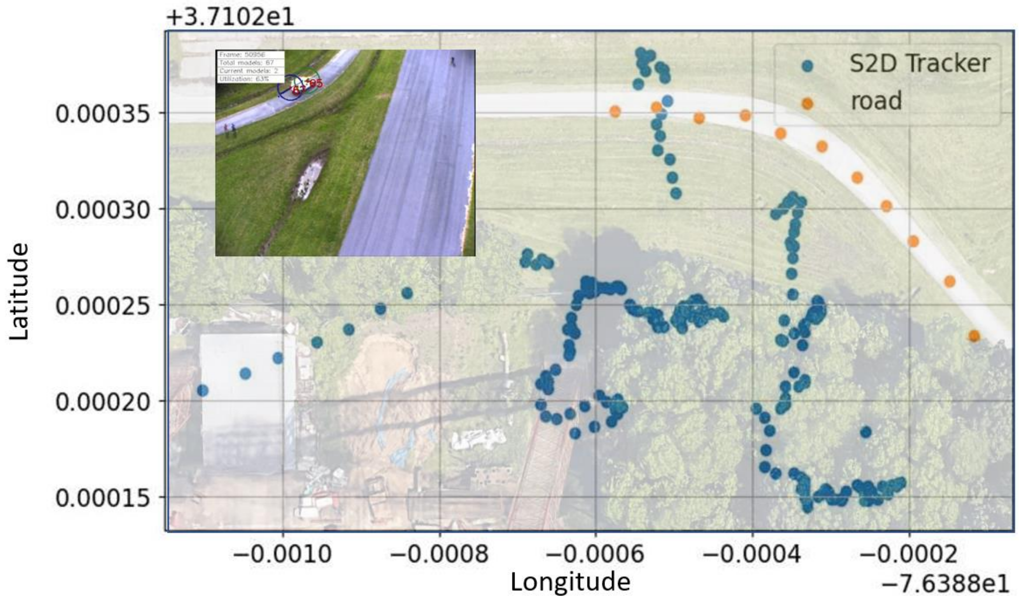

Figure 25: Ground Hazard Detection Track During AELM

It is also important to consider that during the analysis of the ATAM and AELM, these trajectories and maneuvers are directly related to aircraft capabilities. It is assumed that approach flight speeds are maintained during the ATAM. It is also assumed that the AELM will navigate to the emergency landing site approach point at cruise speeds and be capable of establishing a reduced speed 45 degree glide slope. A 45 degree glide slope is used to help keep the fixed-mounted 45 degree look-down camera aimed at the intended ditch site.

Low-Conflict Multi-Aircraft Testing

The test flights supporting these scenarios required two aircraft to be equipped with onboard automation systems to enable the emergency landing maneuver and to keep the ownship well clear. During these tests, it is assumed that the intruder vehicle was a simulated vehicle in distress and has right of way over all other aircraft. As a result, ownship is required to maneuver to maintain well clear. The Independent Configurable Architecture for the Reliable Operations of UAS (ICAROUS) software [7] [8] was implemented to provide autonomous detect and avoid functionality. Through comprehensive data analysis, it was determined that part of the ICAROUS system was not implemented correctly which led to periods of time when continuous and smooth data was not provided for the detect and avoid functions. Overall, ICAROUS performed as expected during testing. More testing is planned for FY2023. These systems were required to be integrated into the aircraft to enable automated maneuvers based on V2V data exchange between the two aircraft. These flight tests that required automated maneuvers were also evaluated in the HDV AOA Simulation activity to provide aircraft crews with expected behaviors for automated maneuvers and automated emergency landings, and to help develop and verify system performance in advance of flight testing. Of the 9 total test runs conducted for the low-conflict multi-aircraft scenarios seen in Table 3, three met all required initial conditions to support both automated maneuvers and automated emergency landings. Analysis was performed on all of the test runs where full data was collected, which can be seen in Table 4. This table shows the horizontal closest point of approach during the ATAM. It also shows the horizontal distance when the ATAM was first initiated. In addition, it also shows how many seconds it would of taken to lose well clear when the ATAM first initiated. All of the flight profiles from the test runs can be seen in Figure 26. The various colors indicate the flight mode of the auto-pilot. Of interest for analysis is the off-board mode which indicates the automated maneuver or automated emergency landing has been initiated by a mission computer connected to the auto-pilot.

Table 3: Low-Conflict Multi-Aircraft Scenario Flight Test Operations

Date	Test Run	Scenario	Aircraft	Satisfactory Data
20220412	1	2A/3A	N559NU/N557NU	Partial
20220412	2	2A/3A	N559NU/N557NU	Partial
20220412	3	2A/3A	N559NU/N557NU	Full
20220412	4	2A/3A	N559NU/N557NU	Partial
20220421	3	2A/3A	N559NU/N557NU	Partial
20220421	4	2A/3A	N556NU/N557NU	Full
20220426	1	2A/3A	N559NU/N557NU	Partial
20220426	2	2A/3A	N559NU/N557NU	Partial
20220426	3	2A/3A	N556NU/N557NU	Full
20220429	4	2A/3A	N556NU/N557NU	Partial

Table 4: Low-Conflict Multi-Aircraft Scenario ATAM Summary

Date	Test Run	ATAM Horizontal CPA (ft)	ATAM Horizontal Initiation (ft)	ATAM Initiation Time to Conflict (sec)
20220412	3	447	690	24
20220421	4	487	620	16
20220426	3	488	770	23

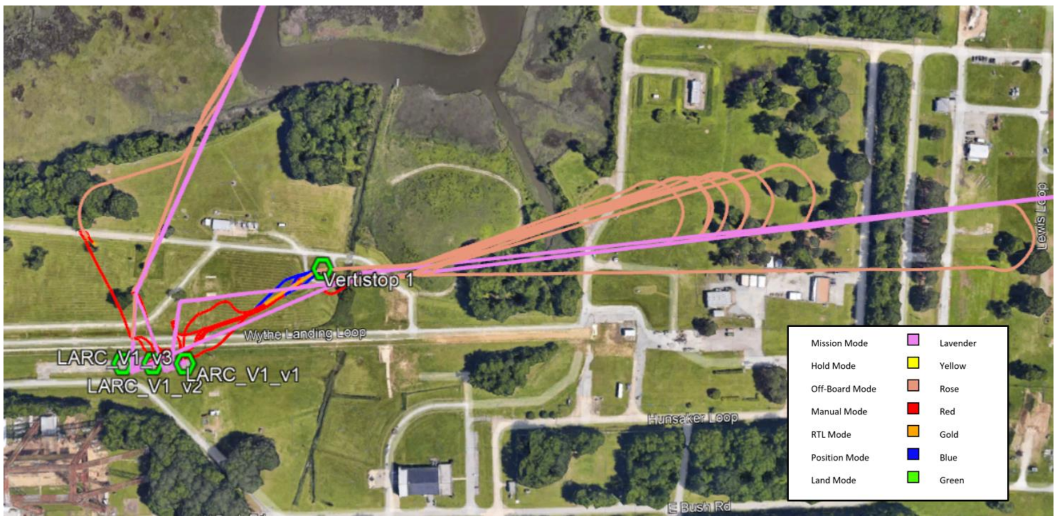

Figure 26: All Low Conflict Scenario Flight Tracks

To help show the automated emergency landing flight profiles, Figure 27 shows a more angled perspective rather than an overhead view. The testing was stopped when the offboard mode ended and the auto-pilot was returned to either a mission mode or initiated a land mode. All automated emergency landings were at the Vertistop for the low conflict scenario.

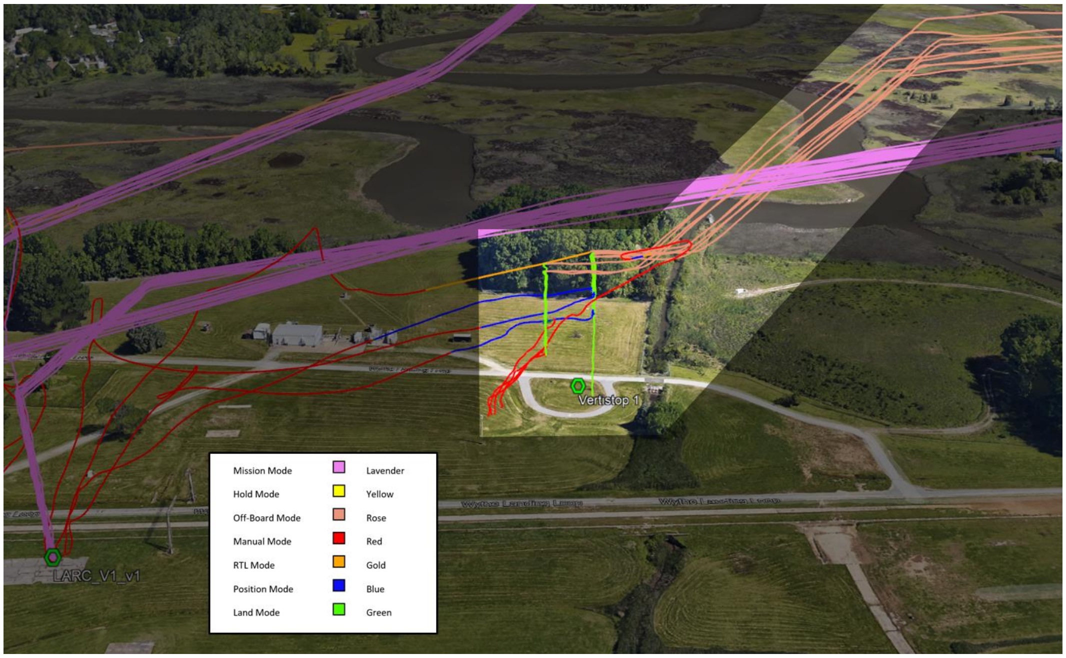

Figure 27: All AELM to a Vertistop

A close up view of the automated maneuvers is shown in Figure 28. Two of the maneuvers were as expected while one was unexpected. The large maneuver within the low-conflict scenario occurred when the intruder aircraft had an unplanned RTL maneuver which brought it closer to the aircraft approaching the vertiport. This was due to a failsafe setting for the emergency landing aircraft which initiated a RTL when the connected mission computer stopped controlling the aircraft after the land mode was sent but not received by the auto-pilot. More information on this event will covered in the April 21st 2022: Test Run 4 Analysis section.

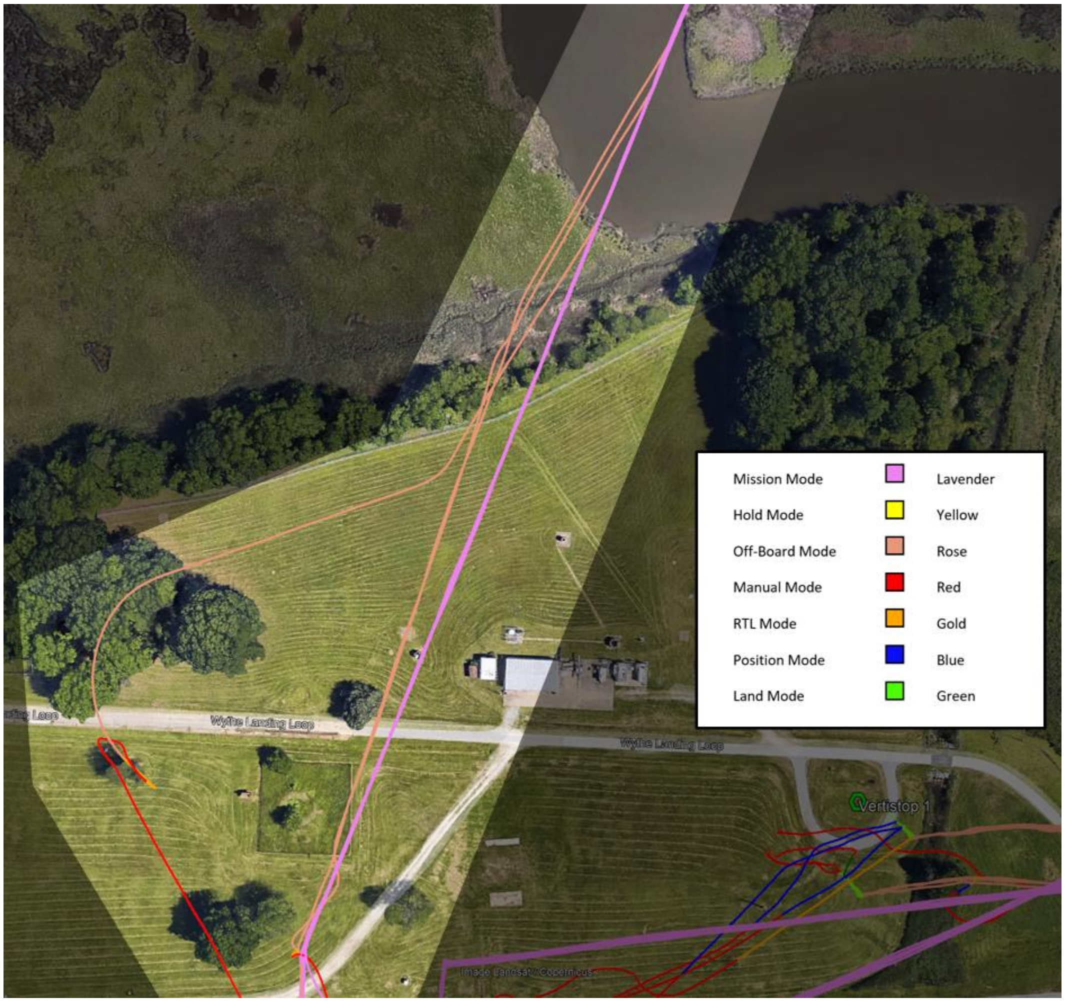

Figure 28: All Low-Conflict ATAM on Approach to Vertiport 1 due to traffic AELM

April 12th 2022: Test Run 3 Analysis

An analysis of one of the traffic encounter maneuvers is provided herein. During this maneuver a minor loss of well clear was experienced. A comprehensive look at this particular test is included to help better convey system performance. The test run, which had a complete data set for both scenarios (i.e., 2A/3A), occurred on April 12th, 2022, on Test Run 3. An overview of the auto-pilot data is provided to show the relative distance between the aircraft, and also the automated maneuver and automated emergency landing. Figure 29 shows both aircrafts flight trajectory during their respective automated maneuvers. For the purposes of generating relative distances, a conversion of 364,000ft for every 1 degree of latitude and 288,200ft for every 1 degree of longitude was used. The data source is from the logged Global Position System (GPS) onboard each auto-pilot data storage SD card.

Figure 29: Mapview of ATAM and AELM (Off-Board Mode) for April 12th 2022 Test Run 3

To help visualize the maneuver start and end in Figure 30, the start is indicated by the red dot and the end is indicated by the blue dot. This overview map shows when the automated maneuver was initiated, the flight path deviation once it began, any follow-on adjustments, and when the automated maneuver ended.

Figure 30: Map view of Test Run 3 Ownship ATAM on April 12th

With Figure 29 showing the flight path of ownship executing an autonomous detect and avoid maneuver, Figure 30 shows the flight profile of the intruder aircraft during this same time period. Although difficult to see from an overhead view, the short flight path shown in Figure 31 is because the aircraft held its position once it reached the Vertistop and then began its descent for landing.

Figure 31: Map view of Test Run 3 Intruder AELM during ATAM on April 12th

The mission computer was running ICAROUS that provided automatic separation from surrounding traffic reporting position using V2V datalinks. The software was configured with a vertical well clear of 100ft and a horizontal well clear of 500ft. A few important notes on the following figures that reference separation values: Data inputs for calculations and plots are based on the auto-pilot GPS data from each aircraft and their associated Universal Time (UTC).

The software conducting the automated maneuvers used a separate independent GPS source. Therefore, the figures should have standard GPS data accuracies associated with the auto-pilot GPS system.

The test run analysis will primarily look at the vertical and lateral separation of the two aircraft during the ATAM. To provide some additional context Figure 32 is provided to understand the inputs used for making the separation plots. The x-axis provides the UTC timestamps with the associated data, and the y-axis show altitude, distance north of vertiport 1 vertipad 1, distance east of vertiport 1 vertipad 1. This is the data that is used as inputs for the separation plot figures. For this test run you can see ownship (N559NU) begin its ATAM at 220ft MSL when the intruder (N557NU) was ~800ft south and ~200ft east of ownship. The time when the ownship goes into an “off-board” mode of control (ATAM started) is shown with the vertical yellow line, and the time when the intruder V2V position was no longer being broadcast (ATAM ended) is shown with the vertical purple line.

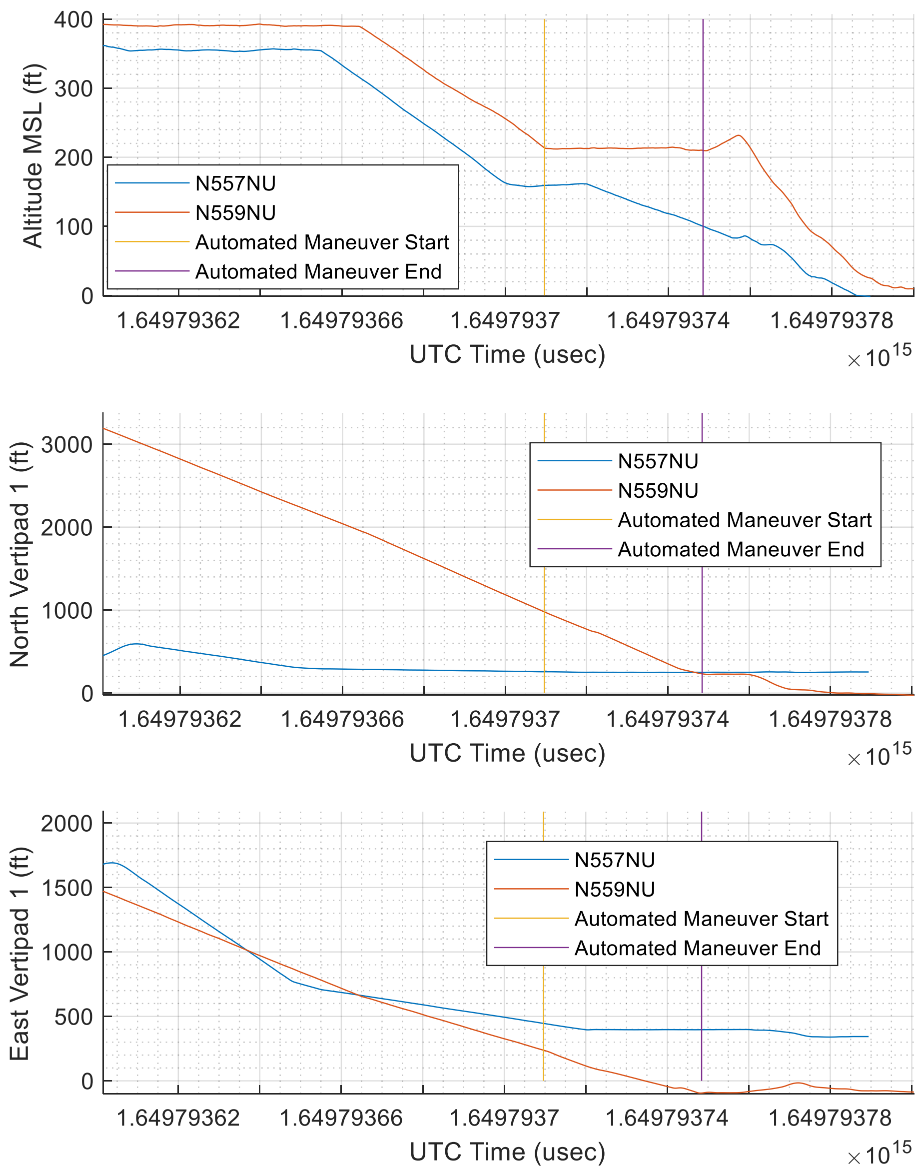

Figure 32: April 12th 2022 Test Run 3 Position Inputs for Separation Figures.

Figure 33 shows that the ATAM initiated when the intruder aircraft was within 100ft vertically and lateral separation was decaying to the point that ICAROUS needed to engage to maintain well clear. In Figure 34, the ATAM initiated when the traffic was 690ft and closing. Although it can be difficult to see a noticeable maneuver in these figures, it is visible in Figure 35. This figure can also be used to get an estimated Closest Point of Approach (CPA) during the ATAM between the aircraft and the emergency landing site. The green line shows the path it would have continued on prior to the ATAM. The red arc shown a 500ft radius circle placed at the emergency landing site location which was the location for the intruder aircraft. There is also a yellow pin at the approximate location on the flight track where the V2V data was terminated on the intruder vehicle. This was done after the AELM was completed and the traffic was at their landing site and descending. Once the ATAM was complete, ownship resumed its automated flight mode at the vertiport approach taxi point.

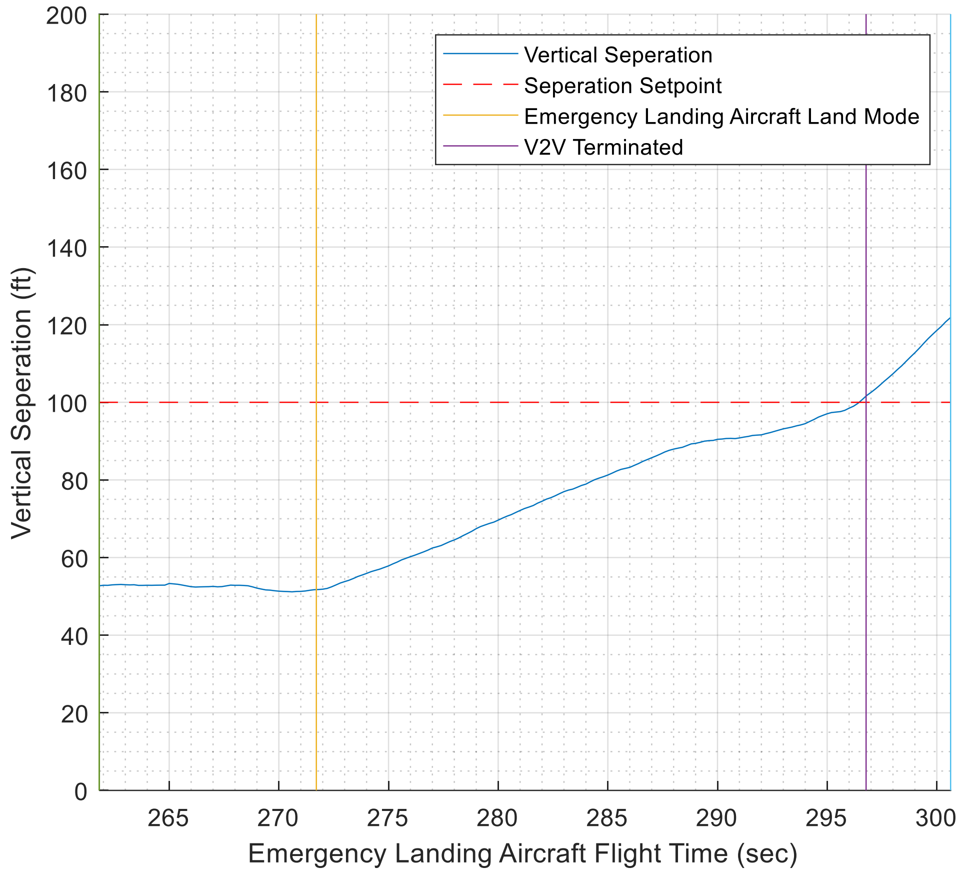

Figure 33: Vertical Separation Plot during Test Run 3 ATAM on April 12th

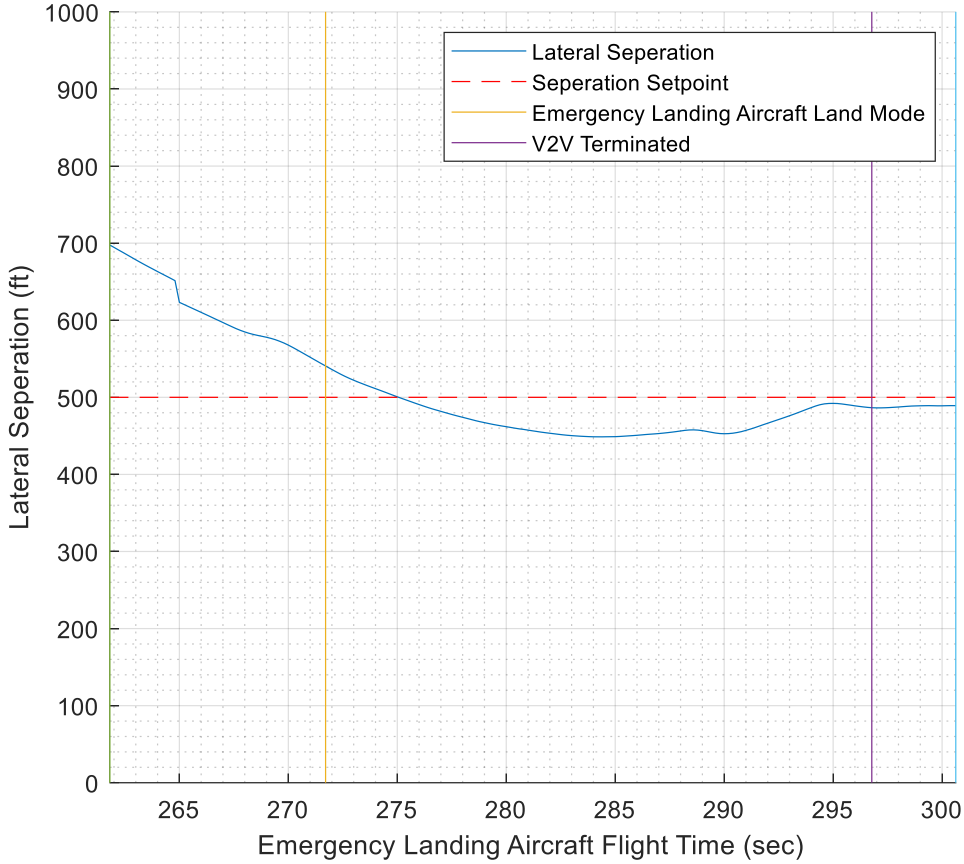

Figure 34: Lateral Separation Plot during Test Run 3 ATAM on April 12th

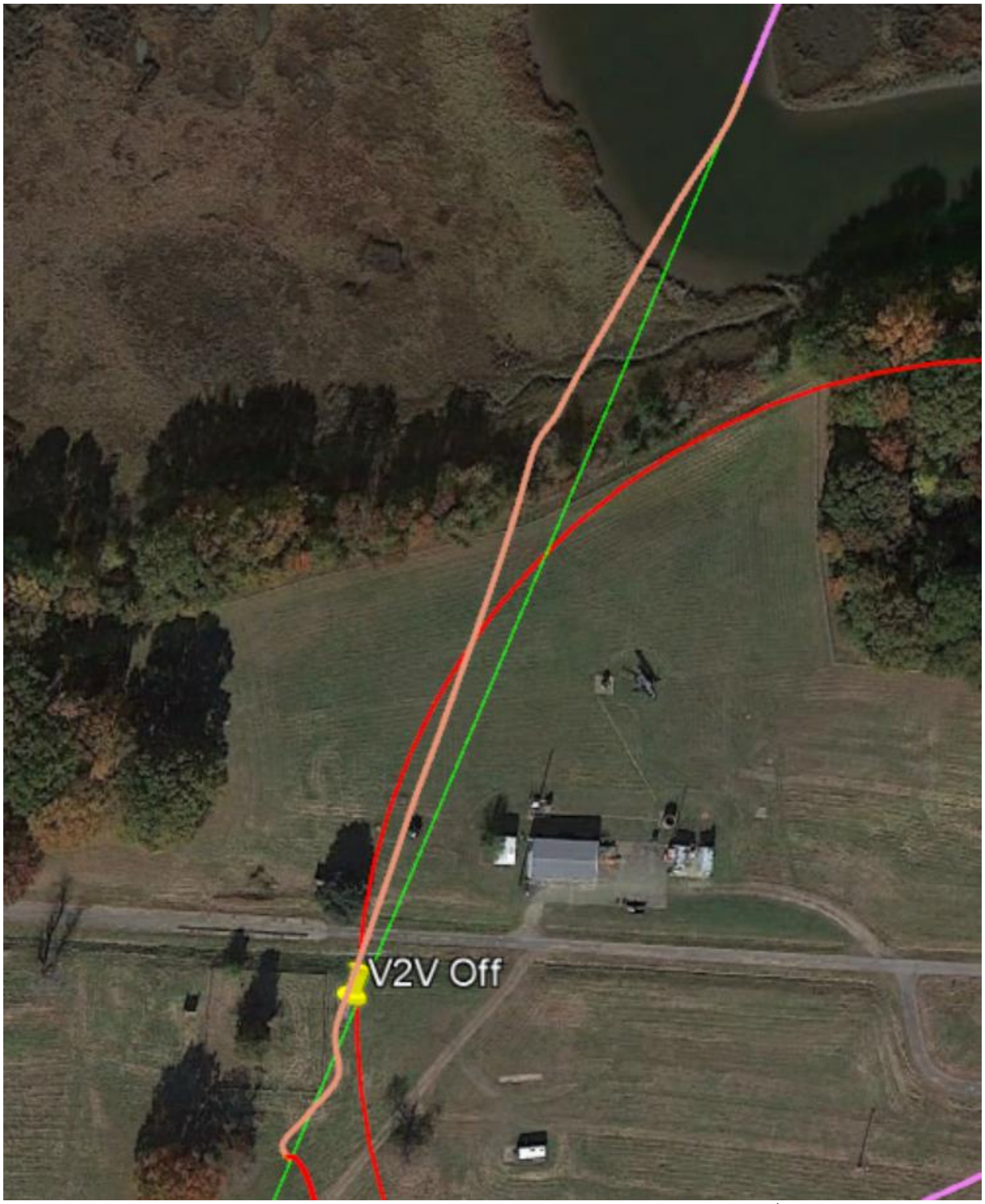

Figure 35:Map view of Test Run 3 ATAM CPA on April 12th

Since the multi-aircraft test runs used two aircraft, the second aircraft executed an AELM during the evolution. The AELM was initiated by a pilot command from the remote operations control room. The AELM can be seen in Figure 36 where the aircraft turns left and heads for the Vertistop. The altitude profile associated with the AELM can be seen in Figure 37 where the altitude was held while navigating toward the Vertistop, and when it reached a 45 degree glide slope to the landing site which was designated as the top of descent. Once there, it began a 45 degree glide slope approach to the Vertistop. Once it reached the minimum safe altitude for the Vertistop on the glide slope, the aircraft held its altitude as it continued to maneuver over the landing site. Once the aircraft reached the emergency landing site, it then initiated an automatic land command to begin landing. Once the landing was initiated, the AELM was complete. At this time the V2V data link was terminated to permit aircraft conducting the ATAM to navigate toward the vertiport Approach Taxi Point and resume the automated mission mode to taxi and land. Figure 38 shows the flight automated maneuver trajectories from a perspective that includes a vertical aspect to highlight the automated maneuver dynamics.

Figure 36: Map view of Test Run 3 AELM on April 12th (Intruder aircraft).

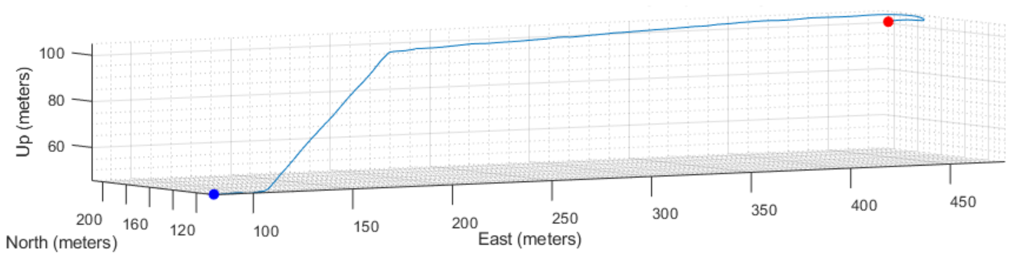

Figure 37: 3D Vertical Profile Plot during Test Run 3 Intruder AELM on April 12th

Figure 38: Mapview of 3D Vertical Profile during Test Run 3 Intruder AELM on April 12th

April 21st 2022: Test Run 4 Analysis

Additional testing was conducted to get more data runs for the scenarios. As a reminder, HF data was being collected from participants during all test runs. The figures below, to include Figure 39 through Figure 47, are set up the same as the previous section. This was a unique test run due to an unplanned RTL after the AELM completed. This can be seen in Figure 41 where it begins heading southwest from the Vertistop after the AELM ended at the Vertistop.

Figure 39:Mapview of ATAM and AELM (Off-Board Mode) for April 21st 2022 Test Run 4

Figure 40: Map view of Test Run 4 ATAM on April 21st

Figure 41: Map view of Test Run 4 AELM during ATAM on April 21st

The software on the mission computer initiated an ATAM when the traffic was 620ft laterally separated and closing. It can be seen in Figure 43 that the aircraft conducting the ATAM had a maneuver reacting to the traffic after it completed the AELM and began heading southwest toward vertiport 1 vertipad 1 when it went into an RTL mode. As a side note, the RTL was determined to be associated with an auto-pilot failsafe setting that initiates an RTL when no commands are received from the mission computer in off-board mode.

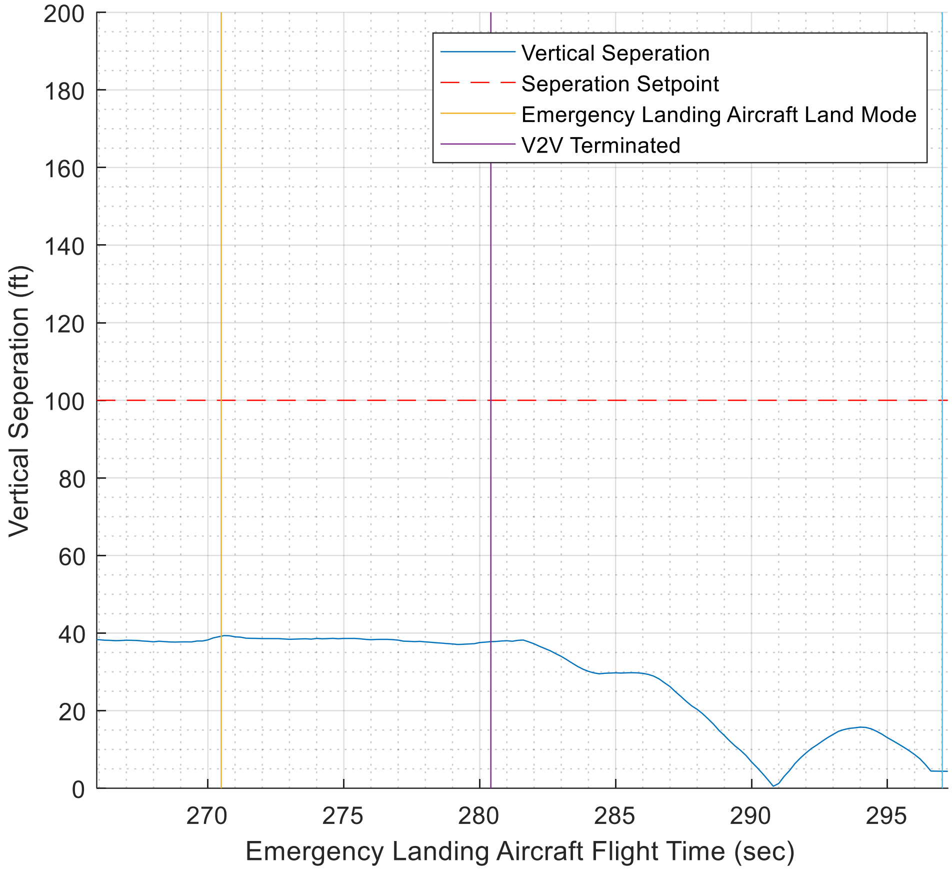

Figure 42: Vertical Separation Plot for Test Run 4 ATAM on April 21st

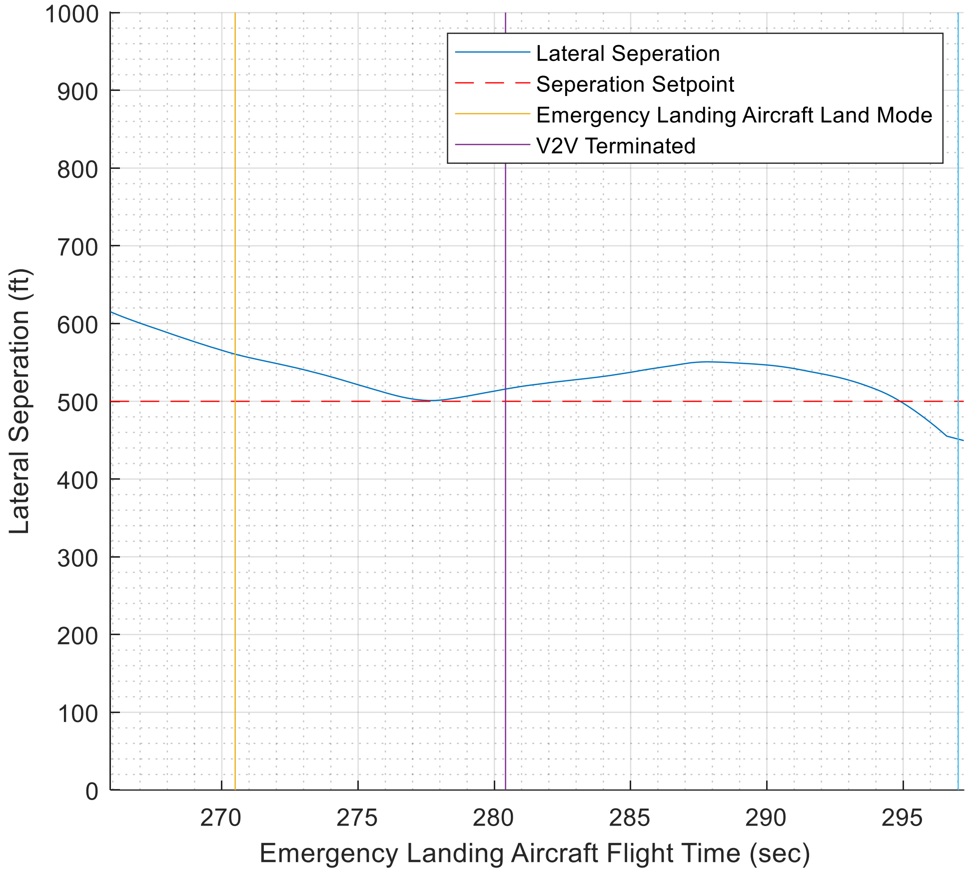

Figure 43: Lateral Separation Plot for Test Run 4 ATAM on April 21st

In Figure 44 the initial heading change is shown where the ATAM started, and the second larger heading change can be seen before the V2V datalink was terminated. In the lateral separation plot, it is clear that the software was able to account for the new traffic encounter and maneuver to maintain separation accordingly.

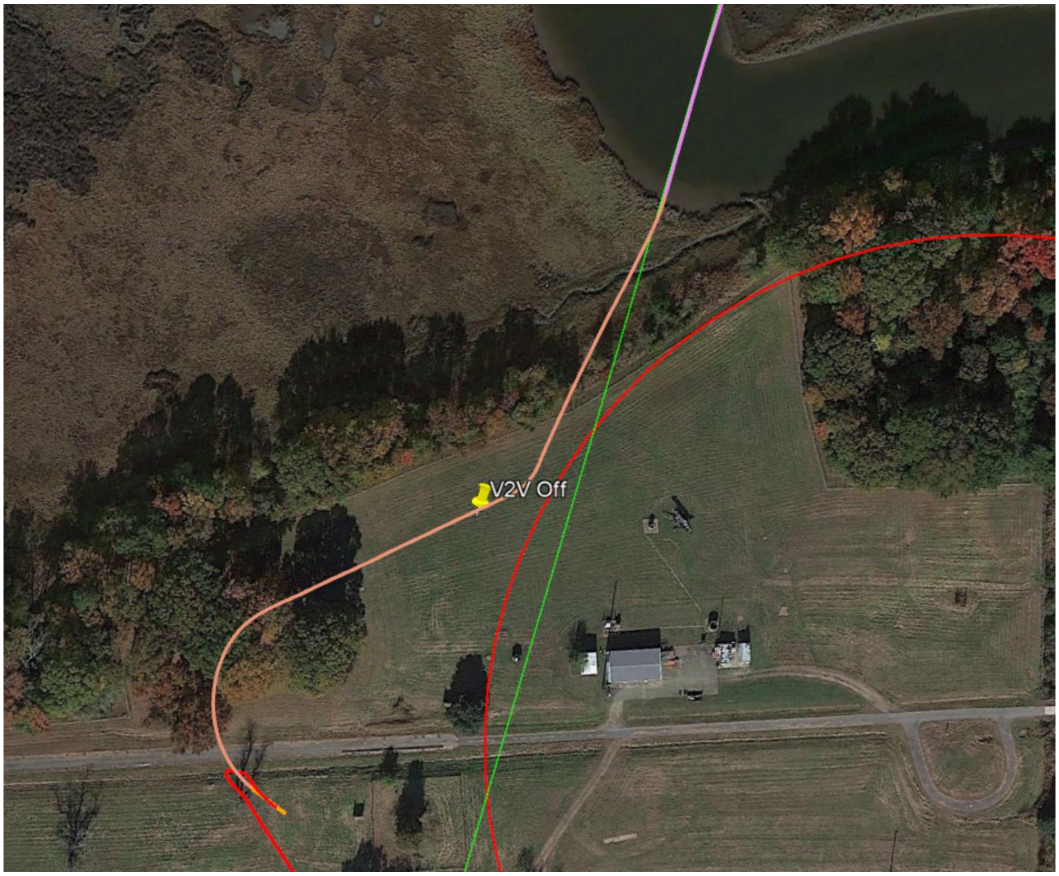

Figure 44: Map view of Test Run 4 ATAM CPA on April 21st

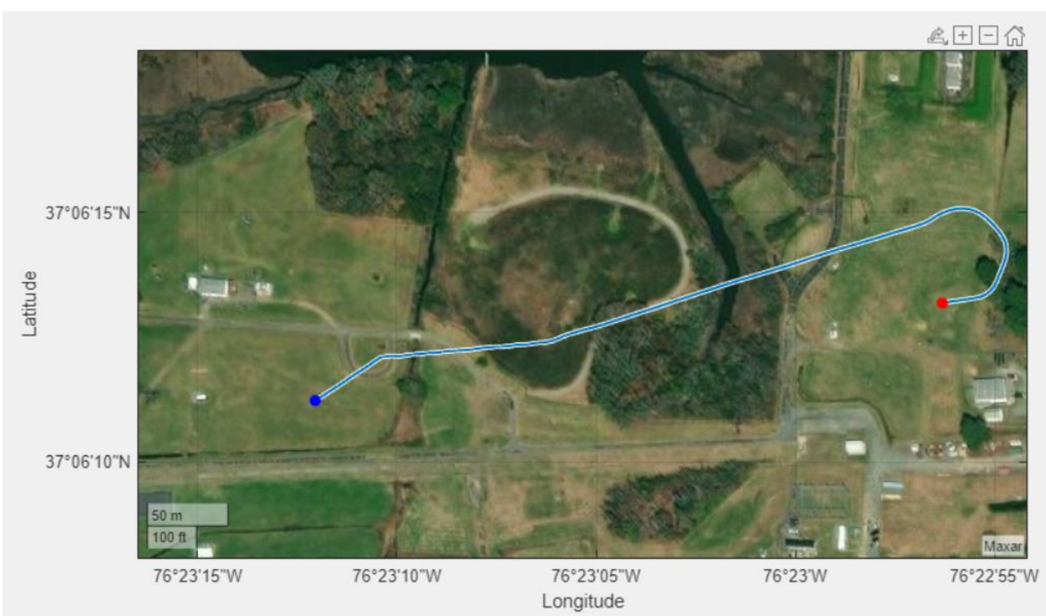

Figure 45: Map view of Test Run 4 AELM on April 21st

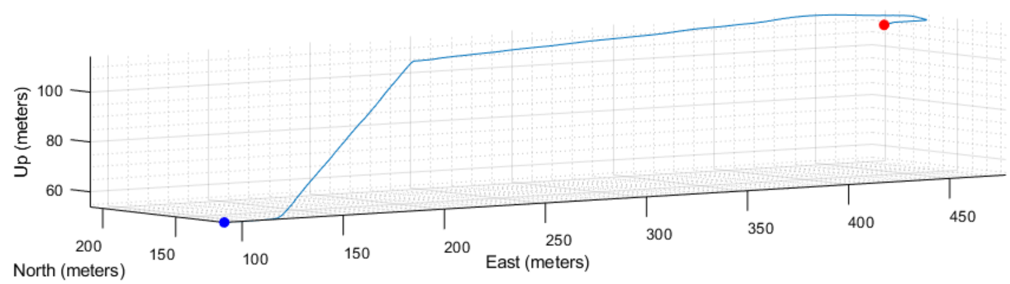

Figure 46: 3D Vertical Profile Plot of Test Run 4 AELM on April 21st


Figure 47: Mapview of 3D Vertical Profile during Test Run 4 Intruder AELM on April 21st

April 26th 2022 Test Run 3 Analysis

This test run showed a minor flight path deviation during the ATAM. The data shown in Figure 48 through Figure 56 shows the automated maneuver initiated when traffic was 770ft laterally and closing.

Figure 48: Mapview of ATAM and AELM (Off-Board Mode) for April 26th Test Run 3

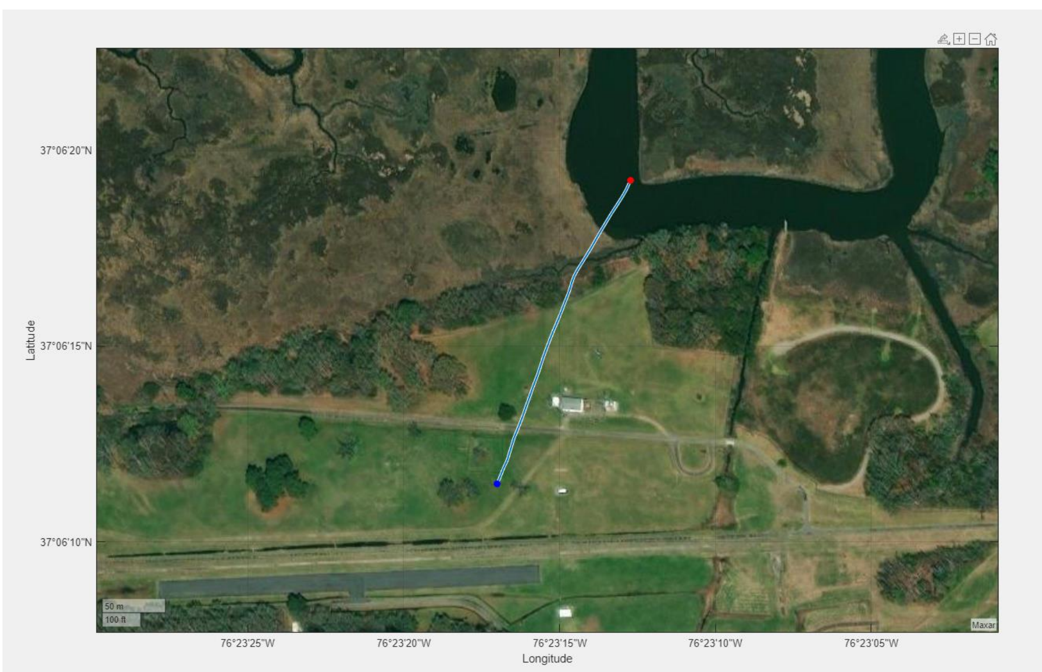

Figure 49: Map view of Test Run 3 ATAM on April 26th

Figure 50: Map view of Test Run 3 ATAM on April 26th

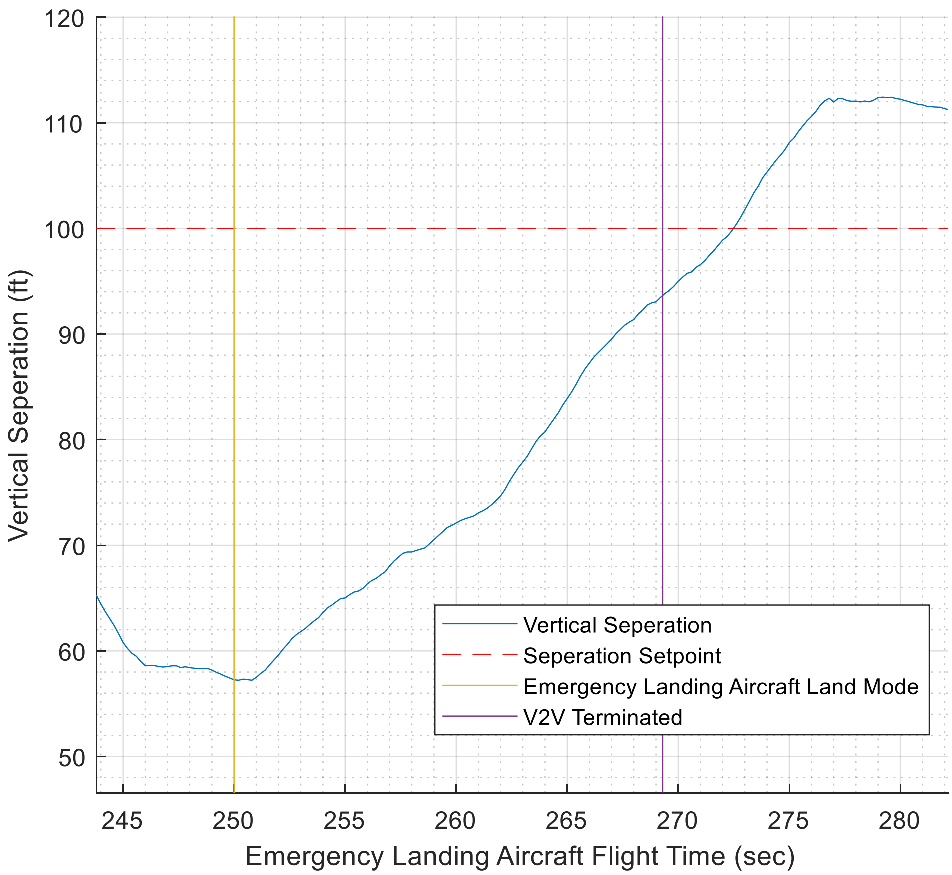

Figure 51: Vertical Separation Plot of Test Run 3 ATAM on April 26th

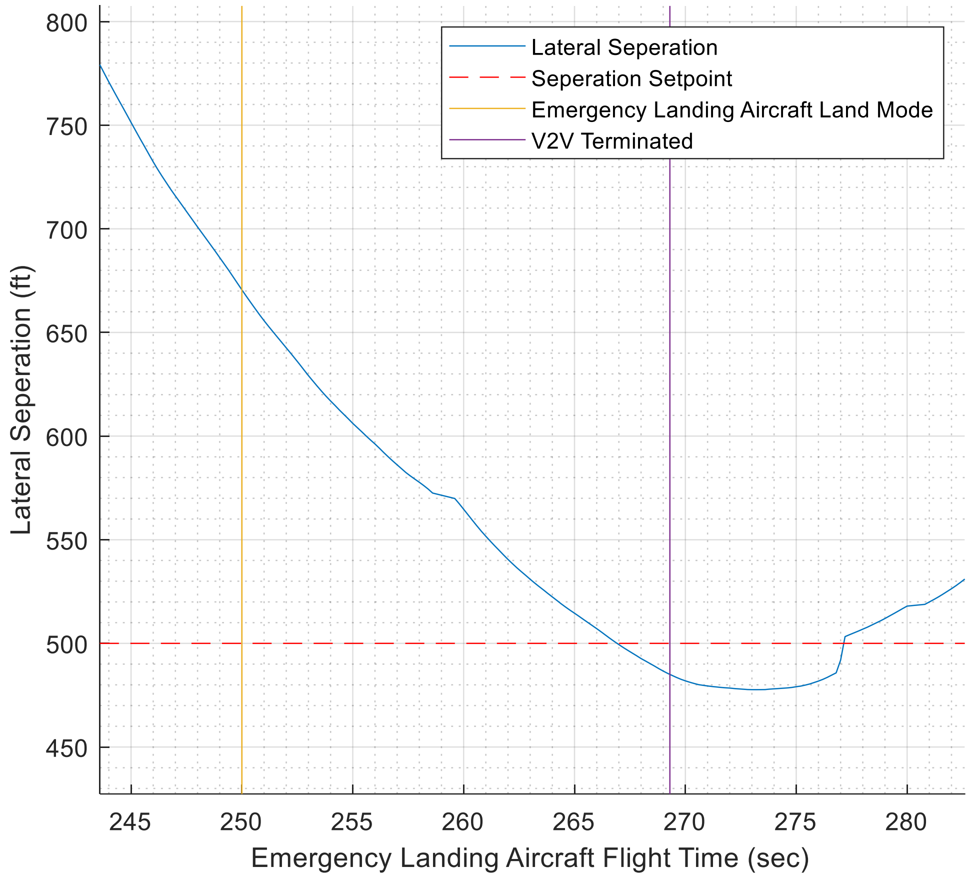

Figure 52: Lateral Separation Plot of Test Run 3 ATAM on April 26th

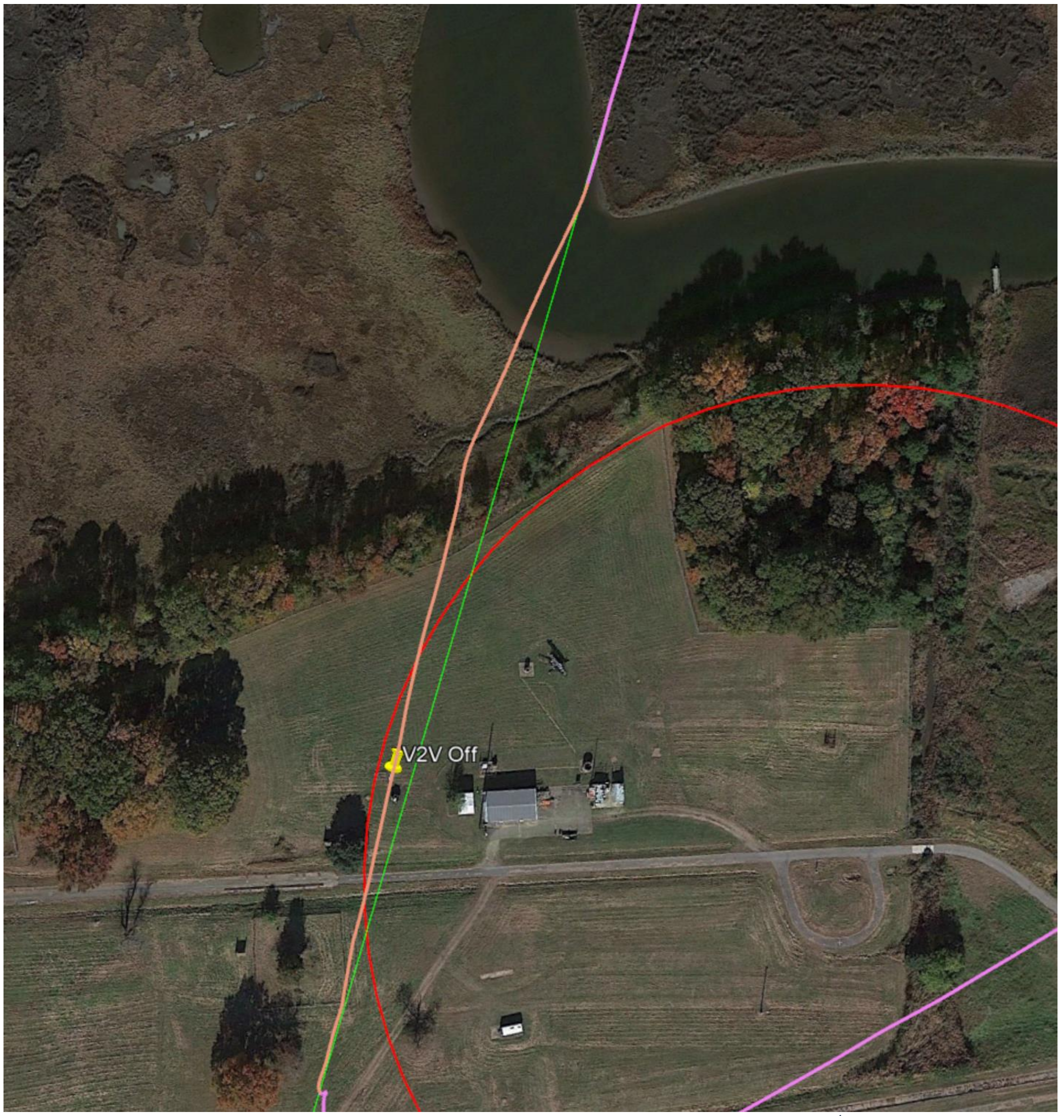

Figure 53: Map view of Test Run 3 ATAM CPA on April 26th

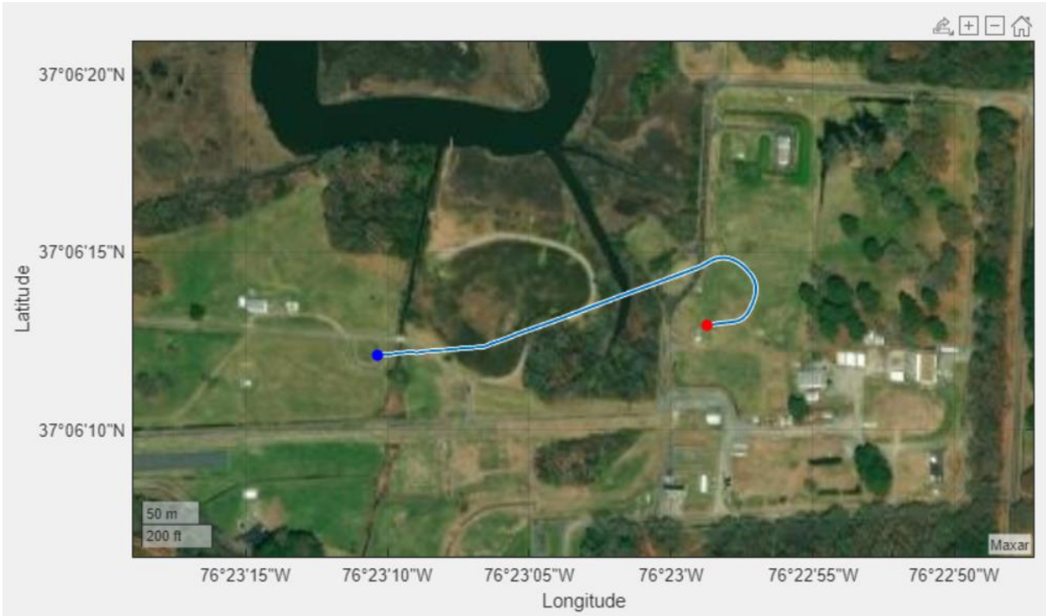

Figure 54: Map view of Test Run 3 AELM on April 26th

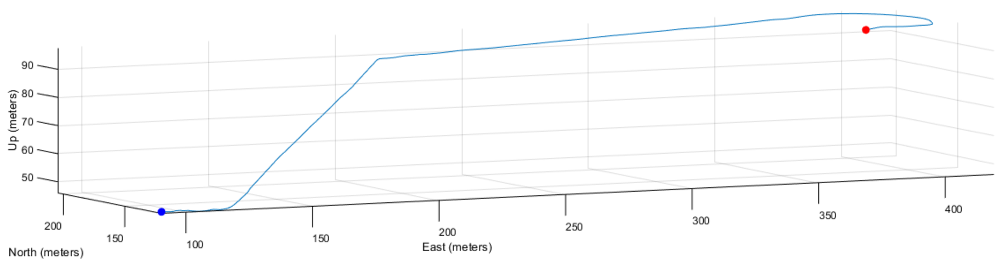

Figure 55: 3D Vertical Profile Plot of Test Run 3 AELM on April 26th

Figure 56: Mapview of 3D Vertical Profile during Test Run 3 Intruder AELM on April 26th-

High Conflict Multi Aircraft Scenarios

The high conflict scenarios consisted of Scenario 2B: Tactical Ownship Conflict Non-Conformant and Scenario 3B: Emergency Re-route S2D Manual. These scenarios consisted of similar automated maneuvers as with the low conflict scenarios, but the emergency landing location was at the vertiport instead of a vertistop. This generated a closer encounter with the two aircraft transmitting V2V data with aircraft position and velocity. It needs to be noted that any aircraft operating within the UAM Ecosystem could enter into an emergency condition at any time. This scenario was created to reflect a situation where a departing aircraft could enter into an emergency state immediately after departure that required an immediate return to the vertiport during high-density operations. This could be a worst-case emergency that would stress test the UAM Ecosystem. As noted previously, an error in ICAROUS implementation resulted in periods of time when smooth and continuous data was not adequately provided for detect and avoid functions. However, ICAROUS did perform as expected for a large majority of the time with expected results as seen in Figure 57 with the magenta lines indicating where the automated flight maneuvers were expected. As with the previous tests, simulations were conducted to allow flight crews monitoring the flight test to understand the expected automated behaviors. As a reminder, once the emergency landing aircraft begins to descend over the landing location, it no longer transmits its position to traffic allowing the approaching aircraft to resume flight towards the vertiport approach taxi point. If this step was not taken, ownship would continue to evade the intruder aircraft as it descended to land at the vertipad. This was not an intended use case for the ATAM maneuver. A blue circle is marked in Figure 50 to show a 500ft lateral boundary around the emergency landing location in this scenario. The designated landing zone for the AELM Intruder aircraft was separated from the ATAM ownship by 100 ft. It also needs to be noted that this application of ICAROUS is somewhat outside of the intended usage and is a demanding test case due to the extended period of time the conflict exists and the dynamic and changing nature of the incursion. For example, a less demanding test would include the intruder aircraft performing a constantly translating flight path. It is also good to note that within the UAM Ecosystem approach, Fleet Managers (FMs) would be engaged to deconflict flight paths before engagement of autonomous systems.

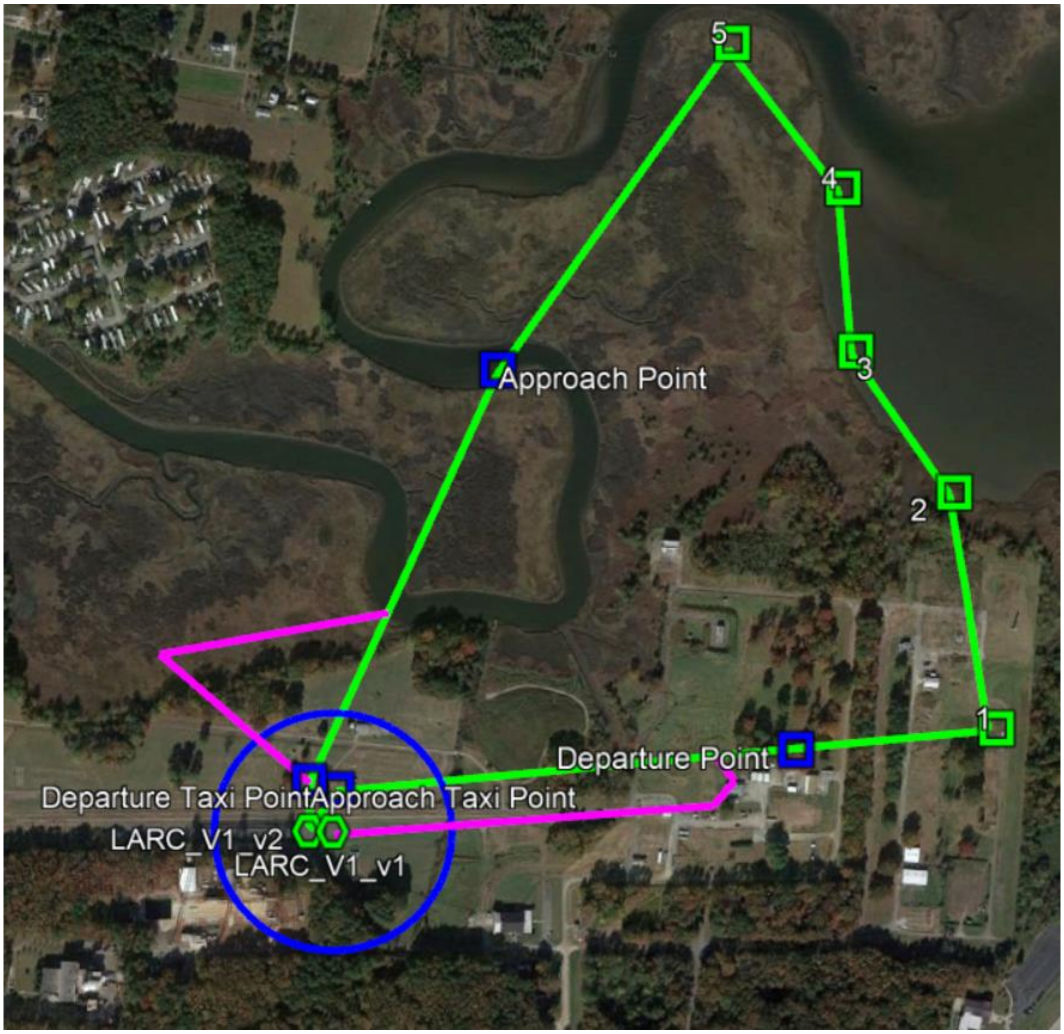

Figure 57: Map view of High Conflict Scenarios Flight Profiles

High-Conflict Multi-Aircraft Testing

For the high conflict scenario, it was easier to set up initial conditions in flight between the two aircraft to initiate a response. This was primarily because the timing to initiate the emergency landing was less sensitive. As shown in Table 5, a total of 6 test runs were conducted to acquire three full data sets. Table 6 shows the analysis summary information for these test runs with full data. Vehicle GPS system pre-flight checks prevented the second aircraft from taking off on the first three test runs which was an unanticipated yet beneficial result. Due to objectives for operation plan conformance with the airspace management system, if the vehicle was not ready to take off at the scheduled time, the test run was noted as “Partial” success because only one aircraft was in flight as a result. When this happened, the first flight was aborted which can be seen in Figure 58 with manual modes and RTL modes for the aircraft taking off from vertipad 2. As a reminder, in order to conduct the approach automated maneuvers in Figure 59, the second aircraft is required to support V2V position reports during the emergency landing.

Table 5: Summary of High Conflict Scenario Testing

Date	Test Run	Scenario	Aircraft	Satisfactory Data
20220329	1	2B/3B	N557NU	Partial
20220330	1	2B/3B	N557NU	Partial
20220405	1	2B/3B	N559NU	Partial
20220405	2	2B/3B	N559NU/N557NU	Full
20220421	2	2B/3B	N559NU/N557NU	Full
20220426	4	2B/3B	N556NU/N557NU	Full

Table 6: High Conflict Scenario ATAM Summary

Date	Test Run	ATAM Horizontal CPA (ft)	ATAM Horizontal Initiation (ft)	ATAM Initiation Time to Conflict
20220405	2	407	620	21
20220421	2	519	760	14
20220426	4	471	940	23

Figure 58: Map view of All High-Conflict Scenarios Flight Tracks

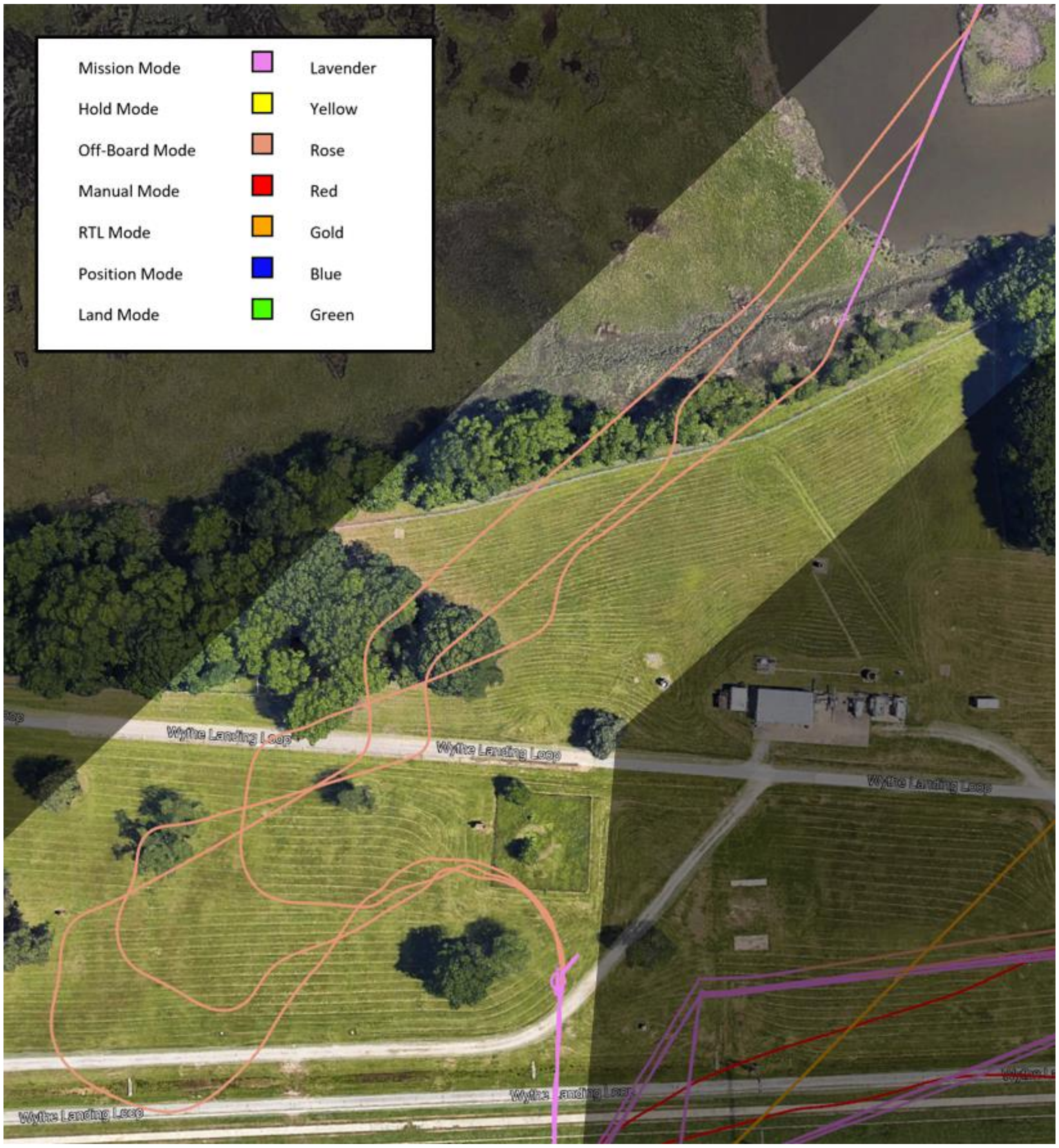

Figure 59: Map view of all ATAM flight tracks on Approach for High Conflict Scenarios

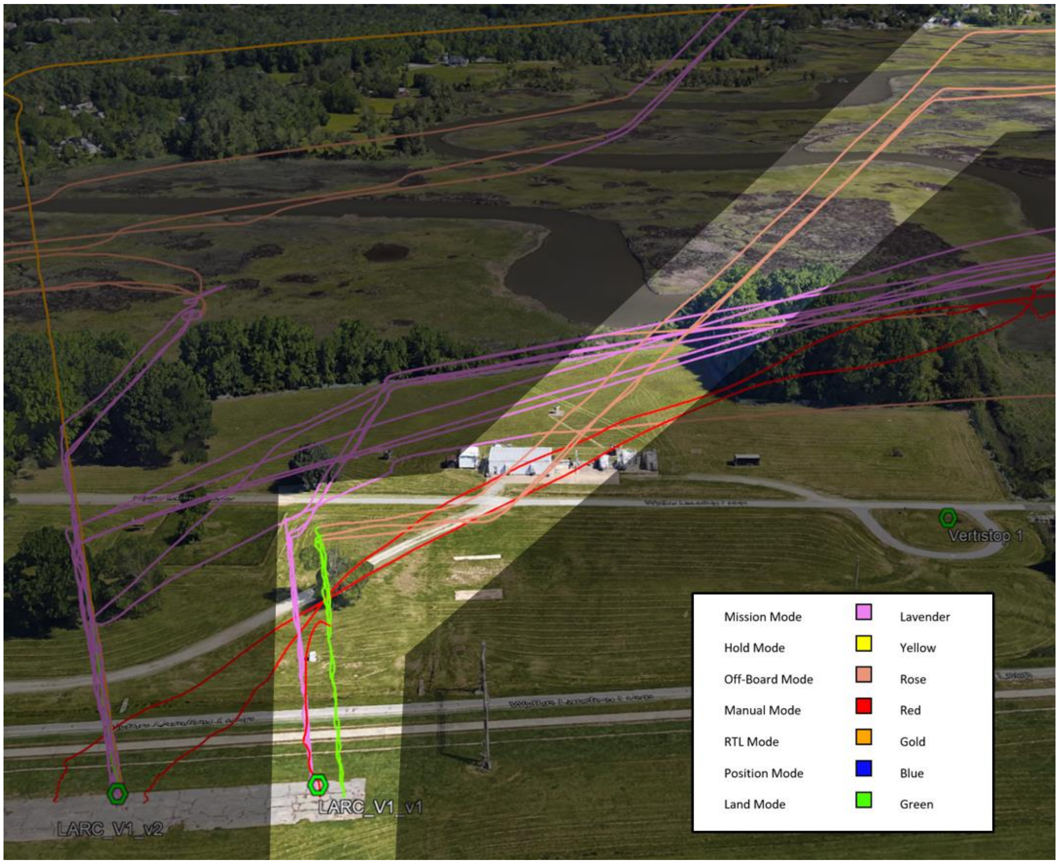

Figure 60: Map view of all AELM Flight Tracks for High Conflict Scenarios

April 5th 2022: Test Run 2 Analysis

The figures in the high-conflict section are set up the same as the low-conflict detection. In reference to Figure 61 through Figure 70, this test run indicates an ATAM initiated when traffic was 620ft laterally and closing. From Figure 62 multiple maneuvers are seen in the ATAM where the aircraft is taken to the west, followed by a maneuver to the east toward the approach taxi point, with a final maneuver toward the north prior to the V2V data link termination. Maneuvers are indicated by the change in flight tracks. The third and final maneuver can be seen in Figure 63 by the green diamond waypoints generated and the flight track history. This test run analysis provides a reference for future automated capabilities to prioritize hazards like the Landing and Impact Research (LandIR) facility in low altitude operational areas during departure and approach. It is assumed this would be considered a geofence data reference that allows the ATAM to produce trajectories that avoid these hazards, which would need to be provided to the system during pre-flight when the flight plan is generated. This data also provides a good reference for putting in a setpoint buffer to assure well clear when ownship is turning toward traffic associated aircraft turn radius. This turn radius can be seen as ownship turns to resume the mission waypoint, but when its trajectory brings it back into conflict with the intruder, it then generates another ATAM and turns away the intruder.

Figure 61: Mapview of ATAM and AELM (Off-Board Mode) for April 5th Test Run 2

Figure 62: Map view of Test Run 2 ATAM On April 5th

Figure 63: Map view of ATAM waypoints generated on the third ATAM.

Figure 64: Map view of Test Run 2 AELM during ATAM on April 5th

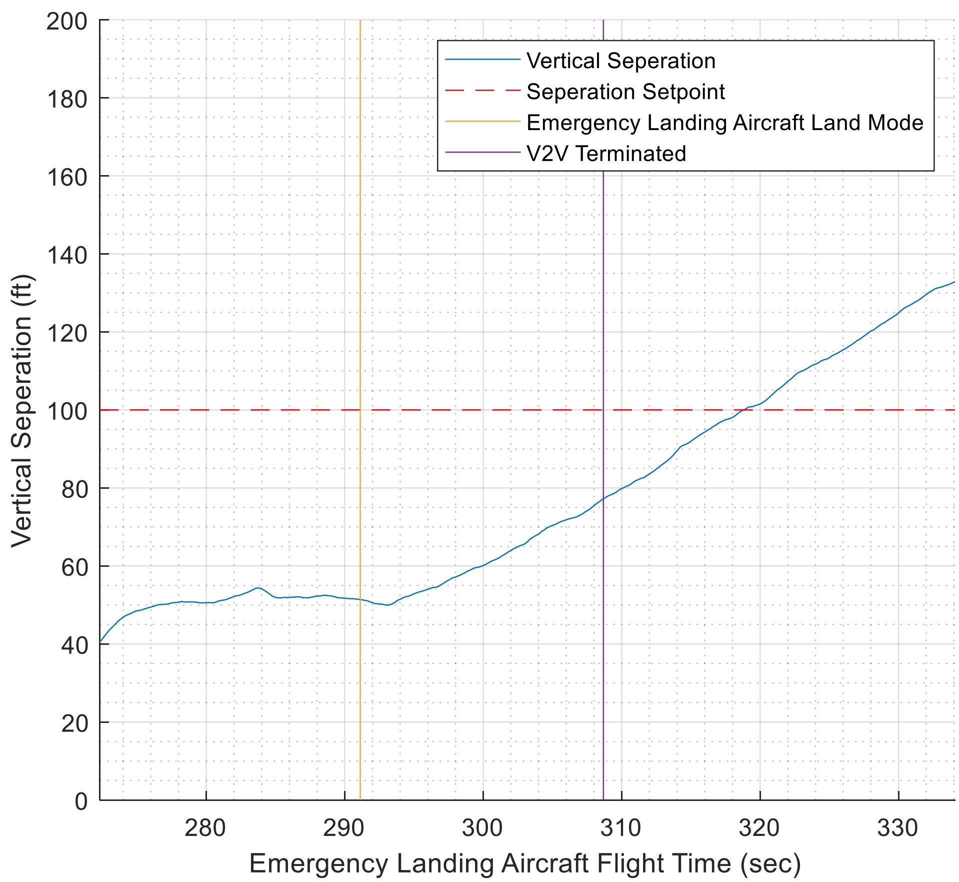

Figure 65: Vertical Separation Plot of Test Run 2 ATAM on April 5th

After analysis of Test Run 2 on April 5th 2022, it has been identified that traffic inputs to the traffic avoidance software were not reported consistently. This was identified due to a fourth avoidance maneuver expected at time 308 seconds in Figure 66 which did not occur. It is also assumed that when the intruder position was not reported, this enabled the avoidance software to determine a recovery waypoint path to resume mission waypoints. Therefore any time a maneuver is seen toward the approach taxi point, the traffic input for the intruder was not reported at that time during the ATAM to the traffic avoidance software. Once ownship was on the flight path toward resuming the mission waypoint, when the traffic was reported and the velocity of ownship and intruder was in conflict, it would begin an avoidance maneuver and continue away from the intruder.

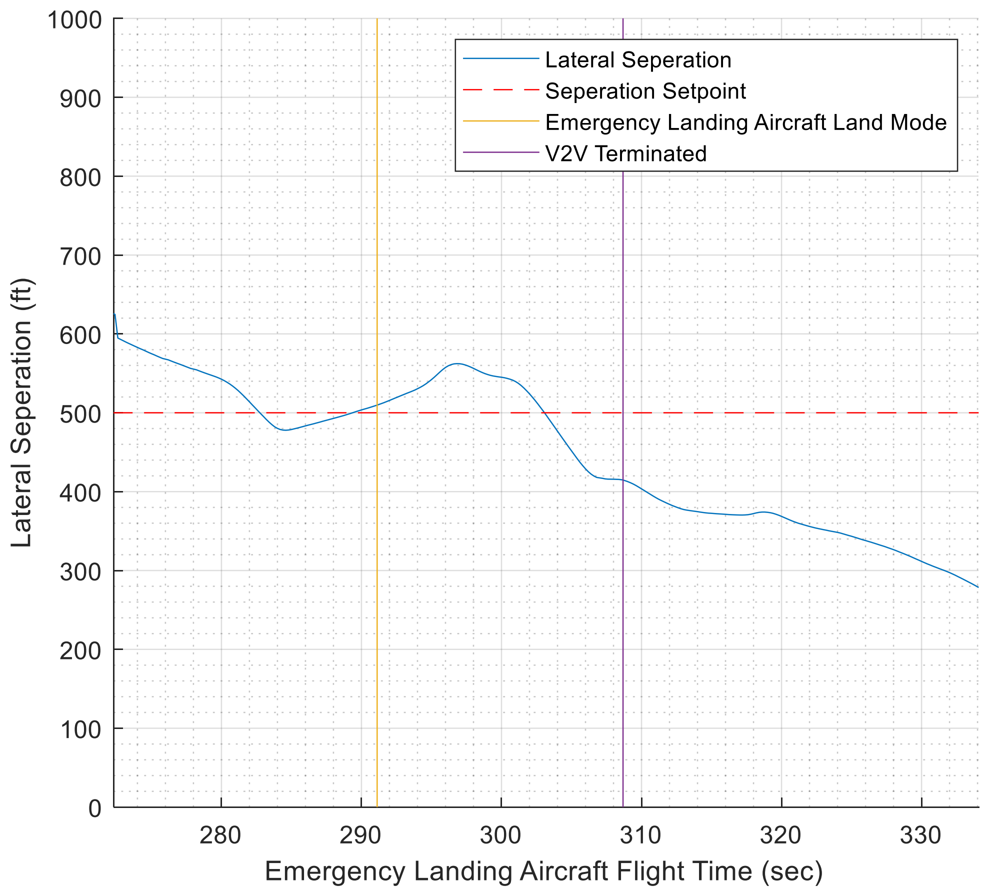

Figure 66: Lateral Separation Plot for Test Run 2 ATAM on April 5th

Figure 67: Map view of Test Run 2 ATAM CPA on April 5th

The AELM seen in the figures shows a turn to the south as the aircraft navigated toward vertiport 1 vertipad 1 for an emergency landing. It is worth noting that the landing site capture radius during the AELM will be related to the offset from the actual landing site coordinates, which can be seen in Figure 68, where the landing was initiated on the edge of the enhanced surface. This is because the AELM system considered the waypoint reached when it was 13ft from the ditch site, therefore it entered land mode 13ft short of the ditch site location.

Figure 68: Map view of Test Run 2 AELM on April 5th

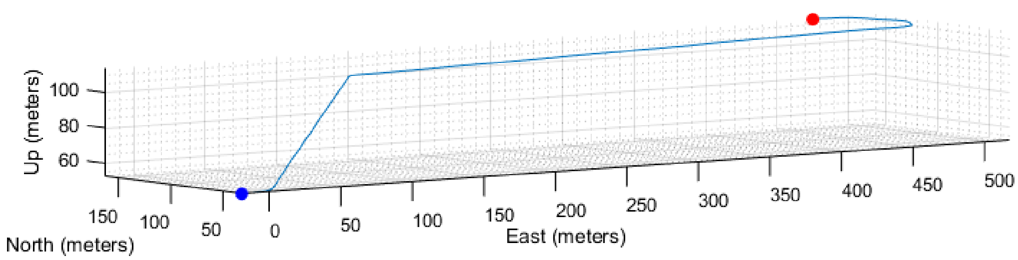

Figure 69: 3D Vertical Profile Plot of Test Run 2 AELM on April 5th

Figure 70: Mapview of 3D Vertical Profile during Test Run 2 Intruder AELM on April 5th

April 21st 2022 Test Run 2 Analysis

This section will reference Figure 71 through Figure 79. The ATAM initiates when traffic is 760ft laterally and closing with 50ft of altitude separation. Two heading changes to the west are seen prior to the navigation toward the approach taxi point to resume the taxi and landing procedure.

Figure 71: Mapview of ATAM and AELM (Off-Board Mode) for April 21st 2022 Test Run 2

Figure 72: Map view of Test Run 2 ATAM on April 21st

Figure 73: Map view of Test Run 2 AELM during ATAM on April 21st

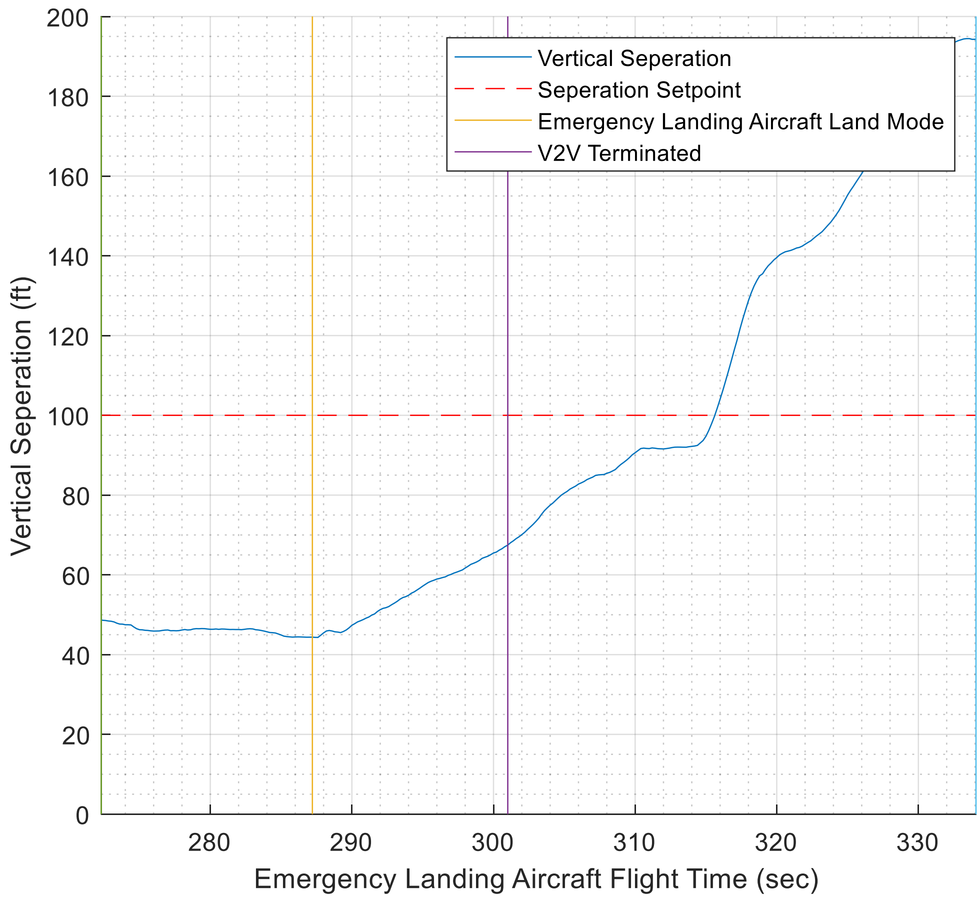

Figure 74: Vertical Separation Plot for Test Run 2 ATAM on April 21st

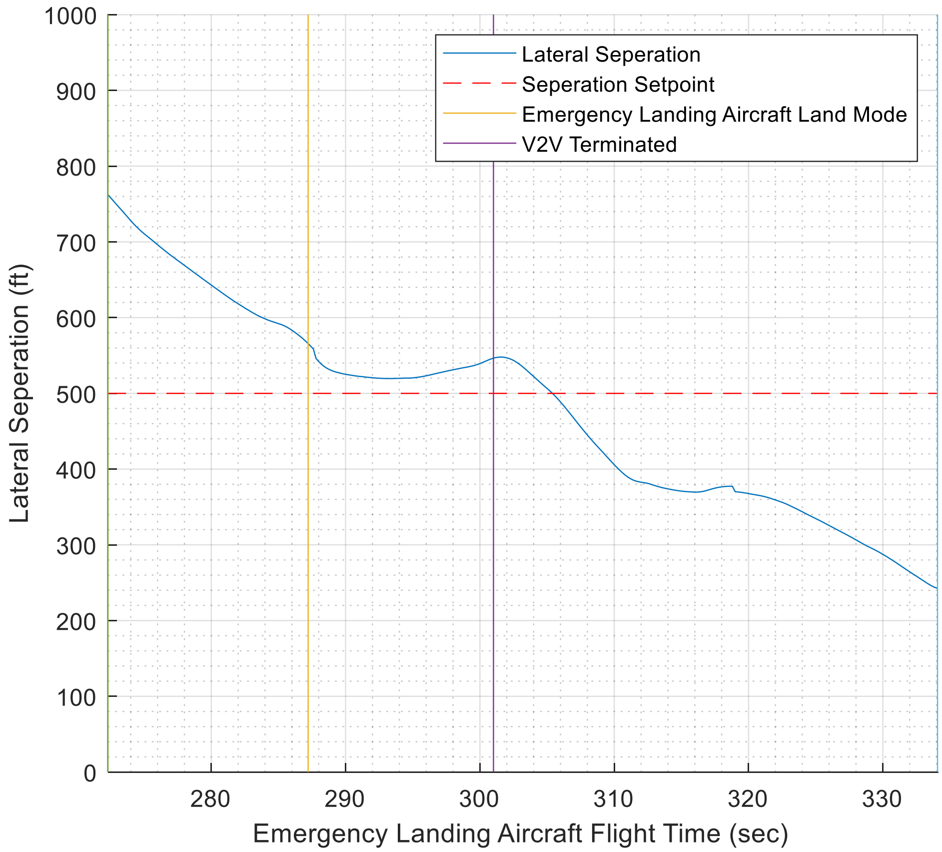

Figure 75: Lateral Separation Plot on Test Run 2 ATAM on April 21st

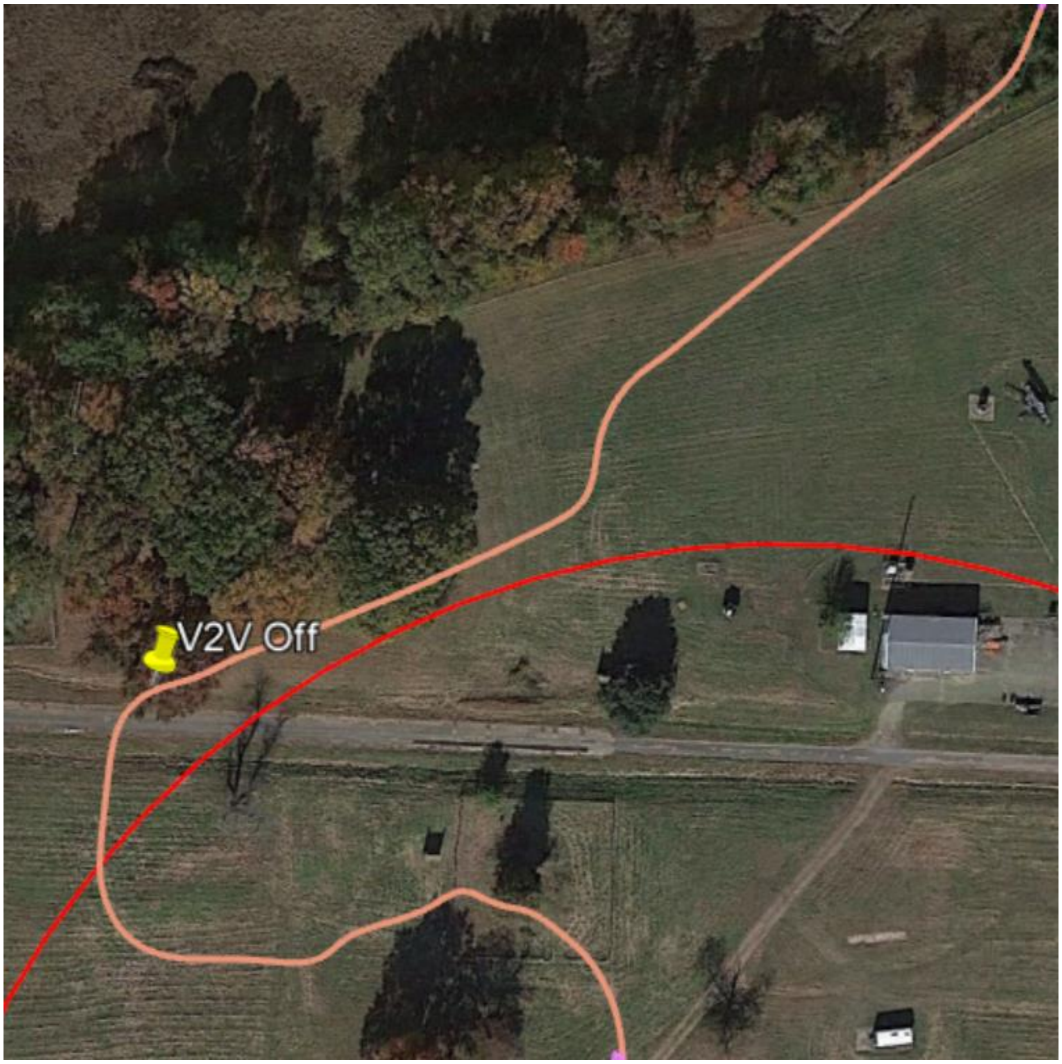

Figure 76: Map view of Test Run 2 ATAM CPA on April 21st

Figure 77: Map view of Test Run 2 AELM on April 21st

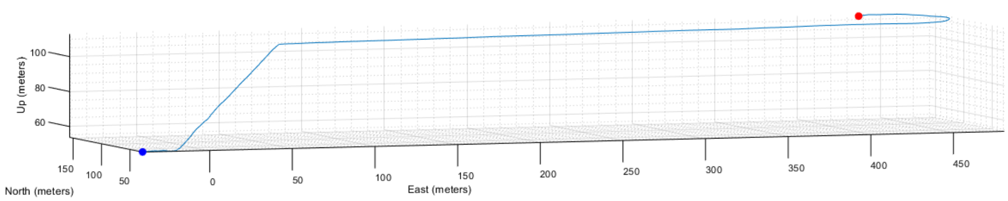

Figure 78: 3D Vertical Profile Plot for Test Run 2 AELM on April 21st

Figure 79: Mapview of 3D Vertical Profile during Test Run 3 Intruder ALEM on April 12th

April 26th 2022 Test Run 4 Analysis

The figures to be discussed include Figure 80 through Figure 88. During this test run the ATAM initiated at 940ft laterally and closing. Three heading changes can be seen in Figure 81, prior to the aircraft heading back toward the approach taxi point to resume taxi and landing. Both the ATAM and the AELM performed as expected.

Figure 80: Mapview of ATAM and AELM (Off-Board Mode) for April 26th 2022 Test Run 4

Figure 81: Map view of Test Run 4 ATAM on April 26th

Figure 82: Map view of Test Run 4 AELM during ATAM on April 26th

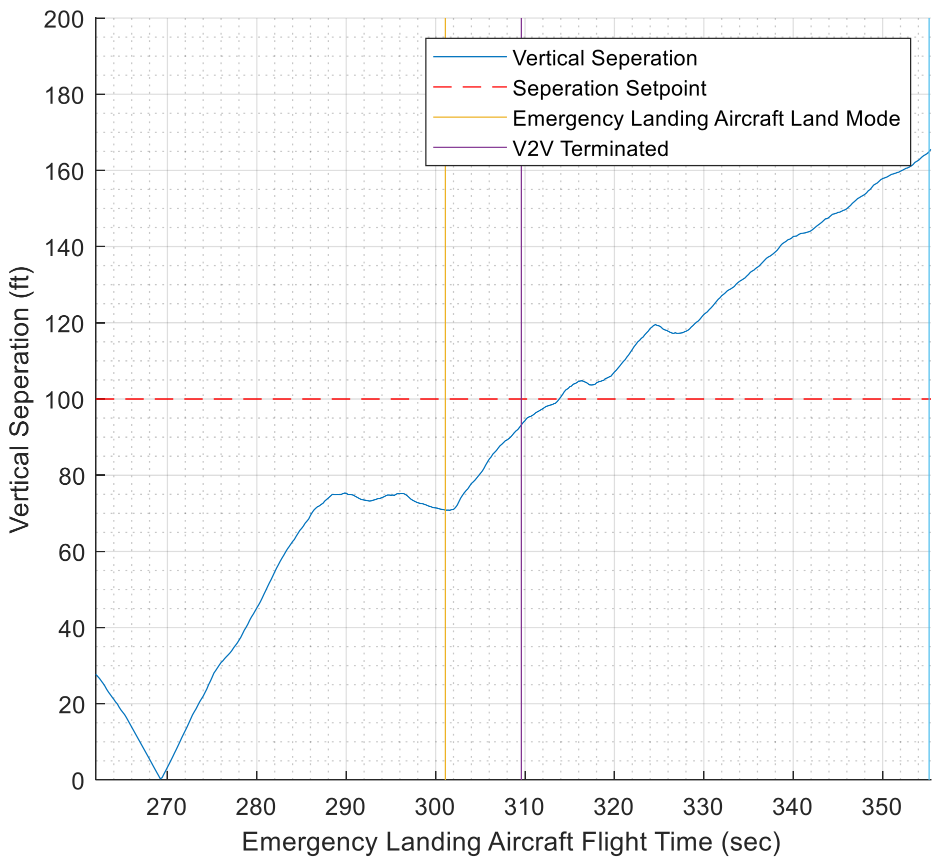

Figure 83: Vertical Separation Plot of Test Run 4 ATAM On April 26th

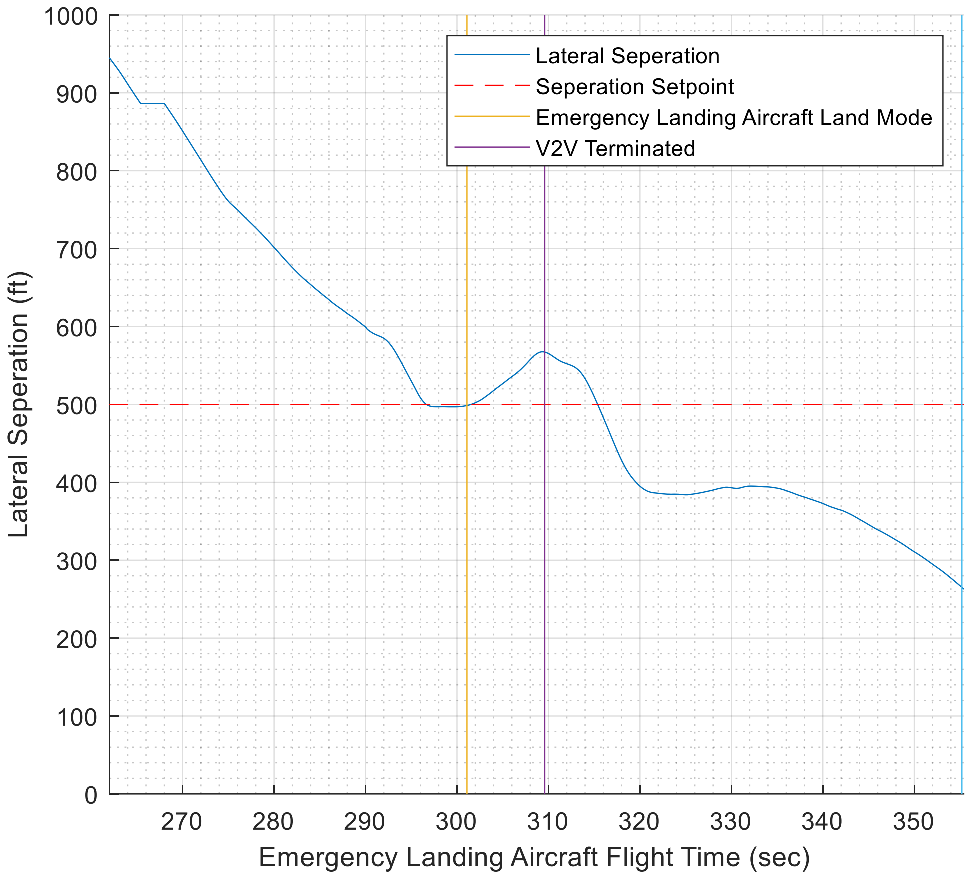

Figure 84: Lateral Separation Plot on Test Run 4 ATAM on April 26th 2022

Figure 85: Map view of Test Run 4 ATAM CPA on April 26th

Figure 86: Map view of Test Run 4 AELM on April 26th

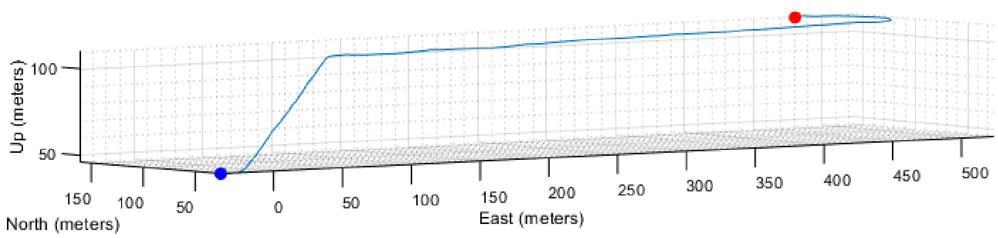

Figure 87: 3D Vertical Profile Plot of Test Run 4 AELM on April 26th

Figure 88: Mapview of 3D Vertical Profile during Test Run 4 Intruder AELM on April 26th

In Flight Re-Route Scenario

The Flight Re-Route scenario included an in-flight re-route that consisted of a take off and departure that mirrored the nominal scenario. Therefore, at scenario start, a flight plan was loaded for the nominal flight scenario. However, prior to the aircraft reaching the vertiport 1 approach point, it would get an update on vertiport 1 status as ‘closed’ initiated by the Vertiport Manager, and was pushed an updated flight plan from the flight crew that directed the vehicle toward vertiport 6. This can be seen in Figure 89 where the flight profile shows a take off and normal departure, but after the approach point there is another route that takes the aircraft to vertiport 6. Vertiport 6 had a hard surface for the vertipad to allow a reliable safe landing with the automated landing of the aircraft.

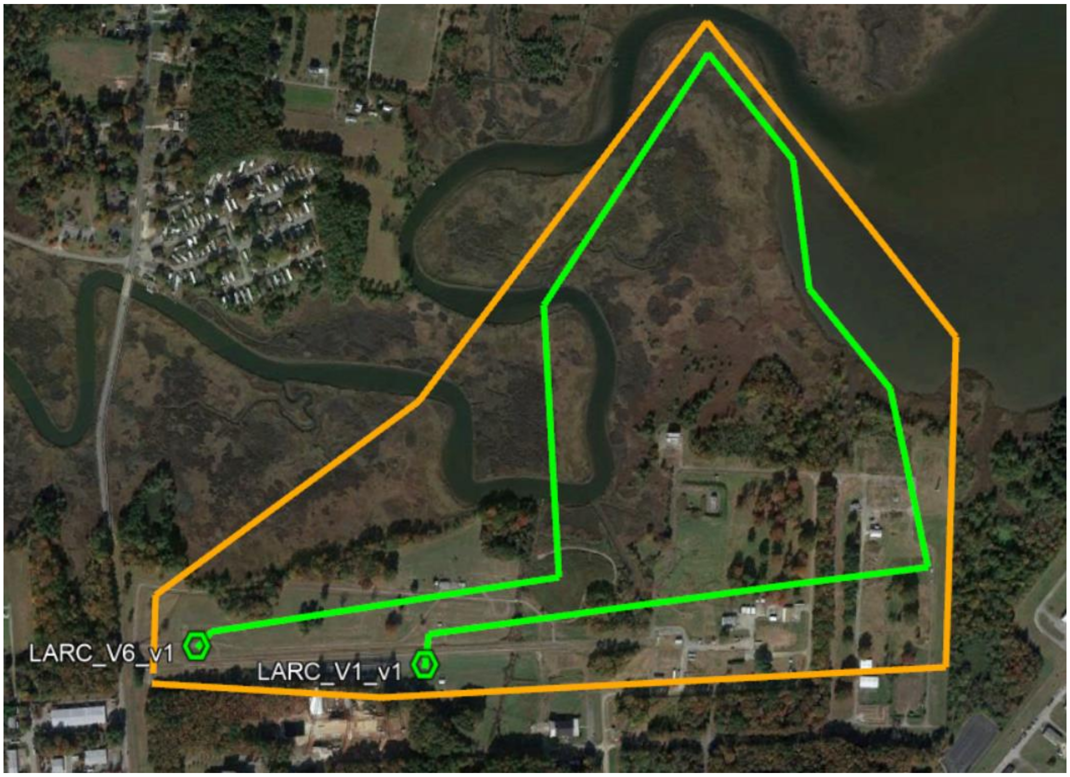

Figure 89: Mapview of Re-route Scenario Flight Profile

A closer view of the vertiport 6 vertipad 1 is shown in Figure 90 where an old asphalt patch was used for the vertipad during testing. Although only one was used for flight testing, it is assumed a similar approach for additional vertipads would be used for additional aircraft that would intend to land at vertiport 6.

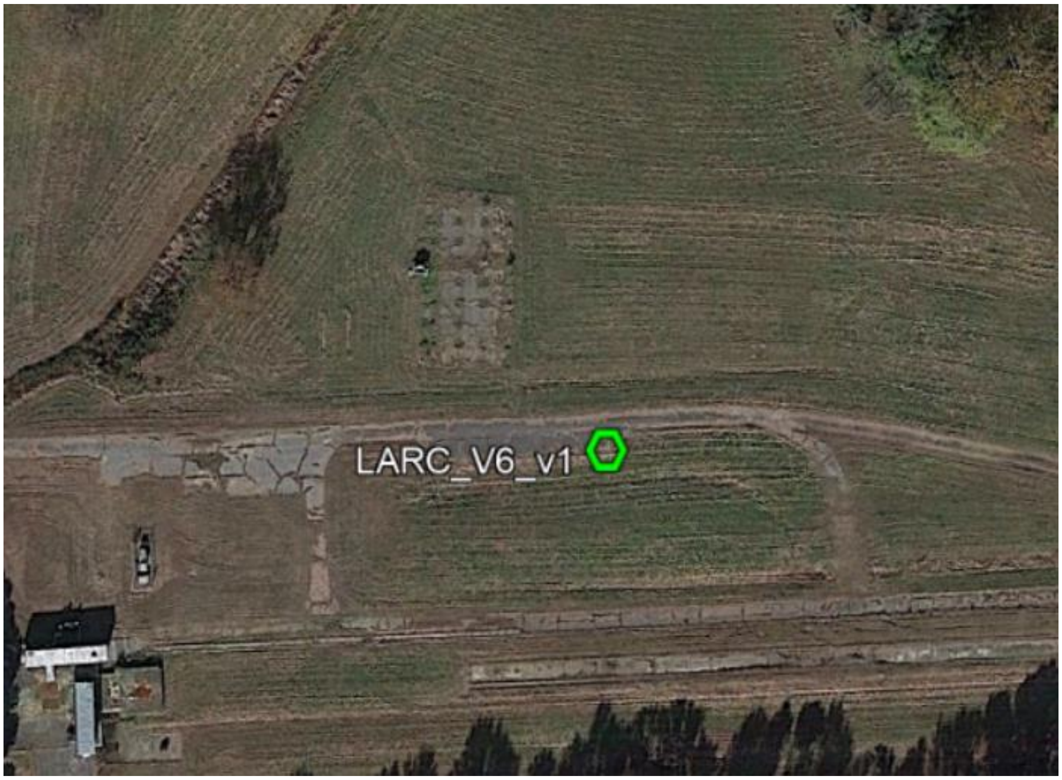

Figure 90: Langley Research Center Vertiport 6 Vertipad 1

Since this test scenario only had live aircraft approaching and landing at vertiport 6, only an approach taxi point was defined to enable the aircraft to establish an equivalent procedure when approaching the vertipad landing area. This can be seen in Figure 91.

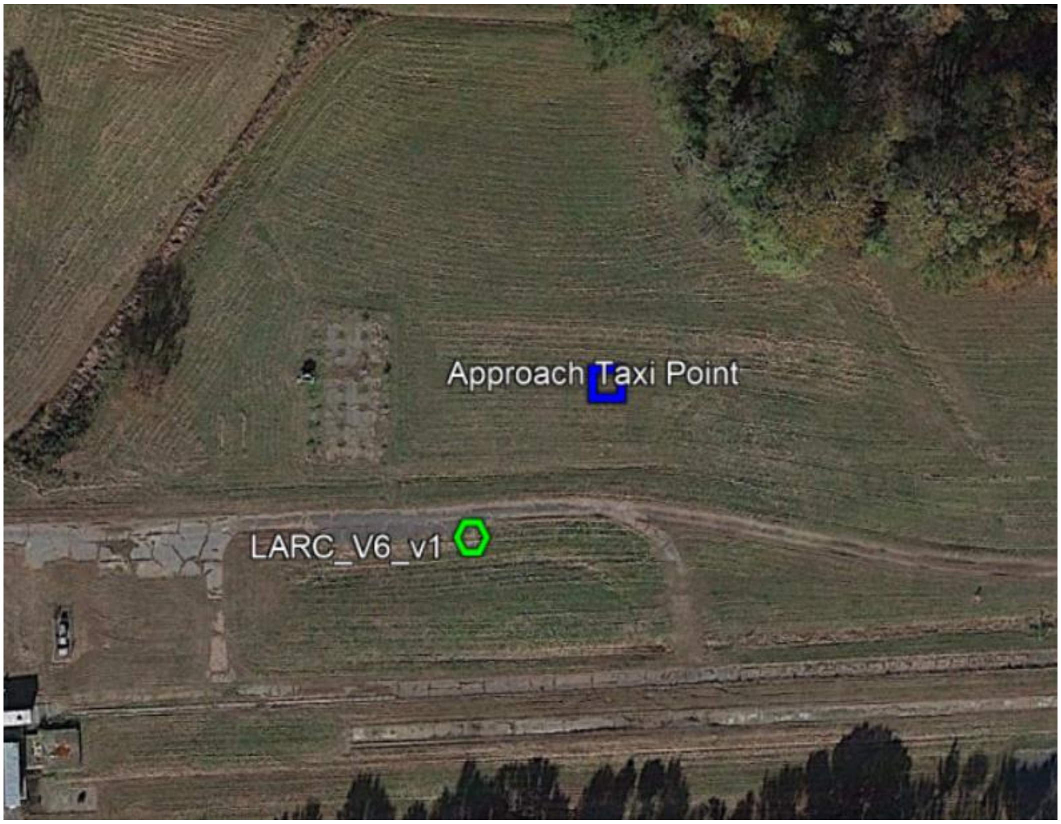

Figure 91: Vertiport 6 Approach Taxi Point

An approach point for vertiport 6 was established with an equivalent distance to establish the same approach flight path angle. This approach path was pre-defined to ensure that aircraft approaching vertiport 1 would have vertical separation with aircraft approaching vertiport 6. This can be seen in Figure 92.

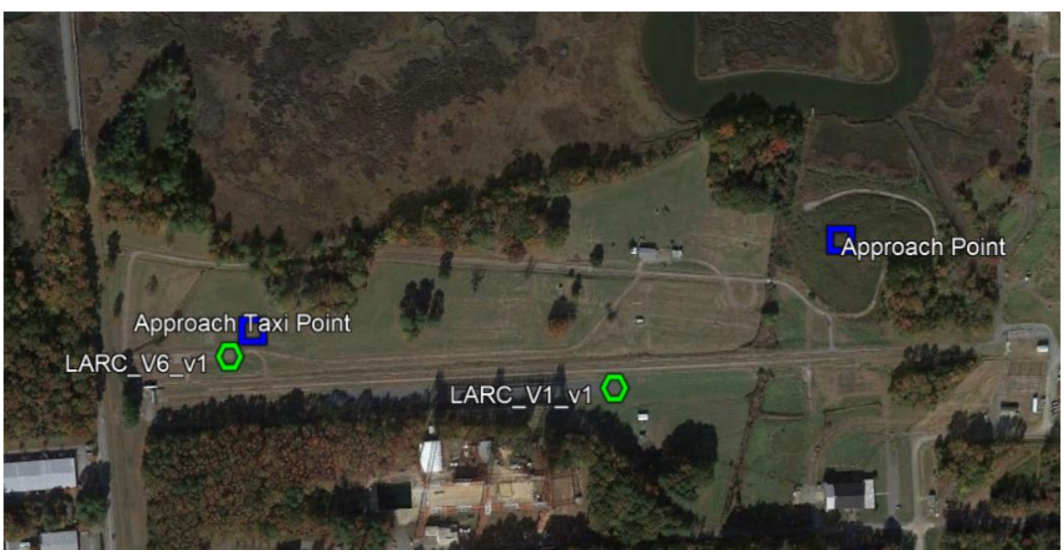

Figure 92: Vertiport 6 Approach Point

When the route was updated in flight, a new flight plan was sent to the aircraft which had the initial waypoint at the vertiport 1 approach point. This allowed the aircraft to stay within the previously approved route and time, as it setup to reach the new vertiport approach point. This can be seen in Figure 93. Once the aircraft hit the vertiport 6 approach point, it began a descent to the approach taxi point at vertiport 6.

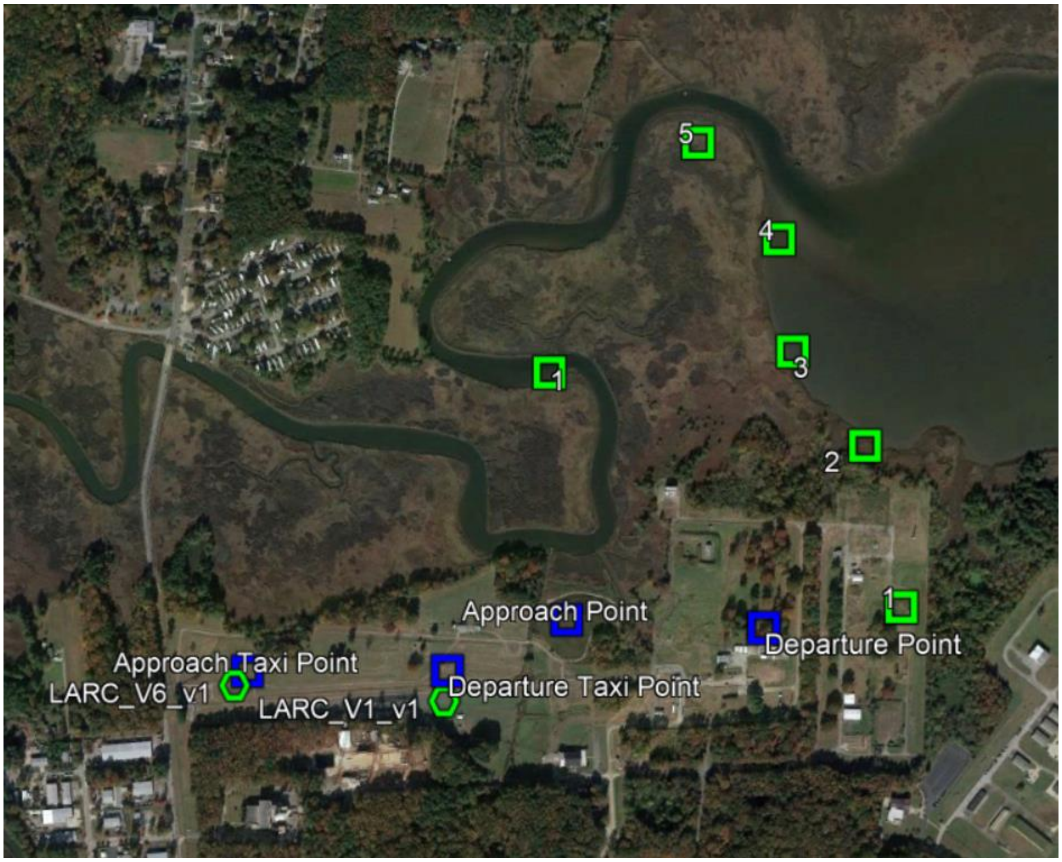

Figure 93: Re-route Scenario Route Waypoints

In Flight Re-Route Testing

During testing a total of 6 test runs were conducted for the in-flight re-route scenario. The details of the test runs are shown in Table 7. Four of the runs were single aircraft operations, and the last two were done during three aircraft operations.

Table 7: Re-Route Scenario Flight Test Operations

Date	Test Run	Scenario	Aircraft	Satisfactory Data
20220201	3	4A	N557NU	Partial
20220203	3	4A	N557NU	Full
20220208	2	4A	N557NU	Full
20220208	4	4A	N557NU	Full
20220429	2	1/1/4A	N559NU/N557NU/N556NU	Full
20220429	3	1/1/4A	N559NU/N557NU/N556NU	Full

This scenario was the most interesting and complex when considering the vertiport and fleet manager roles defined within the project. As seen in Figure 94, each pilot was assigned a unique route associated with the unique vertipad which it took off from and landed. In flight, “gcs1” was updated after vertiport 1 closed, and the new flight plan associated with “Route-140” was uploaded to the aircraft. This enabled the aircraft to approach and land at vertiport 6, since it was originally scheduled to land at vertiport 1.

Figure 94: Vertiport 1 Flight Schedule during Test Run 2 on April 29th

An image of the aircraft’s position and timing relative to the scheduling of the departures and approaches is shown in Figure 95. In this figure it is shown that “gcs2” is landing at vertiport 1 vertipad 2, while “gcs3” is descending toward vertiport 6 approach taxi point. The vertiport status is also shown by a pentagon icon shown that has turned red indicating that the vertiport was closed. This would allow the aircraft remote pilot to see the status of the vertiport change in flight, and prompt them to look for a new route to be issued in the flight schedule display. An image in Figure 96 shows what this looked like from the field during flight testing.

Figure 95: Vertiplex Traffic Management Display during Test Run 2 on April 29th

Figure 96: Picture of Aircraft Re-Route to Vertiport 6 while Aircraft is landing at Vertiport 1

Images of the aircraft during the test run were overlayed on the traffic management display which can be seen in Figure 97. These figures are intended to provide a representation between live flight aircraft and virtual traffic which can be seen on the traffic management display as magenta quad rotor icons.

Figure 97: Onboard View during Test Run 2 on April 29th

Test run flight tracks have been shown on the map view provided in Figure *98*. Although difficult to see, there are yellow segments which are shown with yellow square markers prior to the vertiport 1 approach point, which indicates the locations where the aircraft was put on hold while a new flight plan was uploaded to the aircraft.

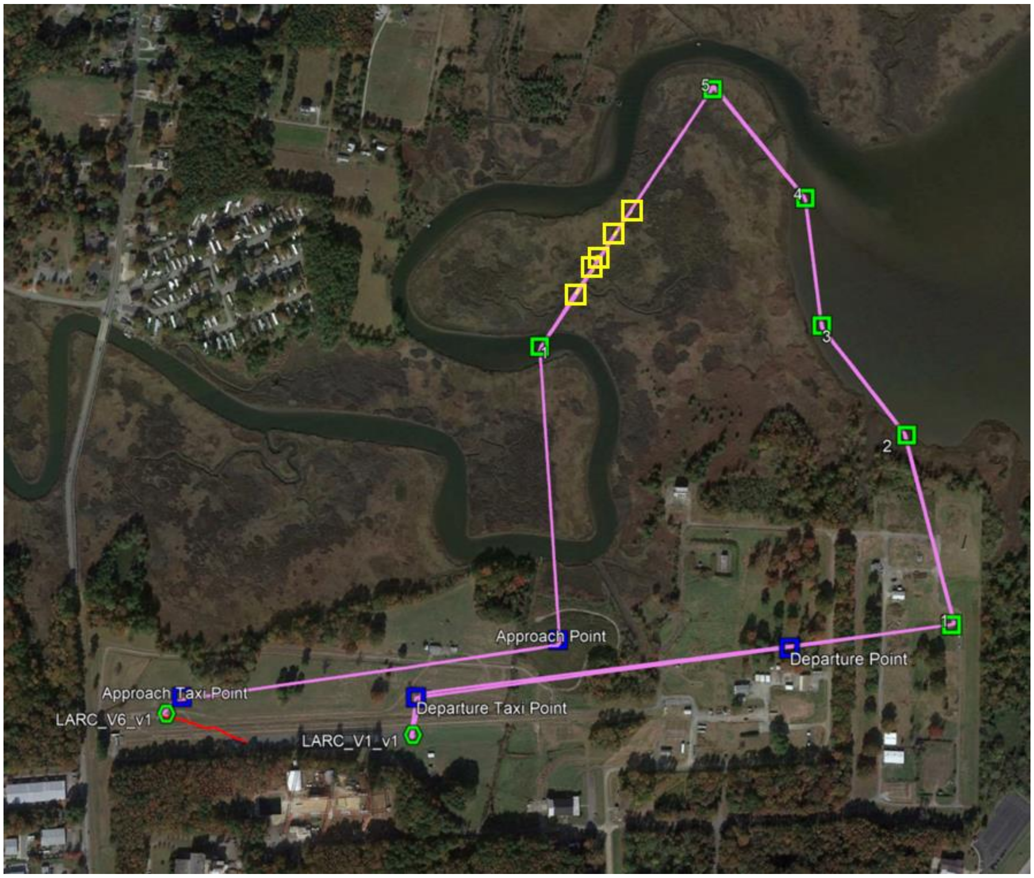

Figure 98: All Re-Route Flight Test Run Flight Tracks

Geofence In-Flight Scenario

In addition to the automated flight maneuvers for traffic and emergency landings, a scenario was also tested that performed an Automated Geofence Avoidance Maneuver (AGAM). This scenario provided insight into how inadvertent maneuvers into unapproved areas would be handled with ICAROUS. This scenario established a geofence violation that would not have been detected and resolved with the basic autopilot flight planning system. Nevertheless, Figure 99 shows the geofence extension that was used to create the geofence encounter. The expected AGAM is shown as a magenta line in the figure. While the basic PX-4 geofence action is to trigger an RTL, ICAROUS can be configured to route around the geofence and continue the mission. This functionality was tested during the AGAM tests.

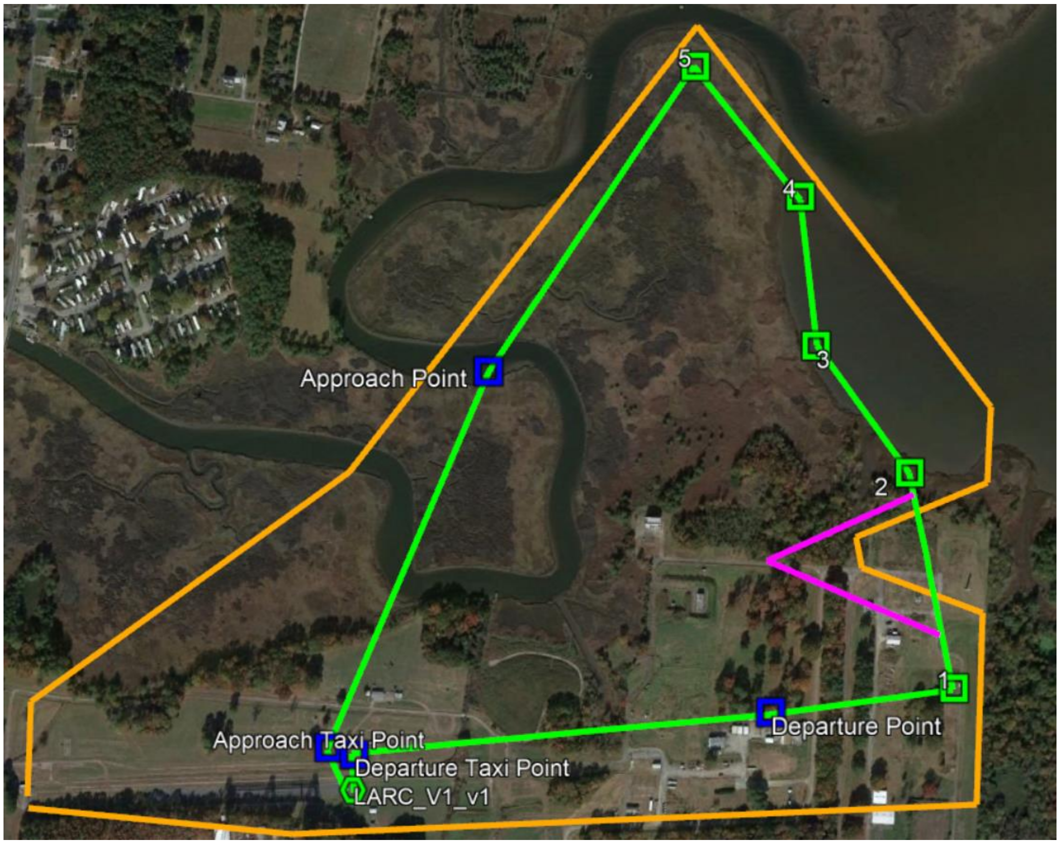

Figure 99: Map view of Geofence In-Flight Scenario Flight Profile

During geofence events, the GCS display in the remote operations room showed a mode change to offboard mode and a secondary path update. This can be seen in Figure 100 where the highlight sections show offboard mode when the AGAM was initiated by ICAROUS. It also shows the secondary path generation message within the traffic avoidance system status window.

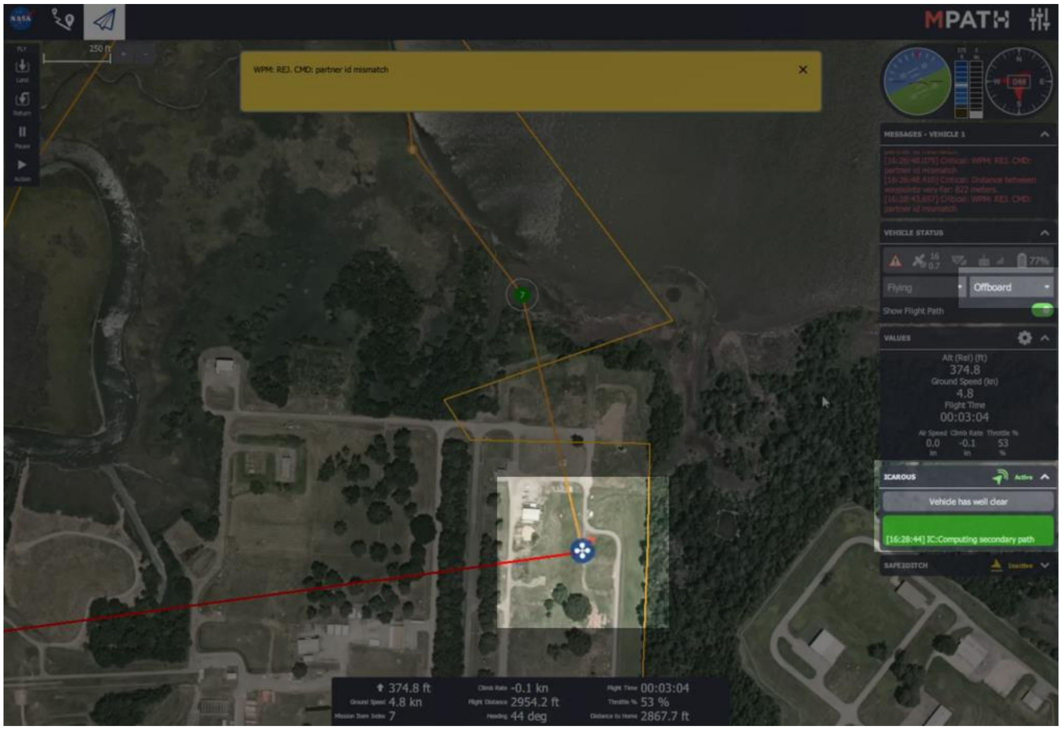

Figure 100: Geofence Avoidance Maneuver Display on GCS

Geofence In-Flight Testing

Two test runs were conducted for this scenario, which can be seen in Table 8. The first test run behavior initiated an AGAM earlier than what was performed during simulation testing, which was aborted with an RTL. This can be seen in Figure 101, where an RTL mode in gold is shown on the flight track map view. While the objective of the AGAM testing was to perform a nominal benign geofence encounter, the flight test team actually created a rather challenging situation. The vehicle flight path was set up to fly directly toward the eastern geofence boundary, then make a left 90-degree turn and proceed north. It was not known by the flight test team how much further east the vehicle could have travelled before triggering an AGAM response from ICAROUS. In addition, the geofence extension was also located in close proximity to the waypoint where the vehicle needed to make a left turn and head north. ICAROUS performs predictions of vehicle location and looks ahead to see where obstructions, traffic, or geofences are located. Given the high level of vehicle maneuvering that occurs during waypoint encounters with the Alta-8 vehicle, and the proximity of the east and north geofence sections, ICAROUS could react to both at nearly the same time. Testing in simulation did not reveal this since all navigation sources are smooth and continuous and vehicle dynamics are not modelled to a very high level of fidelity. As a result of the unknown challenging test condition with the possibility that ICAROUS could react to the east geofence boundary, or north geofence extension, and some slight changes in the test setup, the first AGAM test resulted in a turn to the right away from the north geofence extension that also continued to the right to subsequently avoid the east geofence boundary. A left turn was anticipated from the flight crew, but due to inadequate previous testing and an unknowingly challenging test condition, the vehicle turned right. Overall this was a successful test. The second test was run shortly afterward since a western left turn was observed prior to the initiation of the RTL. After testing, data analysis of the AGAM trajectory for the first run showed the intent that was observed after the test run was stopped, highlighting the value of trajectory intent during automated maneuvers.

Table 8: Summary of Geofence In-Flight Scenario Testing

Date	Test Run	Scenario	Aircraft	Satisfactory Data
20220330	2	5A	N557NU	Partial
20220330	3	5A	N557NU	Full

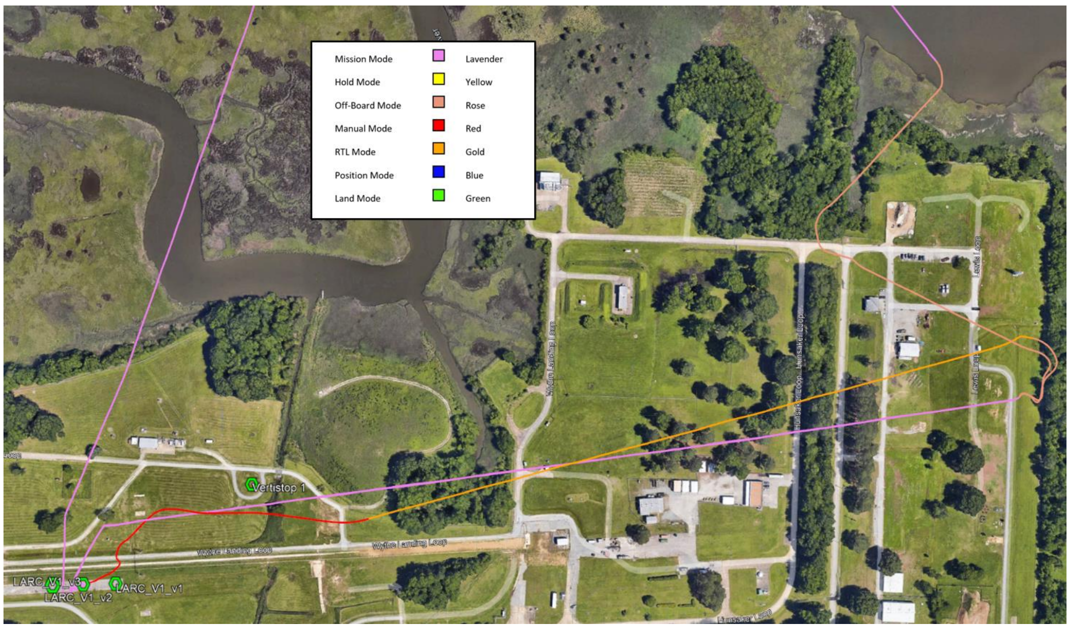

Figure 101: Map view of All Geofence In-Flight Scenario Flight Tracks

The test run which had all data needed can be seen from the GCS map view in Figure 102. This shows the AGAM initiation at mission waypoint 6, shown as the orange circle with the number 6 inside of it, in the lower right of the map view. Once the aircraft established a western heading, the rest of the behavior was as expected based on simulation results. Once the aircraft was on mission waypoint 7, the aircraft went back into mission mode and continued the original flight plan until landing.

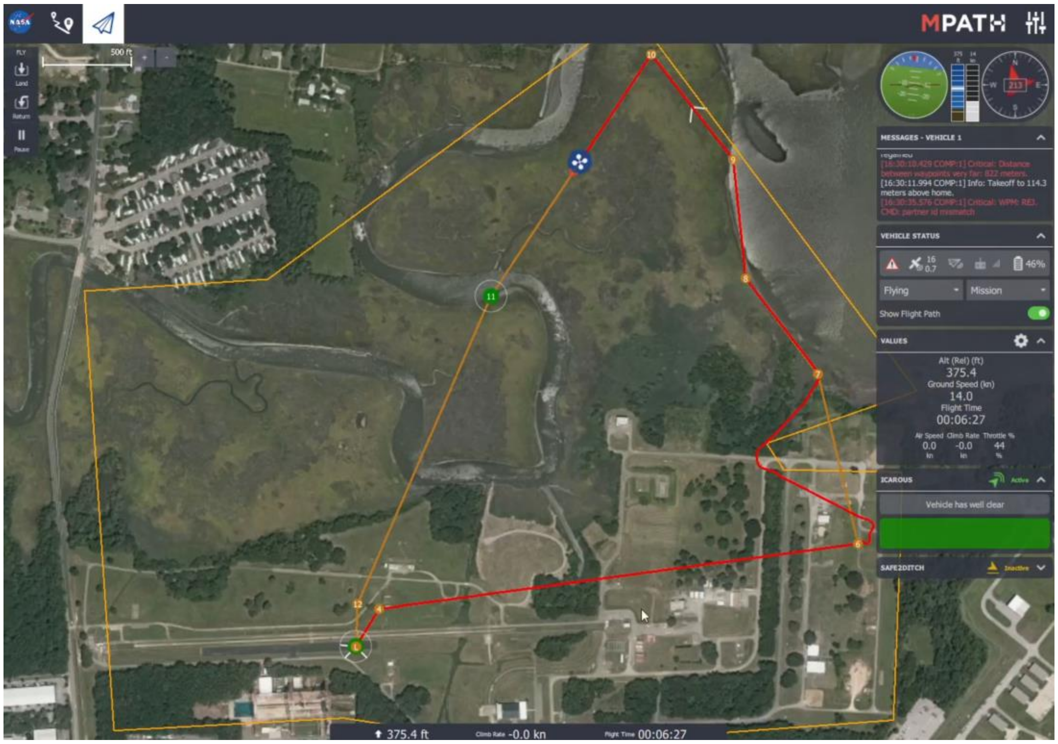

Figure 102: Map view of Flight Track vs. Geofence during Test Run 3 on March 30th

The entire AGAM can be seen in the map view in Figure 103, where it initiated at the red dot and ended at the blue dot. Although the initial turn was south-east, likely the result of the proximity to the geofence extension, the rest of the trajectory followed along the geofence and geofence extension. After review of the AGAM waypoints, and knowing the minimum turn radius for navigation, considering the proximity to two different 90-degree geofence sections, and the dynamic behavior of the Alta-8 vehicle during waypoint maneuvering, the behavior was acceptable based on where the initiation happened. No altitude changes occurred during the AGAM, which can be seen in Figure 104.

Figure 103: Map view of Test Run 2 AGAM on March 30th

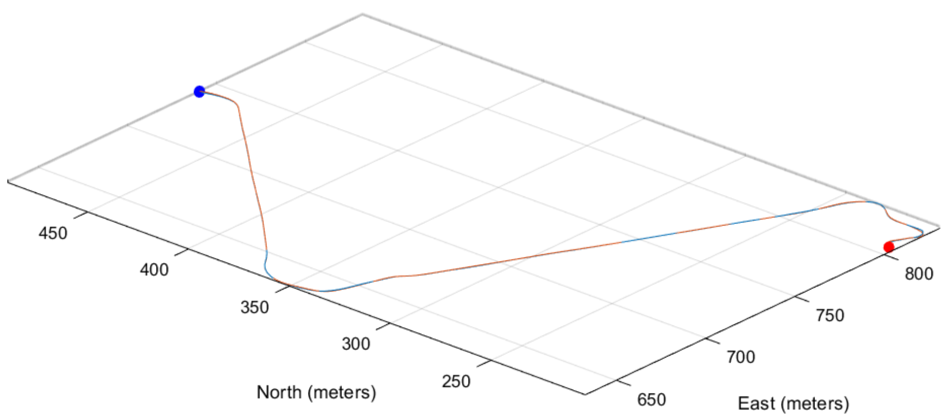

Figure 104: 3D Vertical Profile Plot of Test Run 2 AGAM on March 30th

Flight Test Build-Up Approach

In preparation for conducting the HDV AOA flight test, several systems were tested and built up over months. There are three major categories of systems that were tested and advanced during the build-up: Operational Configuration; Aircraft Configuration; and Role Configuration. Operational configurations focused increasing the number of test aircraft. Aircraft configurations focused on increasing aircraft capabilities. Role configurations focused on creating new or additional responsibilities for flight crews.

The operational configuration focused on testing all aircraft and role configurations at the simplest configuration first and then moving toward a more advanced configuration. The simplest configuration was conducting VLOS operations where only field crew supported flight testing. Once an aircraft or role configuration was tested under VLOS operations, then an Extended Visual Line of Sight (EVLOS) operation was conducted. This allowed the field crew to conduct any pre-flight procedures on the aircraft for the remote operator. The field crew included a PIC that supervised the automated flight commanded by the remote operator.

The aircraft configuration focused on testing all of the new equipment on the aircraft in the simplest configuration first and then moving toward a more advanced configuration. The simplest configuration included hardware that was delivered with the aircraft by the manufacturer. New C2 links were added one at a time and tested and continued until three reliable C2 links were established to support the flight profiles required for PAO scenarios. This allowed radio frequency or electric magnetic radiation issues to be addressed at the least complex configuration and build upon established performance during testing.

The role configuration focused on testing single aircraft operations before adding additional aircraft into the operation. This allowed the simplest configuration to establish procedures and processes with minimal crew in the field before moving into more advanced crew configurations with multiple aircraft operations.

Flight Path Assessment (FPA) Testing

In preparation for PAO flight tests, a series of functional check flights were conducted to test the equipment and procedures designed and planned to support multi-aircraft remote operations. These tests began in August of 2021. A list of the various aircraft configurations with a focus on radio frequency transceivers tested can be seen in Table 9. Since the PAO flight operation would be aborted if we lost two of the three C2 links, it was important to use C2 links with consistent performance.

Table 9: Research Aircraft Configurations

Identification	Date	2.4 GHz ISM C2	915 MHz ISM C2	4G LTE C2	915 MHz ISM V2V 1090 MHz V2V In/Out	1090/978 MHz V2V In
Configuration Baseline	12/10/2020	Futaba T14SG	RFD900x	N/A	N/A	N/A
Configuration 1 VLOS	08/12/2021	Futaba T14SG	RFD900x	Botlink XRD	N/A	N/A
Configuration 2 VLOS	09/10/2021	Futaba T14SG	Anra MP-X1	Botlink XRD	N/A	N/A
Configuration 3 VLOS	11/04/2021	Futaba T14SG	uAvionix microLink	Botlink XRD	N/A	N/A
Configuration 3 EVLOS	01/13/2022	Futaba T14SG	uAvionix microLink	Botlink XRD	N/A	N/A
Configuration 4 EVLOS	02/10/2022	Futaba T14SG	uAvionix microLink	Botlink XRD	PowerMouse	Ping RX

The final configuration used for AOA flight test was configuration 4. An overview of the configuration is shown in Figure 105. The figure shows the additional equipment labeled Avionics Support that was added to support the ATAM, AELM, and AGAM capabilities used in flight testing. Technical specifications for the equipment can be found in Table 10 through Table 16.

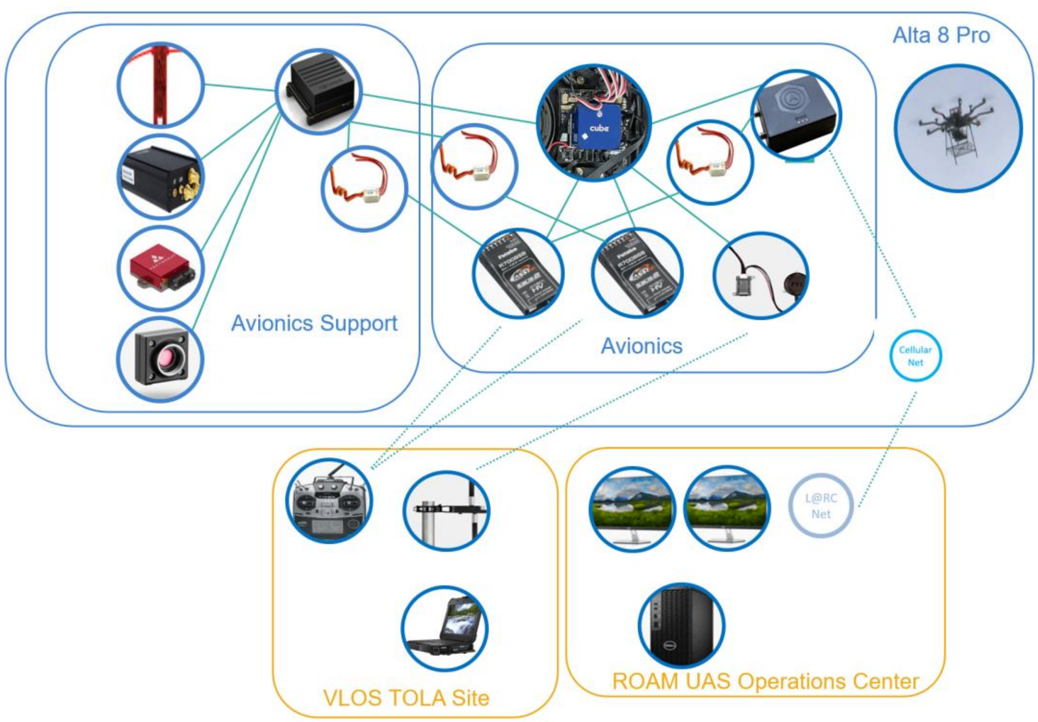

Figure 105: HDV Configuration 4 Remote Overview

Table 10: HDV Configuration 4 Remote Hardware List 1

Component	Function	Sub-System	Quantity
Hex Technology Limited Pixhawk 2.1 Blue Cube	Auto-Pilot	Avionics	1
Hex Technology Limited Here GNSS	Auto-Pilot GPS Receiver	Avionics	1
Futaba R7008SB Receiver	Command and Control	Avionics	2
Freefly Systems Alta 8 Pro	Structure	Airframe	1
Freefly Cargo Landing Gear	Structure	Airframe	1
Freefly F45 384KV Brushless Motors	Propulsion	Propulsion	8
Freefly Silent-Drive Sine Wave ESC	Propulsion	Propulsion	8
Freefly Alta 18 x 6 Propellers	Propulsion	Propulsion	8
Freefly 6S 10AHr LiPo Battery	Propulsion and Avionics Power	Power	2

Table 11: HDV Configuration 4 Remote Hardware List 2

Component	Function	Sub-System	Quantity
Botlink XRD	Command and Control and Data	Avionics	1
Taoglas Antenna	Botlink Transciever	Avionics	2
uAvionix microLink	Command and Control and Data	Avionics	1
1.2 dBi Antenna	microLink Transceiver	Avionics	2
uAvionix FYX GPS	microLink GPS Receiver	Avionics	1
RCATS RC-110X	Payload Power Relay	Avionics	1

Table 12: HDV Configuration 4 Remote Hardware List 3

Component	Function	Sub-System	Quantity
Futaba T14SG RC Transmitter	Command and Control	Ground	1
GCS Laptop/Tablet	Command and Control and Data	Ground	1
Internet Access Point Device	Command and Control and Data	Ground	1

Table 13: HDV Configuration 4 Remote Hardware List 4

Component	Function	Sub-System	Quantity
uAvionix skyStation 2	Command and Control and Data	Ground	1
900 MHz Antenna	Transceiver	Ground	2
GCS Desktop	ROAM Computer	Ground	1
GCS Monitor	Ownship Display	Ground	2
ROAM Wall Display	Operational Area Display	Ground	1

Table 14: HDV Configuration 4 Remote Hardware List 5

Component	Function	Sub-System	Quantity
Jetson AGX Xavier	Companion Computer	Airborne Support	1
Ping RX UAX-90001-01	ADS-B RX	Airborne Support	1
VectorNAV VN200	INS Unit	Airborne Support	1
IDS Camera	S2D Object Detection	Airborne Support	1
LXNAV PowerMouse	ADS-B TX	Airborne Support	1

Table 15: HDV Configuration 4 Remote Hardware List 6

Component	Function	Sub-System	Quantity
RCATS RC-110X	Payload Power Relay	Airborne Support	2
12-16.8V Battery	Payload Power	Airborne Support	1
CC BEC 2.0	Power Relay Regulator	Airborne Support	2
Lume Cube Strobe	Aircraft Lighting	Airborne Support	1

Table 16: HDV Configuration 4 Remote Software List

Component	Function	Software	Version	NASA Software Management Classification
Auto-Pilot Firmware	Auto-Pilot	PX4 Pro	1.8.2 dev	N/A
XRD Firmware	Command and Control	XRD	3.1.24	N/A
GCS Laptop Software	Command and Control	Alta QGroundControl	1.0.6	N/A
ROAM GCS Software	Command and Control	MPATH	1.0.3	N/A
XRD GCS Software	Command and Control	Botlink Relay App	1.4.4	N/A
ICAROUS	Detect and Avoid	ICAROUS	SDAB Managed	Class C
S2D	Emergency Landing	S2D	SDAB Managed	Class C

AOA Flight Test Schedule

To support test design and planning, several phases were identified to facilitate the three components being built-up and also collect research data of interest when available. Initial tests were conducted with single aircraft remote operations, which required an Extended Visual Line of Sight (EVLOS) operation to be established. The dates associated with the various operational configurations and test phases can be seen in Table 17. Due to aircraft flight readiness, weather, and facility and staff availability, the schedule was designed to get the simplest configuration data prior to more complex configurations.

Table 17: Flight Test Schedule

Identification	Description	Start Date	Scenario
Operational Configuration 1	CERTAIN/ROAM:1 Aircraft Operations	25JAN22	N/A
Test 1 (T1)	AVAL/AOL/CERTAIN/ROAM: AOA 1 Aircraft Data Runs	01FEB22	1,4A
Test 2 (T2)	AVAL/AOL/CERTAIN/ROAM: AOA 1 Aircraft Data Runs	30MAR22	5b
Operational Configuration 2	AVAL/AOL/CERTAIN/ROAM: 2 Aircraft Operations	22MAR22	N/A
Test 3 (T3)	AVAL/AOL/CERTAIN/ROAM: AOA 2 Aircraft Data Runs	29MAR22	2A/3A,2B/3B
Test 4 (T4)	AVAL/AOL/CERTAIN/ROAM: AOA 2 Aircraft Data Runs	N/A	2A/3A,2B/3B
Operational Configuration 3	ROAM-3 Operations	21APR22	N/A
Test 5 (T5)	AVAL/AOL/CERTAIN/ROAM: AOA 3 Aircraft Data Runs	21APR22	1,4A

Airworthiness Flight Summary

The expected end state of testing planned for AOA required multiple aircraft, multiple crews, multiple researchers, multiple human factors subjects, multiple labs, and various other constraints to permit a full data collection test run to be accomplished. This required research aircraft to have a high reliability to ensure mission assurance for the required testing. During testing and build-up, a total of 362 flights were conducted with the research aircraft. This can be seen in Table 18. During those 362 flights, over 50 hours of flight time was logged. Although the AOA flight test needed reliability for mission assurance, this data is also needed to establish reliability estimates to support future Beyond Visual Line of Sight (BVLOS) operations where the PIC is planned to be in the remote operations facility. This testing is in addition to air traffic surveillance research that has been conducted with flight range radar systems [9]. To help visualize what these numbers represent, all of the flight tracks for the research aircraft are shown between Figure 106 through Figure 109. This shows all of the various modes that were used during flight operations throughout build-up and test runs. In preparation for future project plans, build-up also included flight testing at the facility designated Unmanned Systems Research & Technology Center (USRTC) at Fort Monroe. These tests can be seen in Figure 108.

Table 18: Research Aircraft Flight Summary

Aircraft	Total Flights	Total Flight Time
N556NU	114	15 Hours 26 Minutes
N557NU	133	18 Hours 25 Minutes
N559NU	115	17 Hours 51 Minutes

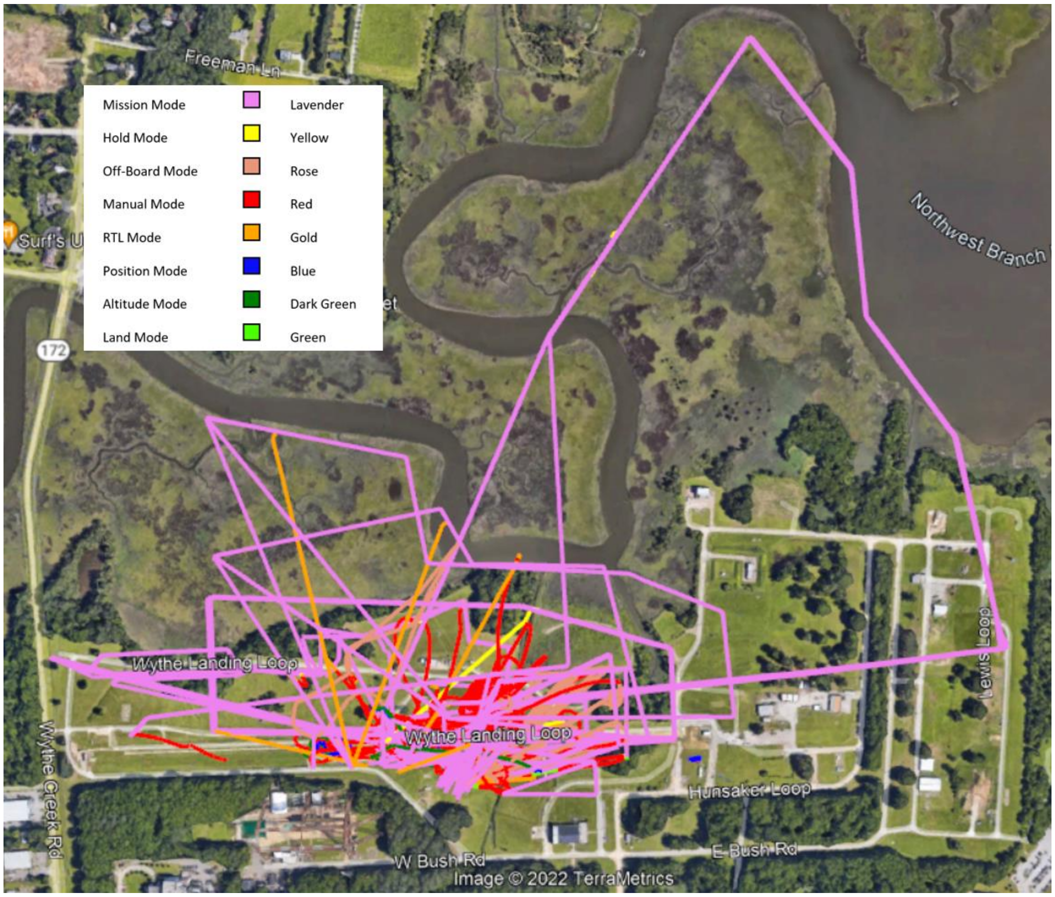

Figure 106: N556NU CERTAIN Flight Tracks

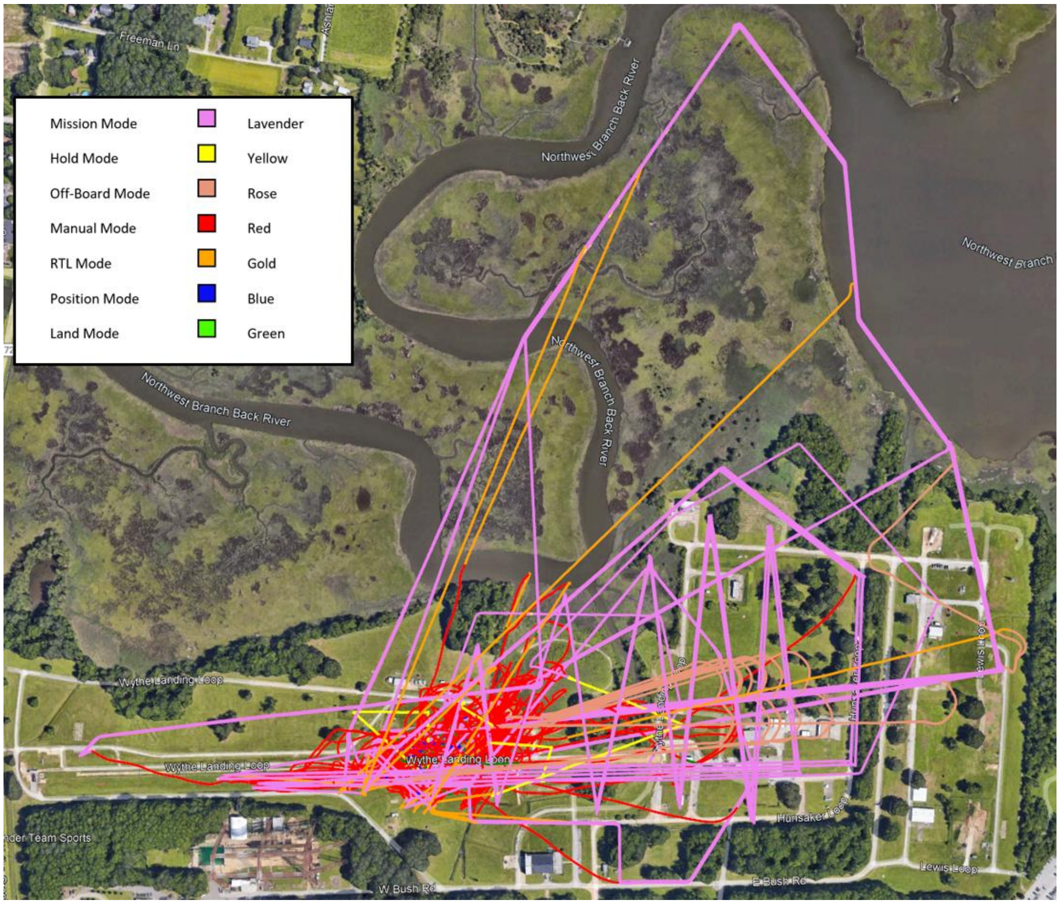

Figure 107: N557NU CERTAIN Flight Tracks

Figure 108: N557NU USRTC Flight Tracks

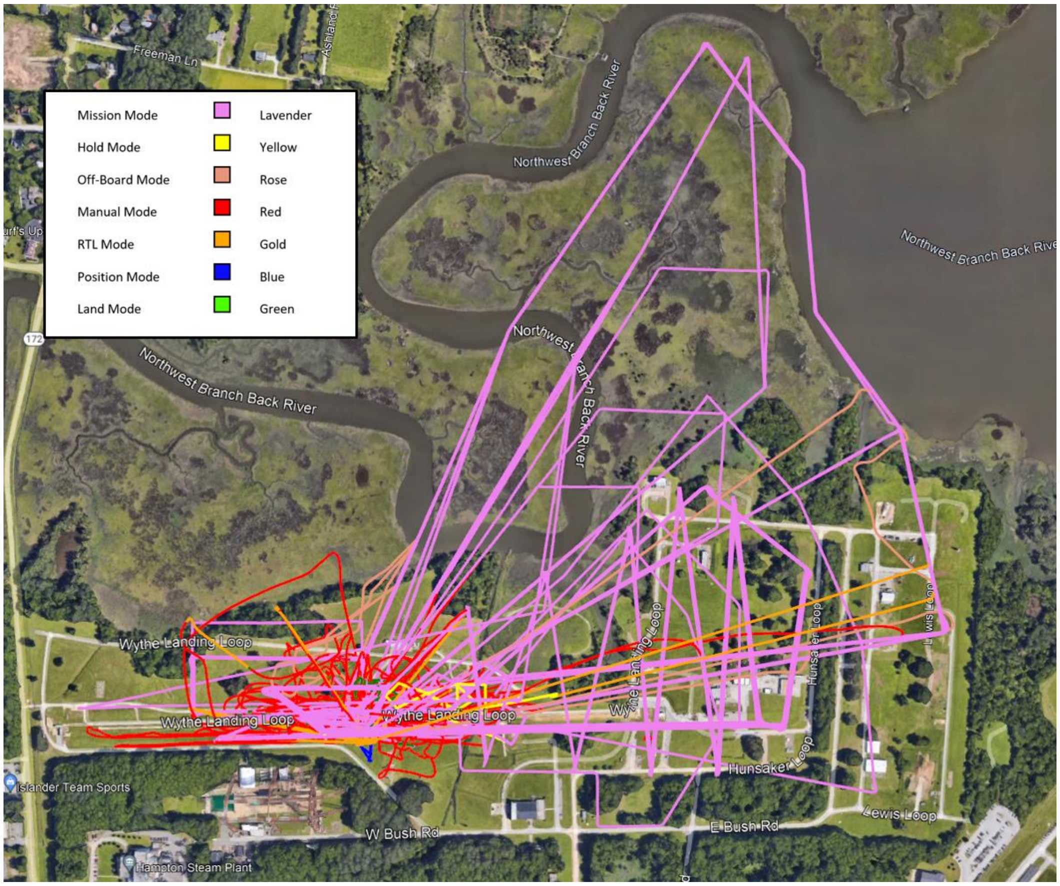

Figure 109: N559NU CERTAIN Flight Tracks

During initial check out of the research aircraft, various failsafe systems were tested. The list in Table 19 shows the four features that were tested prior to conducting research and test for the various aircraft configurations.

Table 19: N556NU Failsafe Testing

Date	Description	Specification
12/10/2020	Geofence Test	Altitude
12/15/2020	Geofence Test	Lateral
12/15/2020	RC Failsafe Test	Position Mode
12/15/2020	RC Failsafe Test	Mission Mode

Over the course of all HDV related build-up and AOA test runs, eight hand controller lost links occurred. This information can be seen between Table 20 and Table 22. Two altitude geofence failsafes occurred. There were no events where all data links were lost, and, therefore, no events where all three C2 links failed. With utilization of uncontrolled spectrum for flight control, it is expected to have multiple redundant links to support the high reliability needs for future BVLOS operations when the PIC is operating the aircraft remotely.

Table 20: N556NU Events of Interest

Date	Description	Specification
12/10/2020	Hand Controller Lost Link	6.5 Seconds
04/21/2022	Hand Controller Lost Link	3.6 Seconds

Table 21: N557NU Events of Interest

Date	Description	Specification
01/13/2022	Hand Controller Lost Link	4.7 Seconds
01/25/2022	Geofence Failsafe	Altitude

Table 22: N559NU Events of Interest

Date	Description	Specification
07/29/2021	Geofence Failsafe	Altitude
09/30/2021	Hand Controller Lost Link	3.5 Seconds, 4.7 Seconds
03/01/2022	Hand Controller Lost Link	1.78 Seconds
03/01/2022	Hand Controller Lost Link	3.6 Seconds
04/26/2022	Hand Controller Lost Link	8.1 Seconds
04/26/2022	Hand Controller Lost Link	4.2 Seconds

To help visualize and gain insight into the 2.4 GHz ISM lost link events, a map view can be seen in Figure 110. In this figure, two regions are shown where issues with maintaining connectivity were experienced consistently.

Figure 110: Map view of All Hand Controller Lost Link Events

Summary and Conclusions

The High Density Vertiplex (HDV) sub-project is part of the NASA Advanced Air Mobility (AAM) project. One thrust of the HDV subproject is to perform rapid prototyping and assessment of an Urban Air Mobility (UAM) Ecosystem within the terminal operational area to help inform future research investments and technology development. Another thrust within HDV is to perform integration, testing, and safety risk assessments required to acquire operational credit for several NASA small Unmanned Aerial Systems (sUAS) beyond visual line of sight (BVLOS) enabling technologies to expand test capabilities and to expedite technology transfer and ultimate effective usage. At this time, the HDV project has recently completed the Advanced Onboard Automation Schedule Work Package (AOA SWP) and is transitioning into the Scalable Autonomous Operations SWP that will feature Vertiport Automation System (VAS) development as well Beyond Visual Line of Sight operations in high-density (Class-D) airspace.

Based on the experience from AOA Flight Test several observations and recommendations are provided:

1. Testing was successfully completed using sUAS as surrogates for larger UAM vehicles providing effective results for the AAM HDV project integrating multiple labs and a remote operations control center at multiple NASA centers.

2. During EVLOS aircraft operations, communications exponentially increase in complexity as more aircraft are operating. Communications plans will need to consider this when considering standard procedures between vertiports and conventional air traffic. Future plans will look at replacing voice communications with equivalent digital means.

3. During automated maneuvers, remote operators will need intent information to support situational awareness, which will need to be considered when designing standard procedures. Future plans will look at how to include additional intent data during automated maneuvers.

4. In-flight re-route of automated vehicles to simulate vertiport closures within a UAM Ecosystem was tested with acceptable results were observed as documented in [5].

5. Onboard autonomous systems that included autonomous detect and avoid (ICAROUS) and emergency contingency management functions (S2D) were tested resulting in acceptable results and performance for the complex conditions tested.

6. Several occasions of limited loss of well clear were encountered related to inconsistent traffic reports of air traffic to the autonomous detect and avoid (ICAROUS) software. Even with this partial data interruption, ICAROUS functioned adequately and predictably. Future testing will look into real-time separation information to support evaluation of ATAM performance during flight testing.

7. During aircraft departure and approach, overflight of people associated with other aircraft on the take off and landing area needs to be considered for standard procedures. A 45 degree keep out cone projected toward the ground was used for all taxi transits.

8. During aircraft departure and approach, groundspeed needs to be reduced when approaching areas with people on the ground when considering standard procedures. A 7 kts ground speed was used during all taxi transits.

9. During aircraft departure and approach, consideration of aircraft that taxi with powered lift is needed when considering standard procedures.

10. Automated maneuvers to address well clear should include a turn radius buffer to mitigate the likelihood of entering the well clear volume when turning into it.

11. Automated maneuver parameters should be adjusted depending on the phase of flight. Future test plans will consider well clear for outside of the vertiport airspace vs. inside of the vertiport airspace.

References

[1] L. J. Glaab, M. A. Johnson, R. G. McSwain, S. C. Geuther, Q. V. Dao and J. R. Homola, "The High Density Vertiplex Advanced Onboard Automation Overview," 13 June 2022. [Online]. Available: https://ntrs.nasa.gov/citations/20220009268. [Accessed 7 November 2022].

[2] J. R. Unverricht, E. T. Chancey, M. S. Politowicz, B. K. Buck and S. C. Geuther, "Eye Glance Behaviors of Ground Control Station Operators in a Simulated Urban Air Mobility Environment," 2 March 2022. [Online]. Available: https://ntrs.nasa.gov/citations/20220003680. [Accessed 7 November 2022].

[3] G. Hodell, G. Dao, J. Homola, M. Goodyear, S. Kalush, S. Swaroop and Y. Jun, "Usability Evaluation of Fleet Management Interface for High Density Vertiplex Environments," 24 June 2022. [Online]. Available: https://ntrs.nasa.gov/citations/20220009874. [Accessed 7 November 2022].

[4] M. Patterson, 22 October 2020. [Online]. Available: https://ntrs.nasa.gov/citations/20205009093.

[5] A. S. Suzuki and Q. V. Dao, "A Flight Replanning Tool for Terminal Area Urban Air Mobility Operations," 14 September 2022. [Online]. Available: https://ntrs.nasa.gov/citations/20220014074. [Accessed 7 November 2022].

[6] N. U. A. I. R. Alliance, 24 May 2021. [Online]. Available: https://ntrs.nasa.gov/citations/20210016168.

[7] B. Duffy, S. Balachandran, A. Peters, K. Smalling, M. Consiglio, L. Glaab, A. Moore and C. Munoz, "Onboard Autonomous Sense and Avoid of Non-Conforming Unmanned Aerial Systems," 30 June 2020. [Online]. Available: https://ntrs.nasa.gov/citations/20205003986. [Accessed 24 10 2022].

[8] M. Consiglio, B. Duffy, S. Balachandran, L. Glaab and C. Munoz, "Sense and Avoid Characterization of the Independent Configurable Architecture for Reliable Operations of Unmanned Systems," 17 June 2019. [Online]. Available: https://ntrs.nasa.gov/citations/20200002709. [Accessed 24 10 2022].

[9] N. M. Gaug and A. C. Tang, "Lightweight Surveillance and Target Acquisition Radar Characterization For High Density Vertiplex Beyond Visual Line of Sight Operations," 13 September 2022. [Online]. Available: https://ntrs.nasa.gov/citations/20220013981. [Accessed 7 November 2022].