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High Density Vertiplex - Scalable Autonomous Operations - Flight Test Report

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Acronyms:

AAM	Advanced Air Mobility
AOA	Advanced Onboard Automation
AOL	Airspace Operations Laboratory
AOSP	Airspace Operations and Safety Program
BVLOS	Beyond Visual Line of Sight
CERTAIN	City Environment Range Testing for Autonomous Integrated Navigation
DAA	Detect and Avoid
eVTOL	Electric vertical takeoff and landing
EVLOS	Extended Visual Line of Sight
FAF	Final Approach Fix
FM	Fleet Manager
FTL	Flight Test Lead
GCS	Ground Control Station
GCSO	Ground Control Station Operator
HDV	High Density Vertiplex
HF	Human Factors
IAD	Integrated Airspace Display
IAF	Initial Approach Fix
MACS	Multi-Aircraft Control System
MAPt	Missed Approach point
MPATH	Measuring Performance for Autonomy Teaming with Humans
NASA	National Aeronautics and Space Administration
PSU	Provider of Services for UAM
ROAM	Remote Operations for Autonomous Missions
RSO	Range Safety Officer
SAO	Scalable Autonomous Operations
SID	Standard Instrument Departure
sUAS	Small Uncrewed Aerial Systems
SWP	Schedule Work Package
TLOF	Touchdown and lift off
UAM	Urban Air Mobility
UMAT	UAS Mission Analysis Tool
VAS	Vertiport Automation System
VM	Vertiport Manager
VPV	Vertiport Volume
VOA	Vertiport Operations Area
xTM	Extensible Traffic Management

1. Introduction

The Advanced Air Mobility (AAM) concept is helping to usher in a new age of aviation that holds the potential to change how people commute, transport cargo, execute missions for the public good, and many other aspects of aviation that can affect the daily lives of people across the globe [1]. The AAM concept is a revolutionary and unique form of aviation highly integrated into society with many access points compared to current airports. Envisioned flights will be frequent, short-duration, and unpiloted using highly autonomous general aviation-sized vehicles (i.e., approximately 4 passengers). The associated AAM industry, regulatory authorities, and relevant stakeholders are deep in the early stages of development across a wide range of necessary topic elements ranging from vehicle manufacturing and testing, system integration, aircraft certification, acoustics assessments, public acceptance, etc. In parallel, research is being conducted to support the near-term operations and far-term scalability with greater levels of autonomy. Ref [2] provides a definition of various levels of UAM capability and performance levels. At the very early stage is simply operating new eVTOL vehicles similarly to todays' helicopter operations. While that may provide some benefit resulting from eVTOL performance, it is anticipated that costs of operations will still relegate this to a niche market primarily serving a small percentage of the population. It is only when the eVTOL aircraft are operated ubiquitously, pervasively, and autonomously as a highly integrated system, that costs could enable most people to consider using it. It is currently considered that all of the constituent ingredients required for a fully implemented UAM transportation system exist at sufficient technology readiness levels to support system level integration. As a result, it can be stated that the primary pacing factor towards realization of this future transportation system is the ability to prototype and assess the overall integrated system. The High Density Vertiplex (HDV) sub-project was a part of NASA's Airspace Operations and Safety Program (AOSP) under the AAM project. HDV was tasked to develop, integrate, and assess integrated autonomous technologies and architectures that support envisioned Urban Air Mobility (UAM) Ecosystem operations. Through this integration and assessment, a glimpse of the future can be established and help to accelerate progress. Within this report UAM and AAM are used interchangeably, however UAM applies more for urban type operations.

The approach taken within HDV is to perform rapid prototyping and assessment of the UAM Ecosystem including representative: 1) Onboard Autonomous Systems, 2) Ground Control and Fleet Management Systems, 3) Airspace Management Systems, and 4) Vertiport Automation Systems (VAS). Small Uncrewed Aerial Systems (sUAS) are employed as effective low risk and inexpensive surrogates for larger proposed UAM aircraft to accelerate the prototyping effort, ensure safety, greatly mitigate costs, and accelerate progress. Testing performed included usability Human Factors (HF) testing to gather critical data at an early stage and perform full end-to-end testing. In addition, the usage of sUAS also generates results applicable to support sUAS operational advancements, such as beyond visual line of sight (BVLOS) operations. Previous work developed an initial prototypical build and analysis of a remote UAS operations center to perform UAM operations, which was done during HDV's initial phase called Advanced Onboard Automation [3].

During 2023, HDV conducted flights tests in support of its second schedule work package (SWP) phase called Scalable Autonomous Operations (SAO) that features a prototype Vertiport Automation System (VAS), automated onboard systems, and airspace management tools to help with high volume vertiport operations. Up to 5 sUAS vehicles were flown simultaneously at the NASA City Environment Range Testing for Autonomous Integrated Navigation (CERTAIN) Flight Range from the Remote Operations for Autonomous Missions (ROAM) UAS Operations Center at NASA Langley Research Center. A Vertiport Manager was also located within the ROAM facility controlling a prototype vertiport at the CERTAIN Range. The Vertiport Manager was assisted in this task by the VAS. The airspace and routing of the sUAS was managed by a Fleet Manager in the Airspace Operations Laboratory (AOL) at NASA Ames Research Center.

During the flight tests, involving flight operation tempos equivalent to 60 operations per hour, contingency scenarios were presented to the operations team. This includes hazards at the vertiport resulting in temporary closures or emergency traffic. These scenarios required a vertiport manager to close and open vertiports in real-time, which resulted in the fleet manager having to adjust vehicle routes mid-flight. After the fleet manager's adjustment, vehicle operators would have to execute a maneuver such as a speed change to hit a new arrival time, a missed approach, or a divert to land at a different vertiport.

This paper will describe the goals and objectives of the project [Section 2], the system and operations under test [Sections 3 and 4], the test plan [Section 5], and the results from the flight test campaign [Section 6].

2. HDV Project Goals and Objectives

The goals of the SAO phase of HDV were to develop and evaluate concepts, prototypes, procedures, and technologies supporting operations at an increased scale from a vertiport. Through pursuit of these goals and objectives, the rapid prototype and assessment of a UAM Ecosystem was possible. From this goal, three objects were derived:

1. Connect fleet management tools and airspace management services to UAS ground control stations.

    Minimum Success Criteria: Connection and ground testing of fleet management and airspace services with at least 5 UAS Ground Control Stations.

    Full Success Criteria: Data collection to verify efficacy of airspace services, multi-aircraft support tools, and interoperability between onboard automation and airspace services and procedures **in a flight test**, considering nominal and off-nominal conditions.

2. Develop and test a vertiport automation system.

    Minimum Success Criteria: Development of a vertiport automation reference architecture that addresses connectivity of a variety of sensors, situation awareness and communication with intended operators (UAS and Vertiport) and systems (GCS and UAS).

    Full Success Criteria: Collect data to verify the efficacy of the vertiport automation reference architecture through analysis, ground testing and **flight testing**.

3. Demonstration of vehicle, airspace and vertiport automation technologies supporting dense operations at a vertiport.

Minimum Success Criteria: Develop scenarios that align with partner UAS cargo operations business cases and eVTOL operations.

Full Success Criteria: Collection of data demonstrating the efficacy of dense operations to/from a vertiport by conducting **a flight test** involving at least 5 live UAS equipped with NASA-developed automation technologies and virtual aircraft to increase density of operation.

3. UAM Ecosystem Overview

The future operational environment of AAM that HDV is developing a prototype of encompasses a variety of areas: vertiports, UAM aircraft, airspace services, vertiport services, arrival and departure procedures, and stakeholder roles and responsibilities. Details of this future operational environment can be found in Ref [4] "High-Density Automated Vertiport Concept of Operations" and Ref [5] "Concept of Operations for Uncrewed Urban Air Mobility."

Below is a brief description of the major elements of the envisioned system. In the subsequent section, a description of the prototype system developed, implemented, and tested during the HDV flight campaign is given.

Vertiports

The vertiport is the ground infrastructure designed for AAM vehicles to take-off at and land. This includes providing services such as charging, cooling, etc. Figure 1 presents some possible future designs, including potential categorization of vertihubs, vertiport, and vertistops, where the services at each may vary. Such as a vertistop may allow for passenger disembarking but not charging capabilities.

The surface and surrounding airspace will be closely monitored for safety assurance, configuration control, and resource management to include balancing of demand and capacity.

Figure 1 Ground Infrastructure: Vertihubs, Vertiports, and Vertistops

Vertiport Management Services

Services supporting vertiport management will likely evolve over time and may vary according to numerous factors. It is envisioned that many of these services and input data will be integrated with a system of systems to aid in vertiport resource management. This system is referred to as the VAS that is an enabler for scalable density operations through the management of vertiport resources, scheduling and sequencing of vertiport resources and providing a means of coordination with external entities (e.g., Fleet Operators). Given the large number of operations from a relatively small location compared to large airports, vertiports will require a range of systems and functions to ensure safety of operations and required operational rates:

- Monitor the touch down and lift off (TLOFs) and ensure their safety.
- Determine and communicate short- or long-term delays to incoming aircraft.
- Ensure safety and conformance of aircraft operating in vertiport environment.
- Establish situational awareness for the Vertiport Manager.
- Provide final authorization to land.

Additional details on the envisioned VAS can be found in Ref [6] which details the software architecture and requirements of the system.

Airspace Management Services

Airspace management services have traditionally been provided by government entities (Area Route Traffic Control Centers (ARTCC), Terminal Radar Approach Control Facilities (TRACONs), Control Towers) or private towers (which follow ATC Tower Requirements) with humans complemented by various levels of system automation. Within the far-term AAM concept, airspace management services under an Extensible Traffic Management (xTM) concept may be offered by independent commercial third-party providers employing integrated and much more automated traffic management initiatives. These xTM systems can provide strategic traffic deconfliction, monitor vehicle conformance with respect to 4D trajectories, and greatly boost overall capacity of the NAS. However, reacting to changes in flight plans and off-nominal situations is a major system integration challenge as information needs to flow seamlessly to an array of systems while maintaining situational awareness of the human participants. It is considered that the role of the Fleet Manager will be more supervisory that could require a series of automated tools to enable this level of human engagement for both nominal and off-nominal operations. This encourages the transition from current day Air Traffic Services to xTM, warranting a paradigm shift.

The types of services that will be available in support of AAM operations will likely evolve over time and the requirements for operator subscriptions will likely vary dependent on factors such as vehicle type and configuration, operation location, mission type, and others. One of the primary airspace services envisioned currently is the Provider of Services for UAM (PSU). This service provides support for operation planning, strategic deconfliction of flight paths, intent communication, messaging and notification, and maintaining the common operating picture. Additionally, there are other services that will provide airspace management support for weather, navigation, and communications services.

Arrival Departure Procedures

Given that vertiports will more directly involve operations in the terminal area in close proximity to the vertiport, they will have an associated set of procedures to impose structure and predictability for arrivals and departures. While UAM vehicles continue in their development and early testing cycles, the specifics on what the fully mature procedures, approach/departure characteristics, as well as the overall integrated system, will look like is currently in the early stages. However, there are assumptions that many of the features of traditional procedures and definitions will carry over in some form.

Definitions of Initial Approach Fix (IAF), Intermediate Fix (IF), Precision Final Approach Fix (PFAF), and Missed Approach Point (MAP) are assumed to carry over to UAM and have importance on how operations are managed with respect to vertiports. Similarly, Approach and Departure Instrument Flight Procedures (IFPs) are assumed to help organize the prototyping and assessments.

Initial designs for airspace at vertiports include defining a Vertiport Operations Area (VOA), and Vertiport Protection Volume (VPV). The VOA is the outermost cylinder of airspace and aircraft will typically enter or exit at the defined points, such as the IAF. Traffic will be funneled into a single or multiple points for entry into the VPV for landing at the vertiport. Only aircraft going to or from the designated vertiport will enter the VPV. Ideas on implementation of this vertiport airspace concept and potential missed approach designs can be found in ref [7].

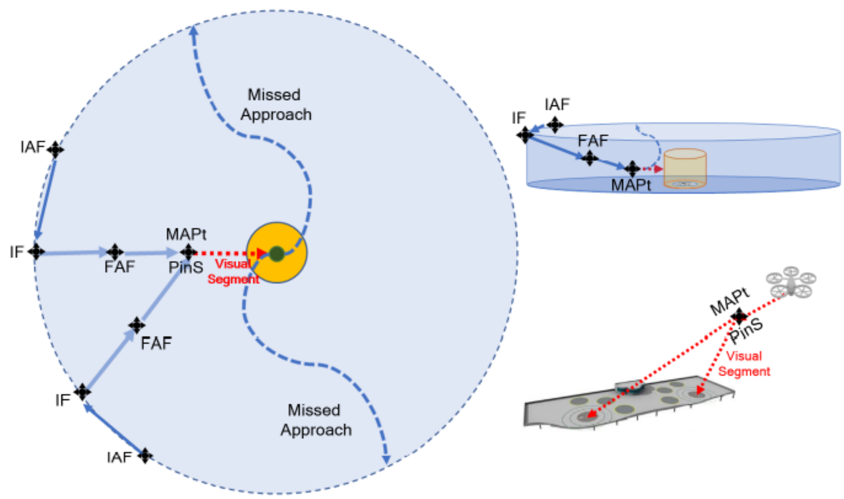

Figure 2 Vertiport Approach Graphic [3]

<u>Roles and Responsibilities</u>

The execution and management of nominal operations as well of situations such as missed approaches in an AAM environment will involve a host of systems and human actors with complementary roles and responsibilities, some of which do not exist today. Below is a brief description of the roles and their assumed responsibilities with respect to the arrival and missed approach procedures that are the focus of this paper:

- *Fleet Manager (FM):* Manages the strategic planning and resource management at the fleet operations level. Operations are scheduled, supervised, and managed in a supervisory capacity with communications and data exchanges with other actors (e.g., Vertiport Manager), as well as services for airspace management. It is assumed that fleets could include dozens of aircraft operating simultaneously. The FM is also responsible for managing or supervising off-nominal contingencies.

- *Vertiport Manager (VM):* With support from automation, services, and sensors the Vertiport Manager oversees operations at the vertiport including its surface and surrounding airspace. This position sets and manages the schedule in accordance with the capacity and resource constraints of the facility and in response to the environment and dynamic situations at the vertiport.

- *Flight Crews:* The team of individuals that manage individual aircraft that make up the fleet and oversee the execution of each flight. The current study evaluated uncrewed fully-autonomous aircraft that were managed by ground control station operators (GCSOs).

- *Ground Crews:* The team of individuals that facilitate passenger and aircraft movements on the ground. Also responsible for flight line servicing of aircraft to include charging and inspections.

UAM Aircraft

To maximize vehicle performance and minimize operational costs, some UAM aircraft will be designed with autonomy in mind. It is considered possible, if not likely, that profitable enduring UAM operations would require uncrewed vehicles. The technology to enable autonomous aircraft has existed for some time in military applications and small unmanned aerial systems (sUAS). Onboard automation systems would include a Flight Management System (FMS) and Autopilot functions, as well as detect and avoid (DAA) systems to ensure well-clear, among many other functions. Other onboard autonomous systems would include autonomous contingency management systems, such as remote landing capability systems to enable safe emergency landings away from managed facilities (i.e., away from airports, vertiports). Onboard autonomous systems could also be used to ensure the TLOF is clear and safe to use during approach and landing. While the command and control (C2) links will be advanced compared to today's standards, some amount of fully autonomous flight capability is anticipated for the optimal integrated system. Integration and testing of the onboard autonomous systems in a relevant environment is an essential step towards the AAM vision.

4. HDV Prototype UAM Ecosystem Architecture

The protype UAM ecosystem developed and tested by HDV includes elements of each of the pieces described above at varying levels of fidelity.

Facilities and resources across two NASA centers, Ames Research Center (ARC) in Mountainview, CA, and Langley Research Center (LaRC) in Hampton, VA, were used for various pieces of the ecosystem and are shown in Figure 3 below.

Figure 3 High level HDV prototype UAM Ecosystem

4.1 Vertiports

A number of prototype vertiports were created at the NASA CERTAIN test range at NASA Langley Research Center. The CERTAIN range boundary is shown in red in Figure 4 below. The location of various vertiports is given, with the primary vertiport for initial development being Vertiport 1.

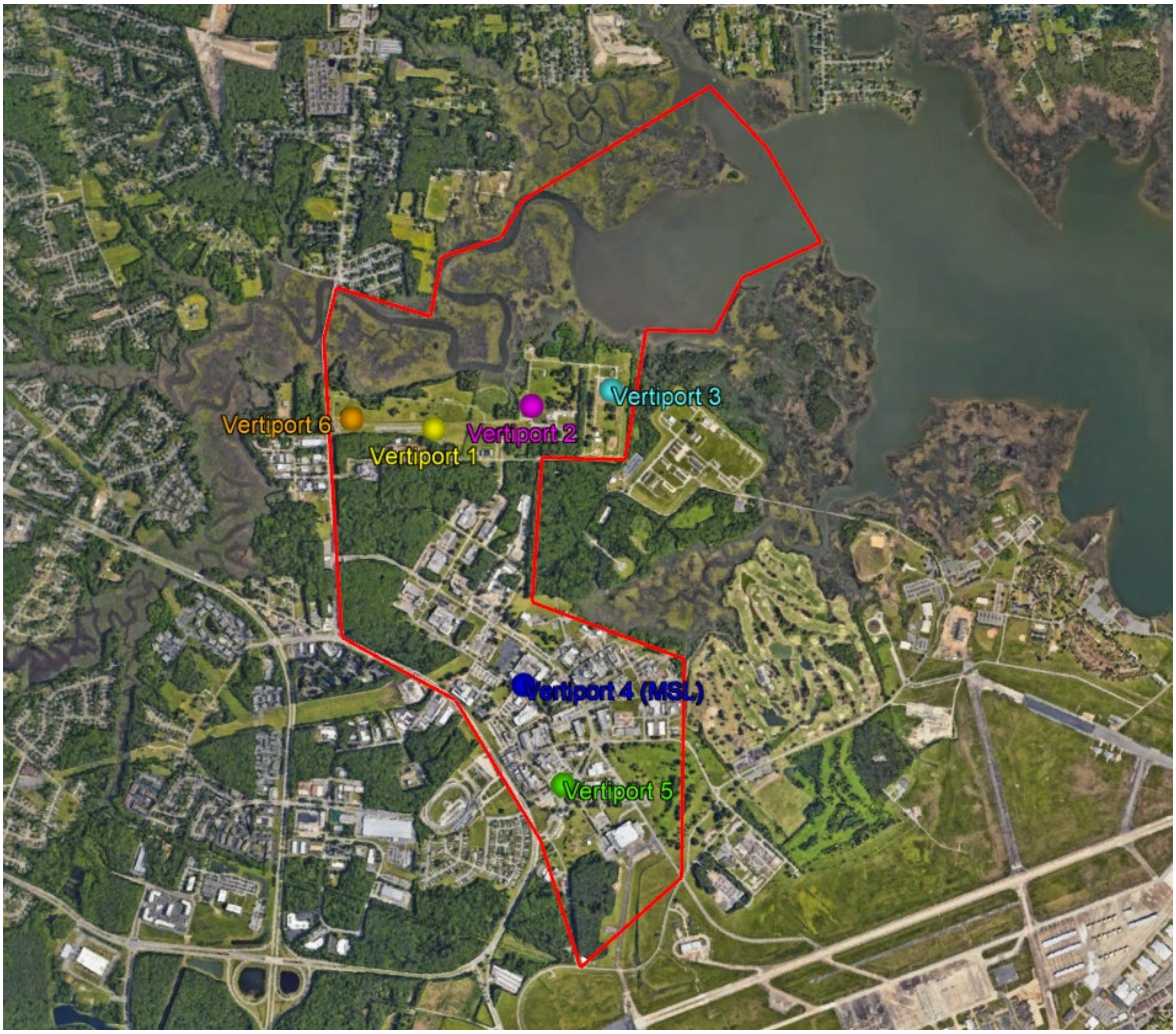

Figure 4 CERTAIN Range and Vertiport Locations

An image of Vertiport 1 from above is shown in Figure 5 below, showing the 3 vertipads at the vertiport.


Figure 5 Vertiport 1 View from the Gantry

The infrastructure capabilities at Vertiport 1 include a paved surface for the touchdown and liftoff (TLOF) areas with preliminary markings based on Ref [8]. Two video cameras provided coverage of the TLOF areas as well as preflight and staging areas and displayed in ROAM. A weather station is located at the vertiport providing real-time wind speed and direction, temperature, and humidity, also displayed in ROAM.

The vertiport had multiple surveillance systems to track vehicles in proximity to the vertiport. Flight Alarm (FLARM) was a system used by participant vehicles to emit their position on the 900 Mhz ISM band, with a ground receiver at Vertiport 1. This was used as an independent means of tracking the vehicles, in addition to the positions reported over the command and control (C2) link. Participating vehicle position was integrated into the Integrated Airspace Display (IAD) in ROAM using the FLARM position data. Additionally, a research system was investigated for visual and radar track of vehicles using distributed sensors around the vertiport, more details on this research is provided in Ref [9].

The vertiport area also had surveillance systems to track non-participant traffic. Two radar systems were used, an Light Weight Surveillance and Tracking Radar (LSTAR) [10] and two GA-9120 panel radars. Multiple ADS-B sensors, uAvionix Ping Station 3s, were positioned around the CERTAIN range as well. The surveillance data was fed to the IAD) which fused the data from the various sources onto one display. The ANRA Smart Skies CTR was used for this.

4.2 Vertiport Arrival Departure Procedures

The vertiports have prototype approach/departure routing that is consistent between vertiports with defined departure and arrival corridors (or pathways).

Departure Route:

All vehicles departing a vertiport initially climb vertically from the vertipad to the taxi altitude. This was typically set at 100-150 ft depending on hazards/obstacles in close proximity to the vertiport. Once at the taxi altitude, the vehicle can then laterally taxi to the taxi departure (TD) point. For these tests the taxi speed was 5 kts. Once the vehicle hits the Taxi Departure point, they can turn and begin the climb out to the Standard Instrument Departure point (SID) at 14 kts. There are two SID points defined, A and B, shown on Figure 6, where each is on a ring of differing radii resulting in different departure climb angles.

Standard Approach:

Vehicles enter the approach at the Initial Approach Fix (IAF). They maintain altitude until the Final Approach Fix (FAF). Once at the FAF, they can start the descent, an 8 degree glide slope was used for these tests. Once at the taxi approach point, typically at 100-150 ft, the vehicles slow to 5 knots and taxi over to their pad. Once over the pad they can descend to landing.

Missed approach:

A missed approach is defined as taking a left hand turn to circle back out to a ring of radius along the IAF. The vehicle will then remain on this circle until cleared to rejoin the approach at which point are allowed to reenter the approach and turn in to the FAF.

Vertiport 1 and 6 approach and departure routing points are shown below. For initial testing a single static approach and departure were used, however future research is envisioned to evaluate dynamic routing with multiple approach and departure routes.

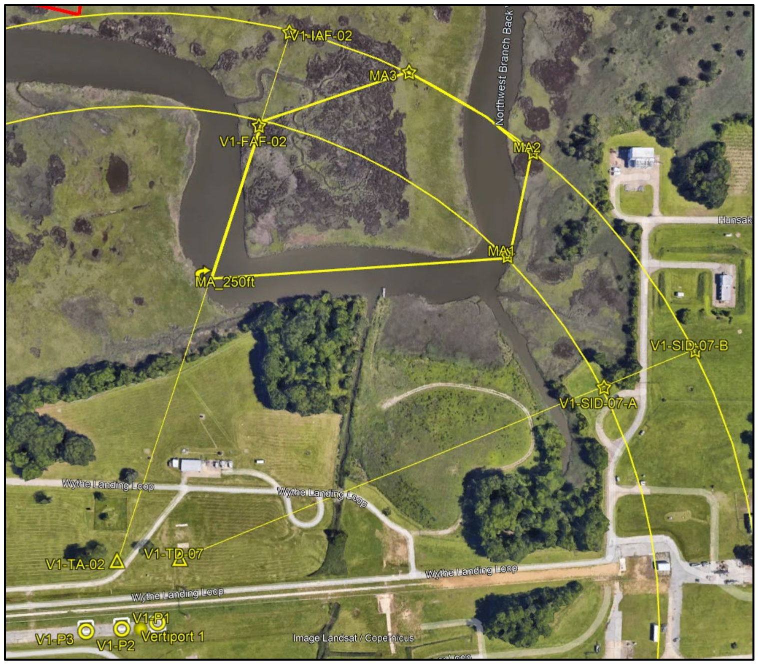

Figure 6 Vertiport 1 Approach and Departure Routes

Figure 7 Vertiport 6 Approach and Departure Routes

4.3 Surrogate UAM vehicles

The test vehicles were Alta 8 Pro multirotor vehicles (Figure 8). A total of five vehicles were used for testing. The vehicles weighed about 30 lbs each and had flight times of approximately 15-20 minutes. The Alta 8s were configured with a mission computer housing several autonomous system technologies including the Integrated Configurable Architecture for Reliable Operations of Unmanned Systems (ICAROUS) [11] that provided autonomous detect and avoid (DAA) functionality along with Safe2Ditch [12] that provided emergency landing/contingency management capability. The resulting vehicle capabilities are considered to be technologically similar to envisioned UAM aircraft. Additional details on the vehicles and the onboard autonomous systems can be found in Ref [3].

Figure 8 Alta 8 Pro Multirotor

The vehicles are flown from a remote ground control station as shown in Figure 9.

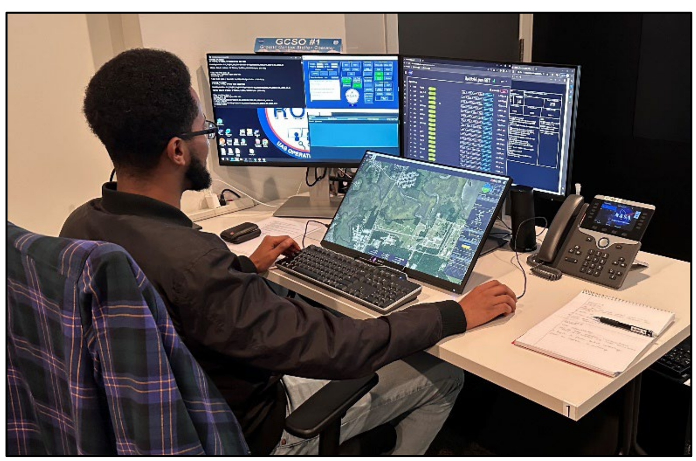

Figure 9 Ground control station

The operator has a primary display with a map showing ownship vehicle location as well as other vehicles nearby. The ground control software is a modified version of QGroundControl, called Measuring Performance for Autonomous Systems Teaming with Humans (MPATH) [13] and is shown in Figure 10. Several DAA features are built into MPATH including conflict bands that show up as red sections around the vehicle. These bands provide direction on which headings would result in loss of well clear volume with other nearby aircraft based on current position and speed of both vehicles. Other features include the ability to activate or de-activate onboard tactical deconfliction (using ICAROUS). As well as the ability to trigger an abort to land at a ditch site if needed using (Safe2Ditch).

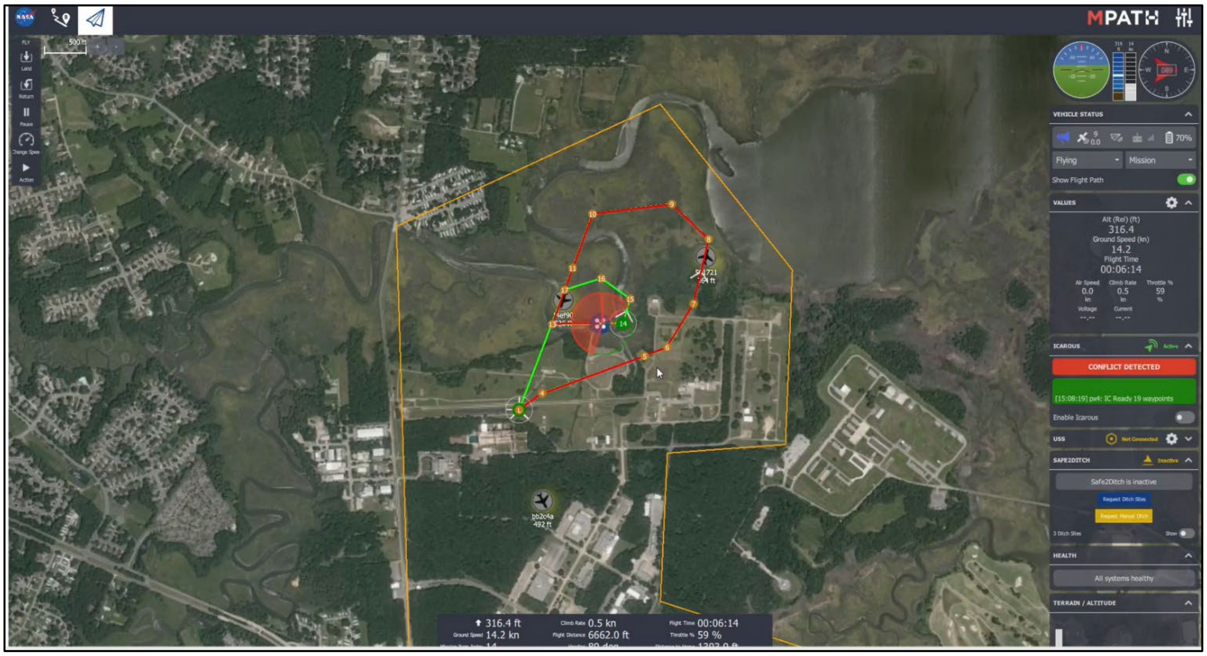

Figure 10 MPATH GCS Display

4.4 Vertiport Management Services

The vertiport management services included a Vertiport Automation System (VAS). The VAS is the system that enables vertiport resource management through data exchanges and synthesis with external systems and local data sources. The VAS is responsible for the scheduling and sequencing of vertiport resources and coordinating with external stakeholders. The VAS has an automated scheduling tool capable of vertiport pad allocation and 4D trajectory sequencing. The VAS also provides a standard interface for other services to access vertiport information about resource availability, aircraft servicing, and any other vertiport-supplied resources. A more detailed description of the VAS can be found in Ref [14].

A vertiport manager was the primary human interface to the VAS. The vertiport manager had the ability to monitor the arrival and departure schedule, current positions of aircraft within the vertiport's operational area (VOA), as well as the ability to open and close the vertiport or individual vertipads. Two of the displays available to the vertiport manager are shown below in Figure 11 and Figure 12. These displays provided information about the status of the vertiport, as well as cameras showing the ground operations at the vertipads. The vertiport manage also had real-time weather information.

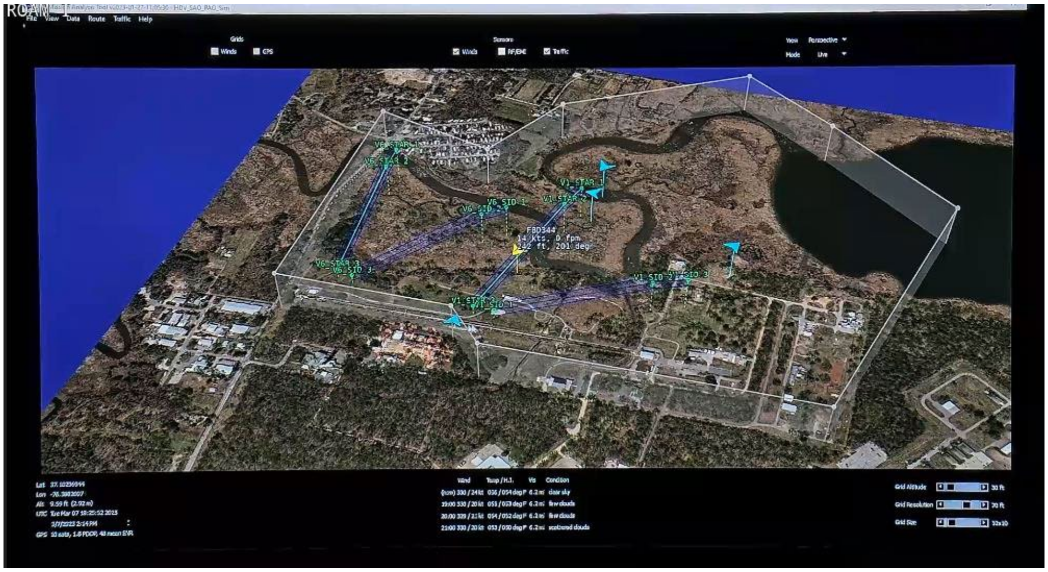

Figure 11 Vertiport Situational Awareness Tool

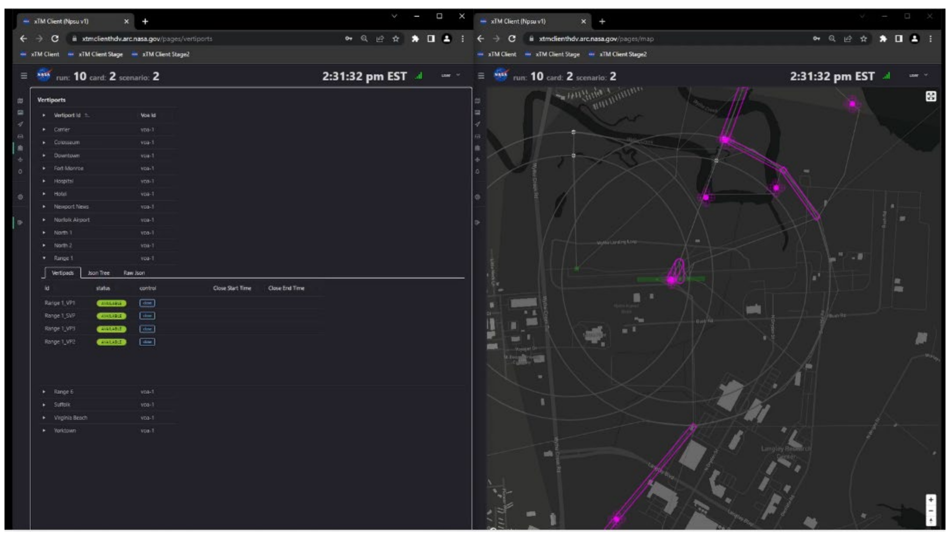

Figure 12 XTM Vertiport control (open/close vertiports)

The VAS also interfaced with the airspace management services described in the next section. Through this interface, operators could request arrival and departure slots.

4.5 Airspace Management Services

The airspace management services were provided by the Airspace Operations Laboratory (AOL) at NASA Ames Research Center and included implementation of an xTM system (called the “HDV Client”) [15]. This service was hosted on Amazon Web Server and allowed operators at both ARC and LaRC to interface with the airspace management system.

The HDV Client display, shown in Figure 13, is an example of the real-time interface that was developed to provide specific capabilities to support the Fleet Manager, Vertiport Manager, and the Ground Control Station Operator in configurations respective of the participant roles. The client interface generally displays the vehicle location in real time through updated position reports from the aircraft. The magenta lines on the map represent the trajectories that the vehicles are intending to fly with the schedule segment highlighted as a volume. This volume is called the conformance volume that the aircraft is expected to be within. Arrival and departure routes as well as potential divert routes are also displayed along with the VPV and VOA concentric circle airspace structures (in grey). An Operations table is also available that displays each of the operations in the system with details such as the state (e.g., Active or Closed), departure/arrival locations, departure and arrival times, and flight phase/status. Each row of the Operations table provides the user the ability to expand and interact with that operation depending on the user's role.

Additional details on the HDV Client can be found in Ref [16].

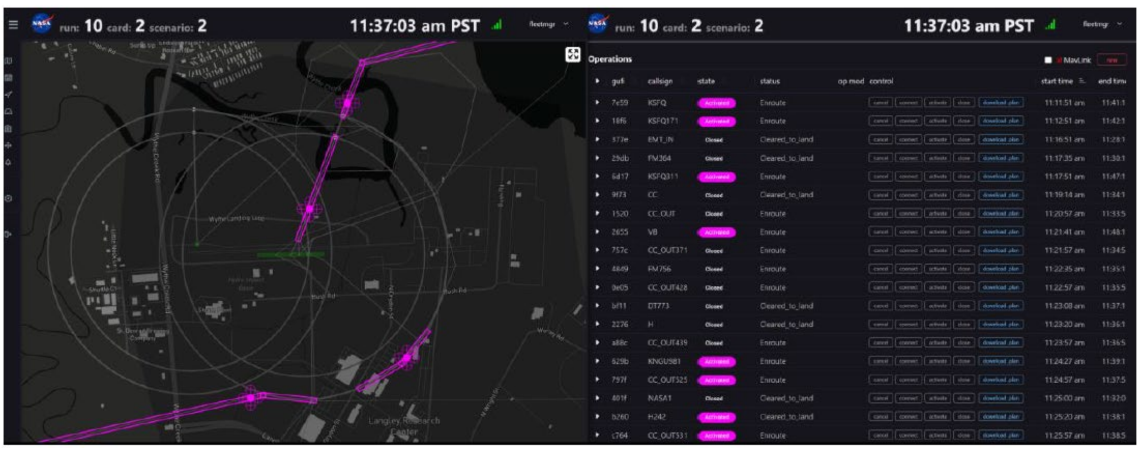

Figure 13 HDV Client display

4.6 Simulated Traffic

In order to prolong periods of maximum density of traffic beyond the five live aircraft, additional simulated traffic was introduced into the system. Using live vehicles, 60 ops/hr could be achieved for several minutes, simulated traffic was added before and after to produce a prolonged 60 ops/hr. The simulated traffic used a tool called the Multi-Aircraft Control System (MACS) [17]. This traffic interfaced with the airspace management system and vertiport automation system to increase the density and operational tempo. Digitally, the traffic appeared the same as the live aircraft in the HDV client and VAS.

The live traffic would be a sequential stream of departures and arrivals, with the simulated traffic being stacked before and after the real world live departures and arrivals. This provided the test environment with a steady stream of aircraft to and from the vertiport, in which the live traffic would be injected.

4.7 Operators and Roles

During operations, there are a number of people required for both safety of flight as well as for research roles. The flight operations crew were located in three geographically different locations; the field location at the vertiports, at the Remote Operations for Autonomous Missions (ROAM) facility at LaRC, and at the Airspace Operations Laboratory (AOL) at ARC.

4.7.1 Field Crew

In the field, there's a single visual observer for safety monitoring of the airspace. A waiver from the FAA allowed for a single visual observer to cover the airspace independent of the number of aircraft. Also in the field there's a safety pilot for each aircraft, that can takeover and fly the aircraft via a 2.4 Ghz remote control link. Nominally, the pilot manipulating the controls is the remote ground control station operator and not the safety pilot in the field. This required an additional waiver from the FAA to conduct Extended Visual Line of Sight (EVLOS) operations.

4.7.2 Remote Operations for Autonomous Missions Control Center

The primary location of the flight crew was in the Remote Operations for Autonomous Missions (ROAM) control center [18]. A layout of the ROAM facility is given in Figure 14 below. There are two separate rooms.

ROAM I houses the flight test lead who coordinates each test mission. A Range Safety Officer (RSO) provides safety oversight of the entire mission. Two supporting roles, an Airspace Monitor and Radar Operator monitor the ground based surveillance radars and sensors. During these flights they were not required as there was a visual observer in the field, however these roles were under evaluation for future BVLOS flights without a visual observer.

ROAM II housed all of the ground control station operators, up to 5 for PAO flight operations. This was to provide a sterile cockpit like environment from the rest of the flight operations crew.

Communications between crew members is described in a later section.

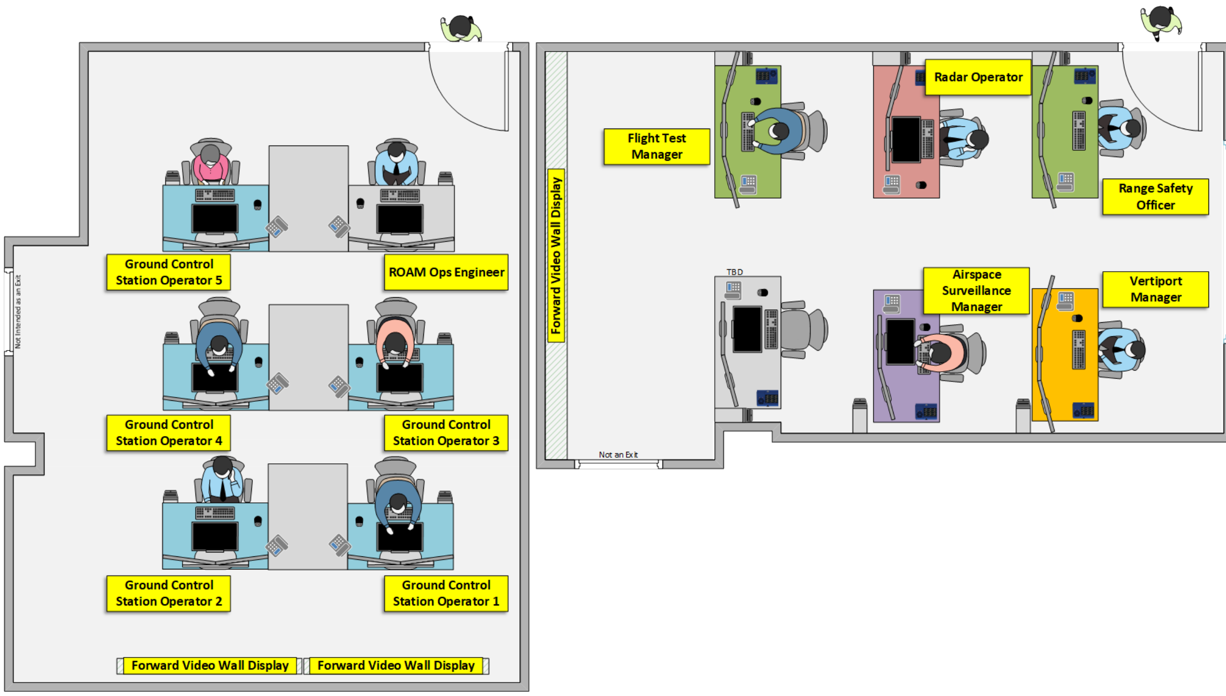

Figure 14 ROAM UAS Operations Center Layout for SAO PAO Flight

Figure 15 ROAM UAS Operations Center During PAO Flight

4.7.3 Airspace Operations Lab

The Airspace Operations Lab is at NASA Ames and is where the airspace management and fleet operations research was conducted [19] . A diagram of this facility is given below in Figure 16.

The fleet manager was located at the AOL and used the HDV client display to interact with the other crew members at ROAM. The fleet manager would approve/disapprove of vehicle schedules. They would also monitor the flights and issue any reroutes due to contingencies/emergencies at the vertiports. This information would be communicated through the HDV client from the vertiport manager. These reroutes involved mission changes to reroute or divert to different locations or adjustments to arrival times. A more detailed description of the role of the fleet manager can be found in ref [20] and [16].

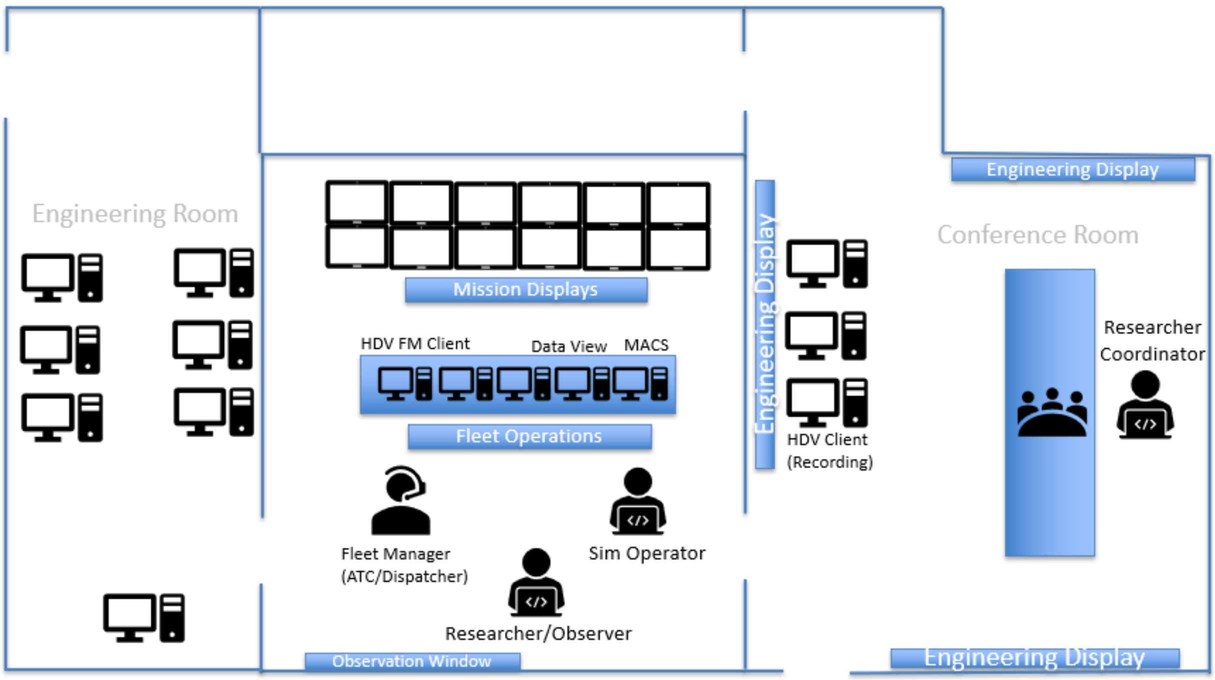

Figure 16 Airspace Operations Lab Layout

Figure 17 AOL during Operations

4.7.4 Communications

Communications was an important factor for conducting safe operations with a large test team at three geographic locations. A voice communications plan was developed using an intercom system by Clear-Com, as well as the use of Microsoft Teams. A diagram of the communications plan is shown below, where black boxes are individual people and circles are communication channels.

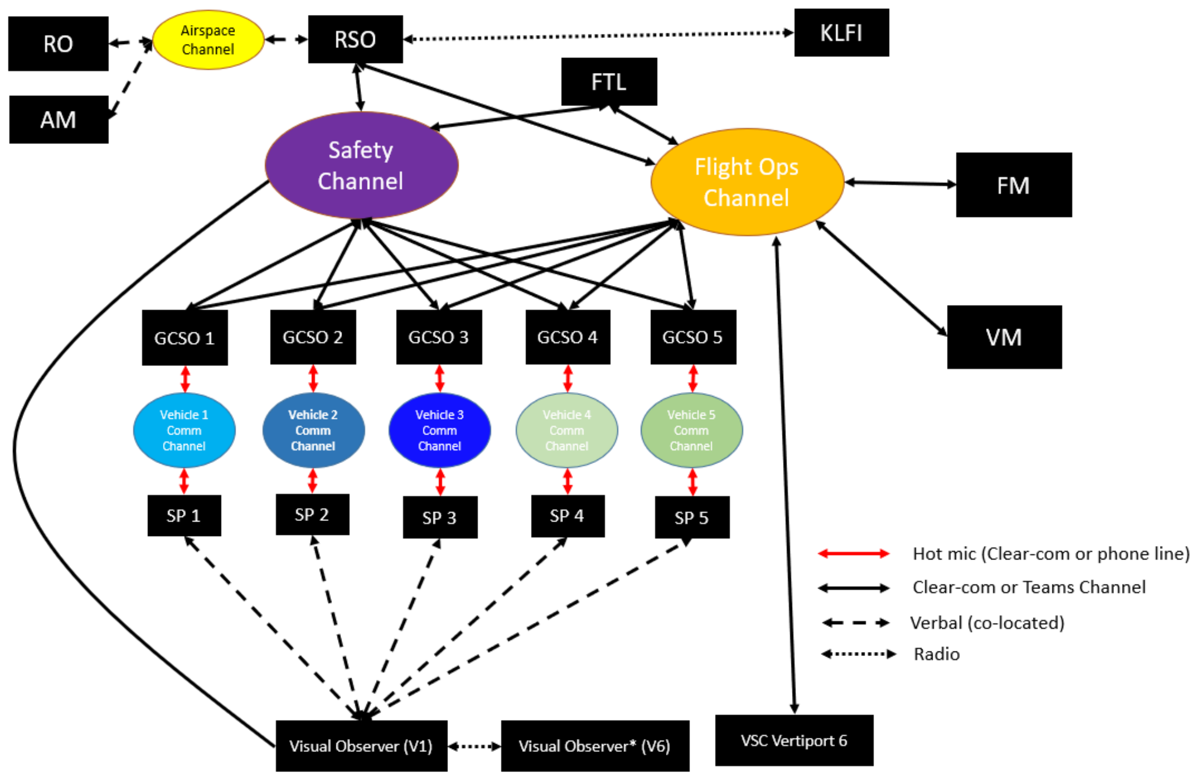

Figure 18 Crew Communications

4.8 Integrated System

The integrated UAM ecosystem prototype developed by HDV that is comprised of the elements discussed previously in this section is shown in Figure 19.

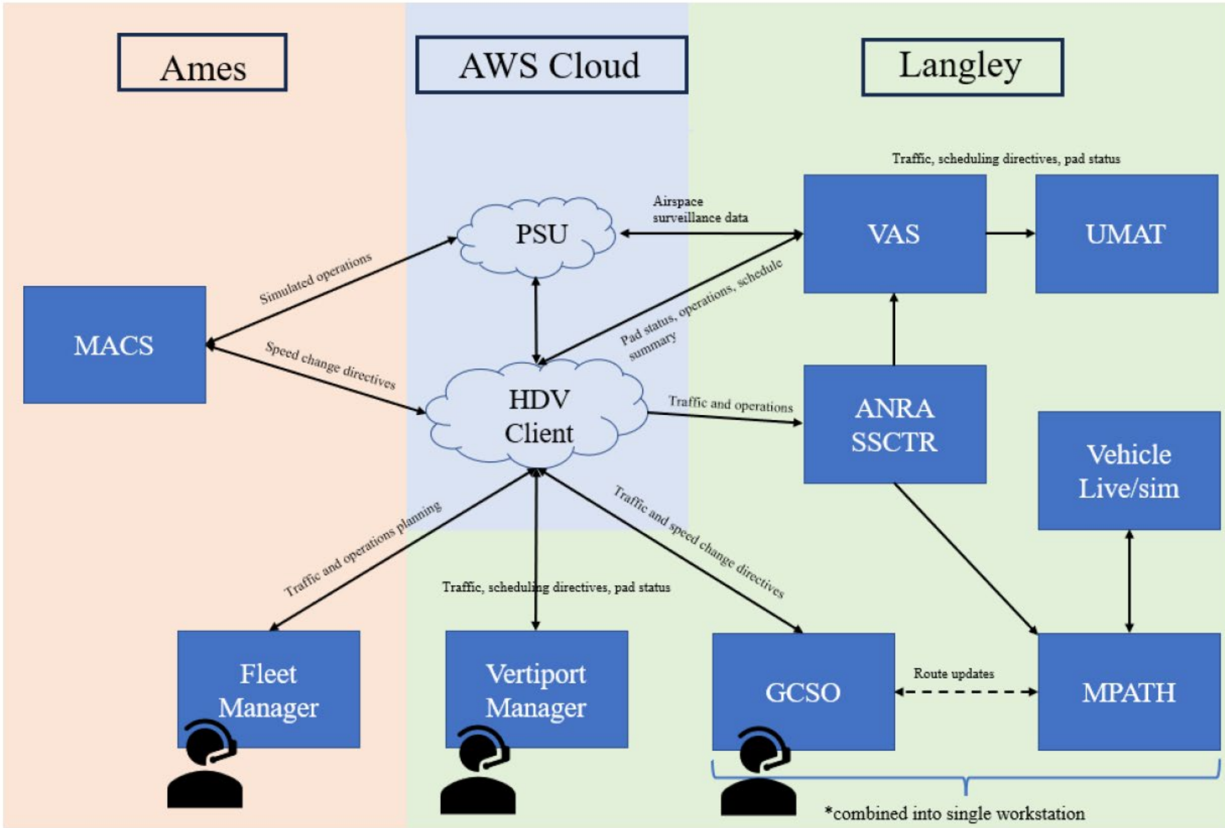

Figure 19 Integrated HDV prototype of the UAM ecosystem [15]

5. Flight Test Plan

The goal of the flight test campaign was to conduct missions to exercise various elements and interactions between components of the prototype UAM ecosystem. To do this, both nominal missions were planned as well as off nominal where a contingency scenario was presented and the operations crew had to adapt and adjust.

5.1 Mission Routes

There were two primary mission routes that were used, Vertiport 1 to Vertiport 1 (Figure 20 and Figure 21) and Vertiport 6 to Vertiport 1 (Figure 22 and Figure 23). These routes follow the standard departure and approach procedures for vertiports outlined in a previous section. Once outside the vertiport, a short route around and loop back in was performed to simulate some mission beyond the vertiport.

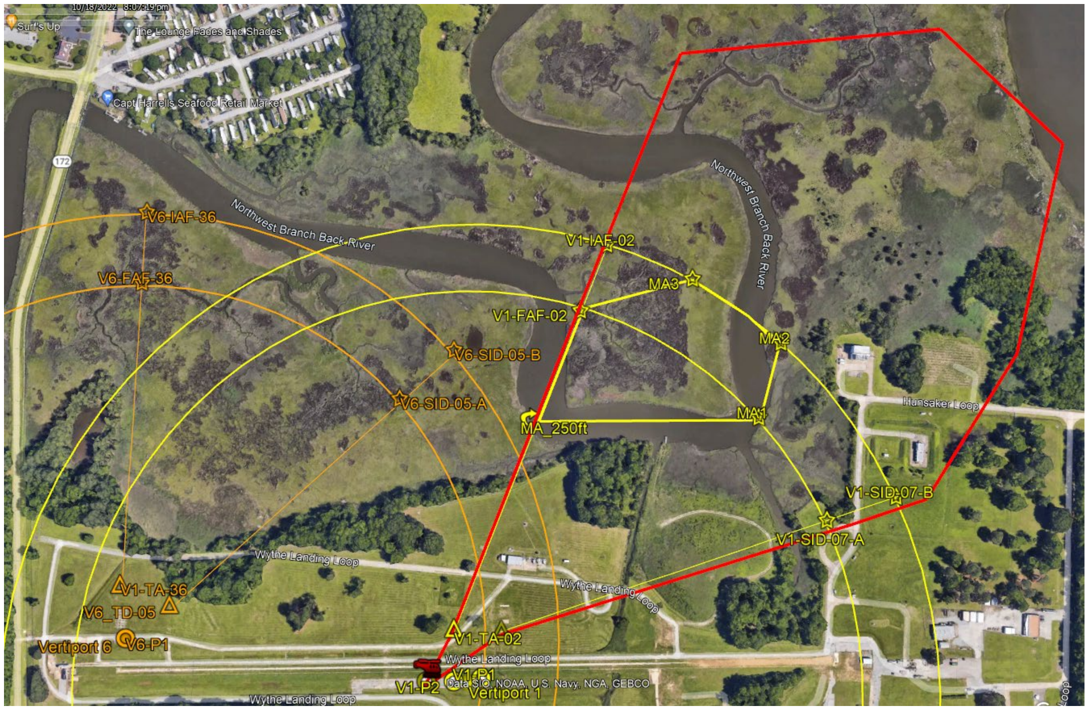

Figure 20 Nominal Vertiport 1 to Vertiport 1 Route, Top View

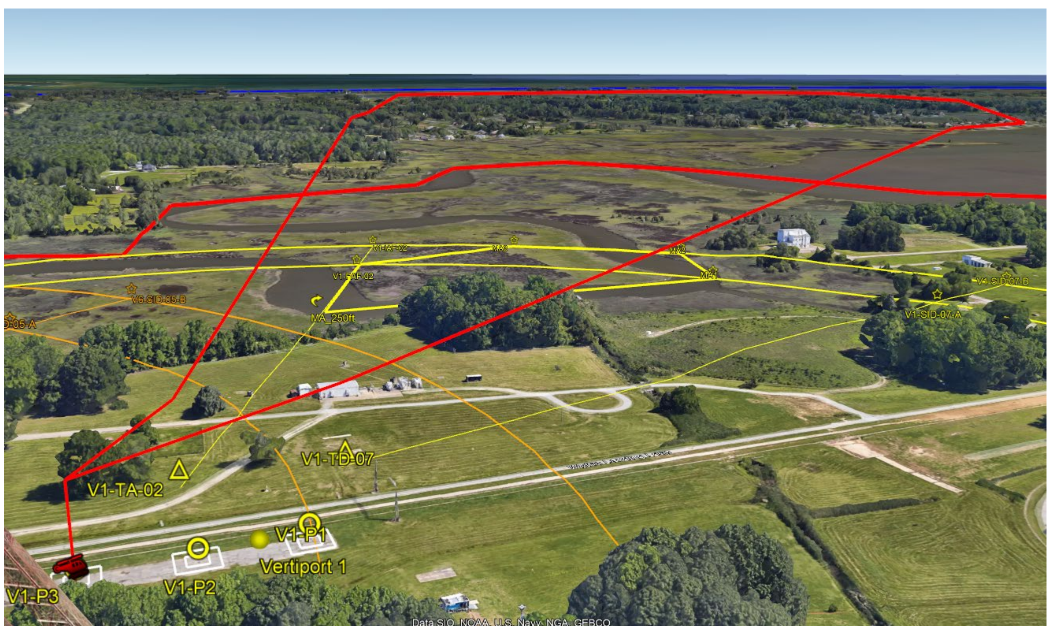

Figure 21 Nominal Vertiport 1 to Vertiport 1 Route, Side View

Figure 22 Nominal Vertiport 6 to Vertiport 1 Route, Top View

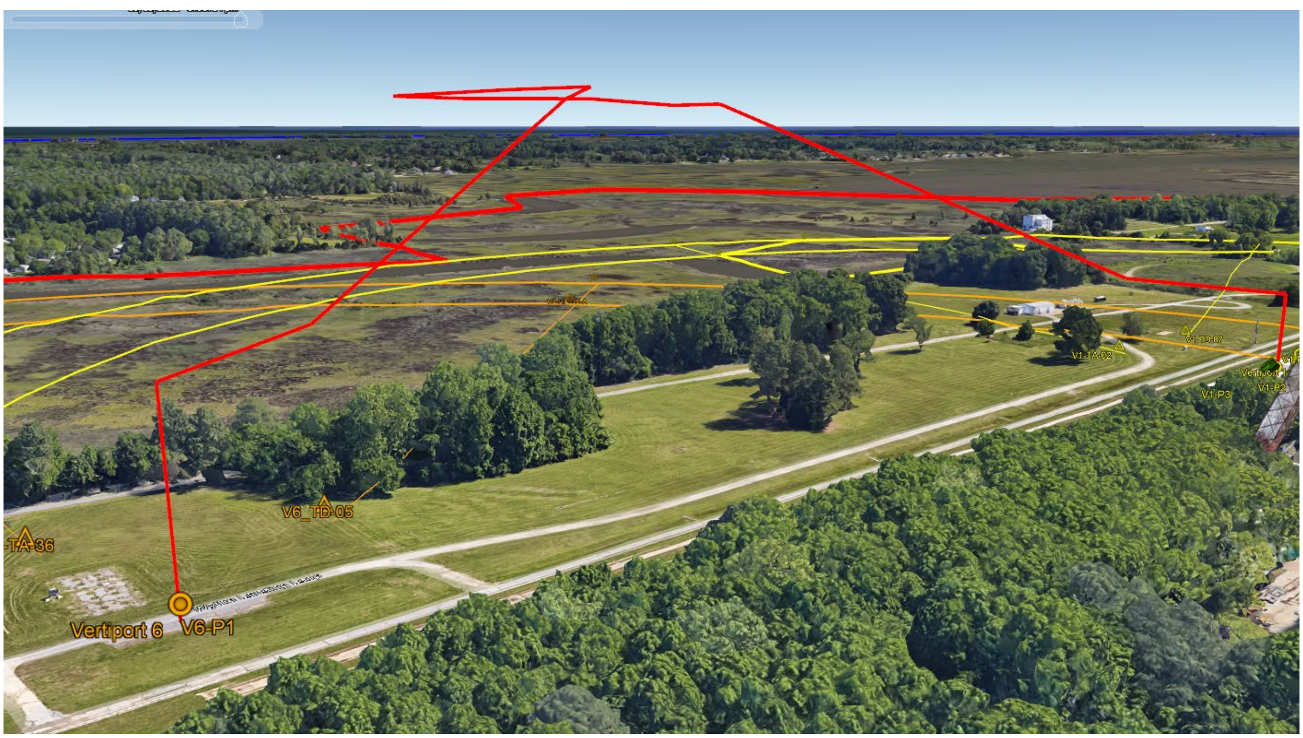

Figure 23 Nominal Vertiport 6 to Vertiport 1 Route, Side view

5.2 Contingency Maneuvers

While flying on these nominal mission routes, there were then 5 contingency scenarios presented that resulted in requiring deviations from the nominal missions via reroutes and arrival time shifts.

There were three maneuvers the GCSOs could take to react to a contingency. The three actions are; missed approach, speed change or divert. These actions would be taken by the GCSO to react to an immediate issue or could be instructed to be performed by the Fleet manager who would adjust their approved mission in the HDV client. In this case, the HDV client would alert the GCSO of a change and provide input on which action to execute.

The methods of executing the three contingency maneuvers are provided below:

1. Speed Change

For a speed change contingency, the FM would instruct the GCSOs to slow or speed up their vehicles to result in a newly scheduled arrival time at the vertiport. To do this maneuver the GCSO click speed change on upper left action bar of their GCS display, slide the bar on the far right to the desired speed, then slide the confirmation bar at the bottom. The vehicle would then adjust speed to the new command.

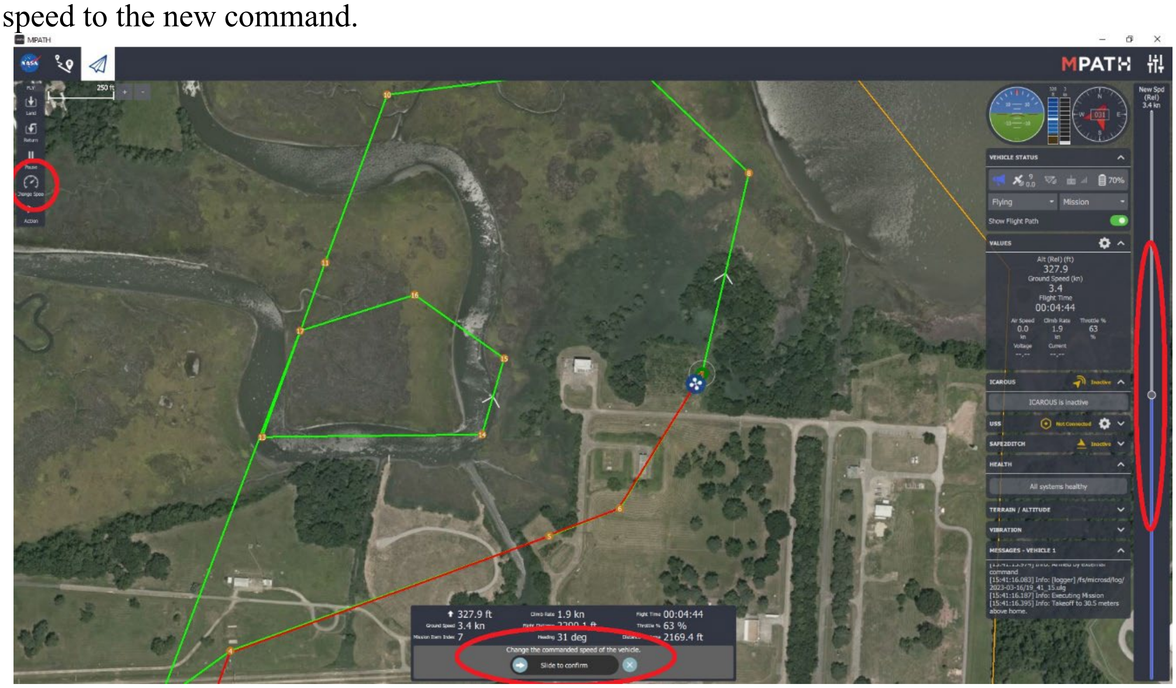

Figure 24 MPATH Speed Change

2. Missed Approach

The missed approach scenario was intended to represent a situation where a vehicle must circle back around after the initial approach and land at a different slot than originally intended. The flight plan always has a missed approach route built into it in case of a contingency. This route is normally bypassed, waypoint 13 at the FAF is a jump to waypoint 19 (Taxi Approach point), thus nominally skips the missed approach.

Figure 25 Missed approach segment built into flight plan

In the event of a missed approach is desired, the GCSO clicks on waypoint 15 (the first missed approach waypoint) and then slides the bar at the bottom of the screen to continue mission from pt 15. The vehicle will then turn and fly to way point 15 and fly the missed approach route, circling back in to landing.

3. Divert

When the divert scenario was executed, the FM engaged the trial planner aspect of the HDV client which allowed them to generate a new trajectory to a nearby vertiport and to avoid a closure at the previously planned landing location. The new trajectory was provided to the GCSO through the HDV client. The GCSO would download the new plan and then upload the new flight plan to the vehicle which updated the trajectory to the nearby vertiport.

For the case of a divert, the GCSO would pause the mission:

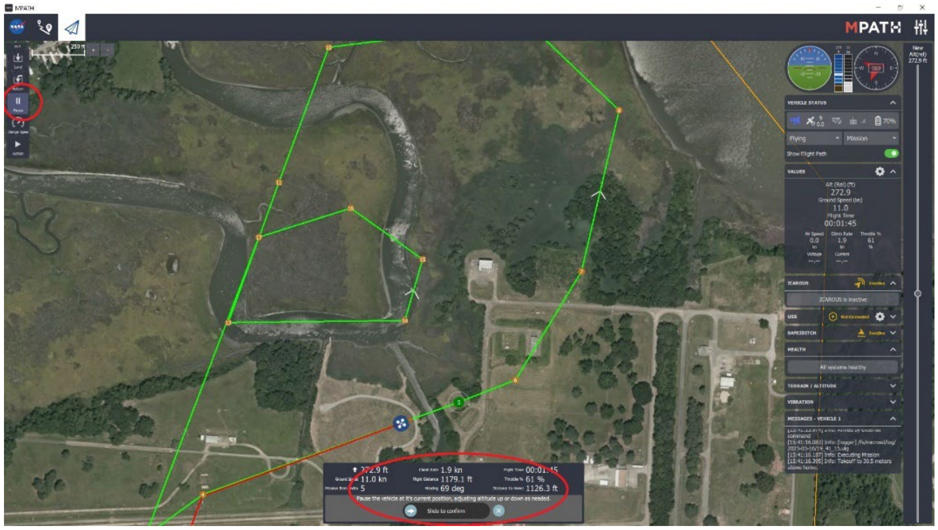

Figure 26 MPATH Hold/Pause Mission

The GCSO would then download the new mission plan file from the HDV Client that was provided by the fleet manage, using trial planner.

The GCSO will then open the new flight plan on ground control station (divert_V6.plan).

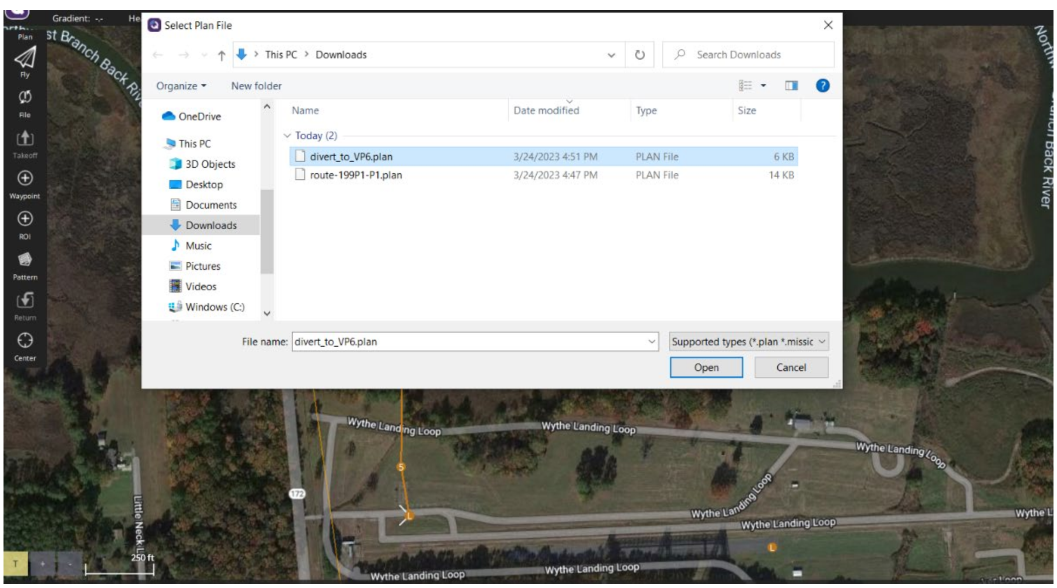

Figure 27 GCS load flight plan

The GCSO will verify the altitudes are correct:

- route and IAF/FAF points are at 325-350 ft
- Taxi approach and over pad hover at 150 ft

The GCSO will then upload the mission to the vehicle, and continue mission from waypoint 2:

Figure 28 Divert to V6 route

5.3 Mission Scenarios

During each mission, the participating GCSOs, VMs, and FMs were presented with five unique scenarios, each of which represented different potential situations of vertiport operations. While the scenarios were playing out, a contingency would occur, requiring the Vertiport Manager to close the vertiport or vertipads which altered the arrival times at the vertiport. This required the Fleet Manager to take action and replan by issuing an action to the GCSO through verbal communications and/or the HDV Client. The GCSO then takes the associated actions.

The five scenarios (multivehicle missions) that were flown and repeated are listed in the table below.

Table 1 Mission Scenarios

Scenario #	# of live vehicles	Nominal Routes	Contingency Maneuver	Description
1	1 - 5	V1-V1, V6-V1	None	• Demonstrate 60 ops/hr
2	2 - 3	V1-V1	Missed Approach	• Vehicle #2 has emergency • Vehicle 1 gives way and does Missed Approach

3	2 - 3	V1-V1	Speed Change	• Vertiport Manager Temporarily Closes Vertiport 1 with minor delay 30 sec • vehicles slow down for delayed arrival times
4	2 - 3	V1-V1	Divert	• Vertiport Manager Temporarily Closes Vertiport 1 with moderate delay, ~3 mins, • Vehicles divert to V6
5	3 - 4	V1-V1	Spd Change, MA, Divert	• Vertiport Manager Temporarily Closes Vertiport 1 with major delay >3 mins • Vehicles divert to V6 and some slow down

5.3.1 Scenario 1 - Nominal

Scenario 1 was a nominal mission with no contingencies. Anywhere from 1 to 5 vehicles could be flown on this mission. The first vehicle would depart from Vertiport 1, and then each subsequent vehicle would alternate between departing Vertiport 6 and vertiport 1. All vehicles would then arrive back at vertiport 1, with planned arrival times every 60 seconds. A diagram of this mission is shown in Figure 29 below:

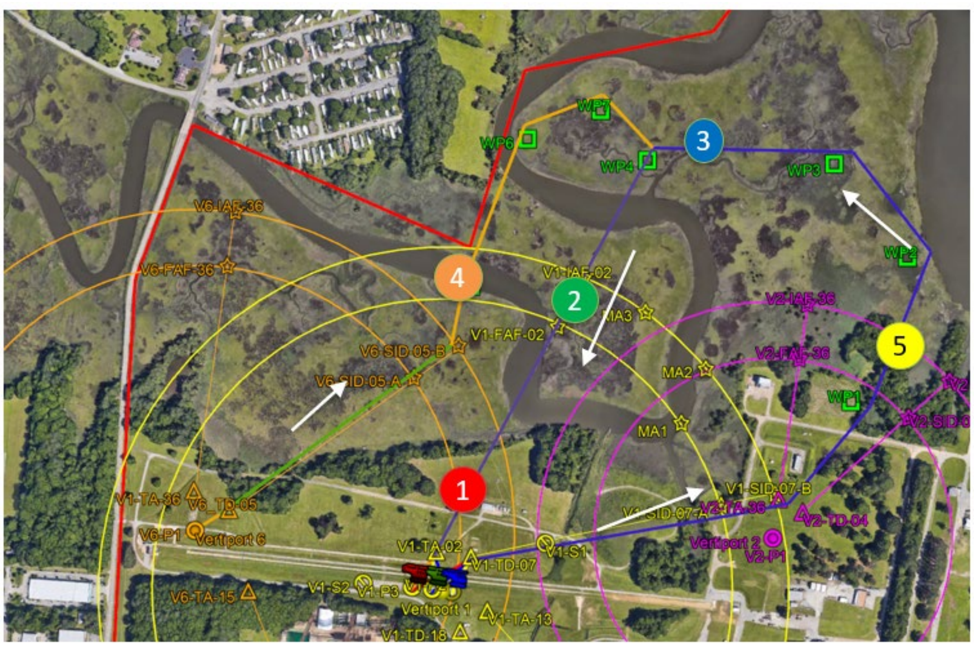

Figure 29 Scenario 1 routes

A summary of takeoff locations and landing locations for each vehicle is give in Table 2 below:

Table 2 Scenario 1 - Overview

Vehicle	Takeoff	Contingency	Landing
1	V1-P3	Nominal	V1-P3
2	V6-P1	Nominal	V1-P2
3	V1-P2	Nominal	V1-P1
4	V6-P1	Nominal	V1-P3
5	V1-P1	Nominal	V1-P2

The planned arrival times at vertiport 1 are spaced at 60 seconds. This provided each vehicle with a +/- 15 second window to land in while providing a 30 second separation gap between vehicles as shown in Figure 30 below where the x axis on the timeline is time difference from the first vehicles planned arrival, at T=0.

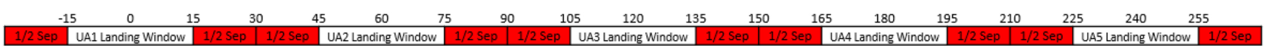

Figure 30 Scenario 1 Landing Times

An interaction diagram for the nominal scenario is shown in Figure 31. This starts with the GCSO requesting a timeslot. The fleet manager then creates the operation and submits it to the HDV client. The VAS then checks if the vertiport can support that operation (open departure/arrival slots). Once approved, the HDV client then creates the flight plan and notifies the GCSO who then uploads it to the vehicle. At the assigned takeoff time, the GCSO commands the vehicle to takeoff. Once airborne the operation is activated by the GCSO and telemetry data is sent to the HDV client to monitor the status of the flight and conformance. Once the vehicle reaches the IAF, the VAS is queried to approve the approach. Once at the FAF the VAS gives the clearance to land.

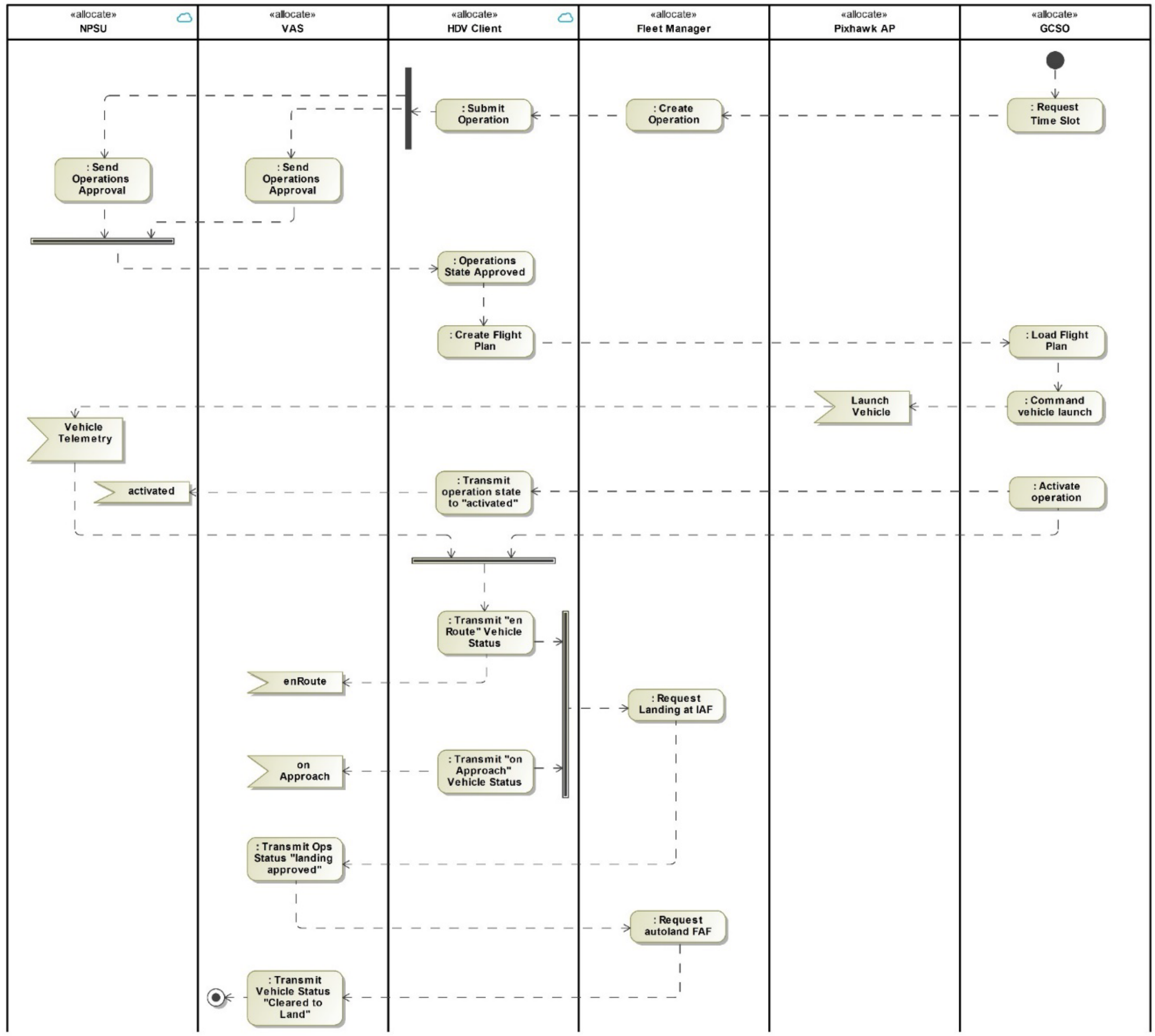

Figure 31 Nominal Scenario Interaction Diagram

5.3.2 Scenario 2 – Emergency Traffic resulting in a Missed Approach

Scenario 2 involves 2 to 3 vehicles flying the V1 to V1 route. A simulated medical emergency on vehicle #2 is conveyed by the flight test lead to GCSO 2. GCSO 2 then requests an earlier landing time. This occurs at a time where vehicle #1 has already passed the IAF and is on approach to land. This required the fleet manager to issue a command to GCSO 1 to perform a missed approach. Once this occurs, vehicle 2 is given the okay from the fleet manager to speed up for a newer arrival time. While vehicle 1 is on missed approach, it gets an updated arrival time and circles back in onto approach and lands. Vehicle 3 behind is unaffected.

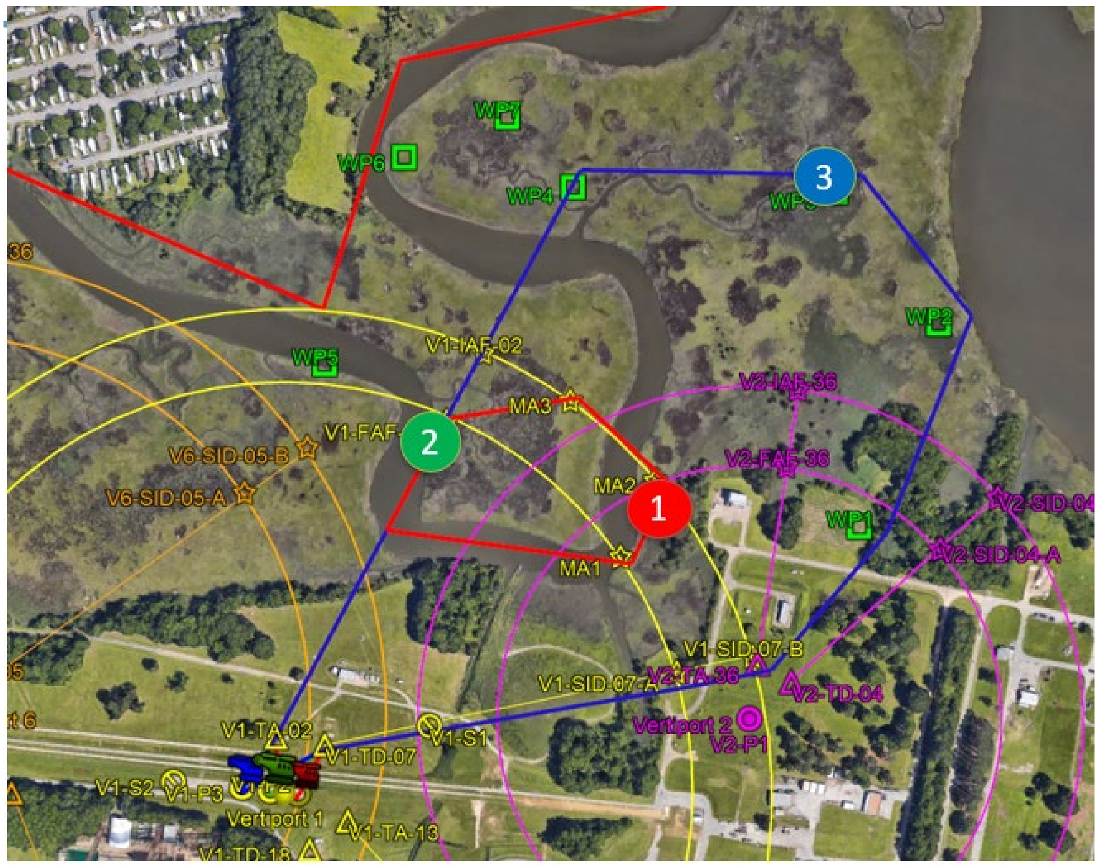

Figure 32 Scenario 2 Routes

Table 3 Scenario 2 overview

Vehicle	Takeoff	Contingency	Landing
1	V1-P3	Missed Approach	V1-P3
2	V1-P2	Speed up	V1-P2
3	V1-P1	Nominal	V1-P1

The landing times for the planned nominal mission, initial condition (IC), are shown below, as well as the expected landings times after contingencies are executed, ending condition (EC).

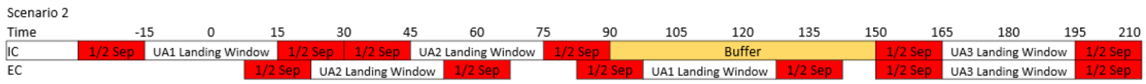

Figure 33 Scenario 2 landing times

The interaction diagram for this scenario is shown in Figure 34. This scenario runs per the interaction diagram from the nominal scenario with the added actions shown in the figure below. When the vertiport manager takes the action to close the vertiport, this then triggers to flow to the fleet manager who determines the impact to the operation. If a missed approach is required, that command is sent to the GCSO and executed on the vehicle. Once on missed approach, when at the FAF a new clearance is requested from the VAS, if approved the vehicle is cleared to reenter the approach and land.

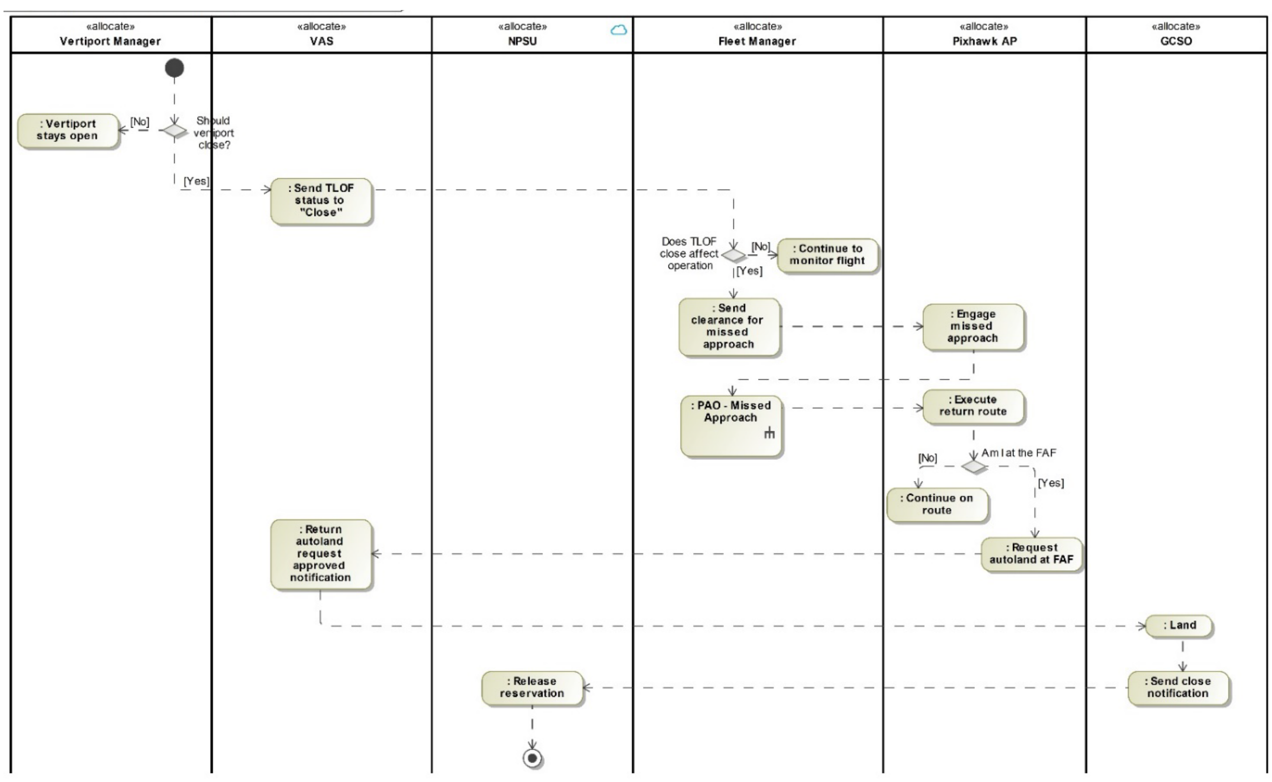

Figure 34 Missed approach interactions

5.3.3 Scenario 3 – Short Closure causing Arrival Delay

Three vehicles are flying V1 to V1 route. A minor delay causes the vertiport to close temporarily for 30 seconds. This shifts the arrival time of vehicle 1.

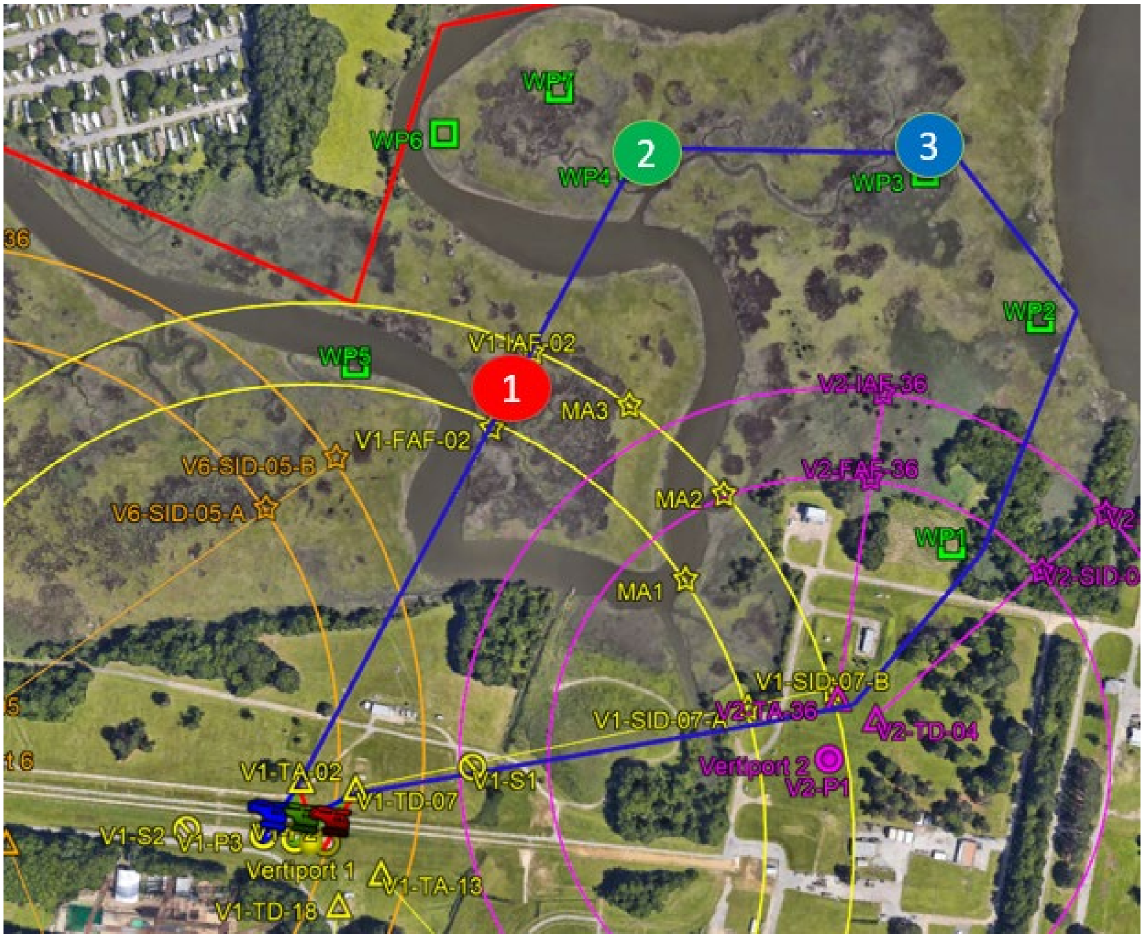

Figure 35 Scenario 3 Routes

Table 4 Scenario 3 overview

Vehicle	Takeoff	Contingency	Landing
1	V1-P3	Speed Change	V1-P3
2	V1-P2	Speed Change	V1-P2
3	V1-P1	Nominal	V1-P1

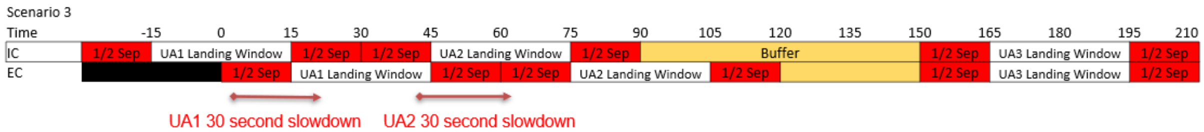

Figure 36 Scenario 3 landing timing

The interaction diagram for an arrival time change is shown Figure 37. This scenario initially follows the nominal scenario interaction diagram until the vertiport manager requested a TLOF closure which triggers the interactions in the diagram below. In this case the GCSO receives a new arrival time which is sent to the fleet manager who determines a new speed to arrive at the new time. The GCSO then executes that speed change command and arrives at the FAF at the newly planned time and gets approval to land.

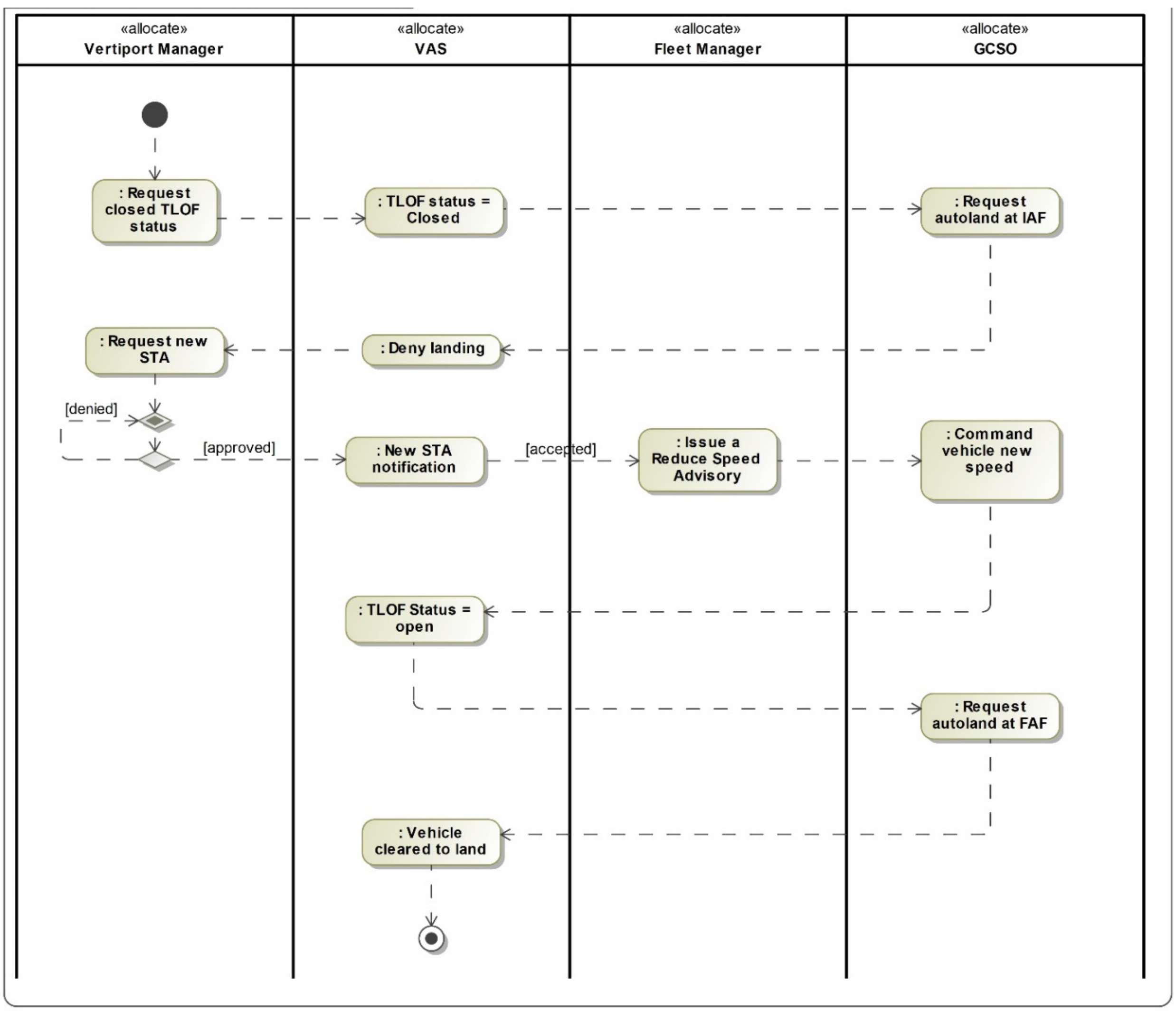

Figure 37 Arrival time shift interaction diagram

5.3.4 *Scenario 4 – Moderate Closure causing Diverts*

Three vehicles flying V1 to V1 route. A more significant delay causes vertiport 1 to close for 3 minutes or more. Vehicles 1 and 2 divert to Vertiport 6.

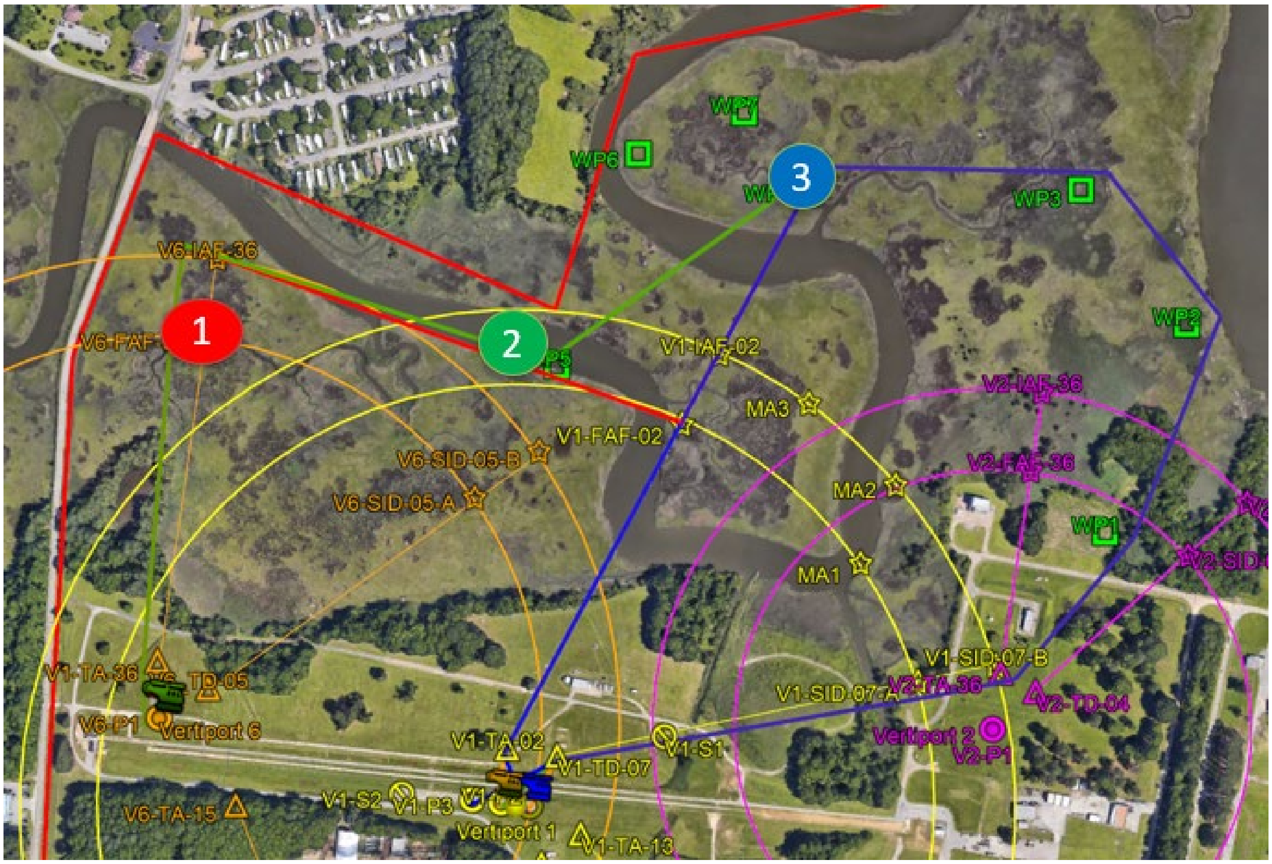

Figure 38 Scenario 4 routes

Table 5 Scenario 4 overview

Vehicle	Takeoff	Contingency	Landing
1	V1-P3	Divert	V6-P1
2	V1-P2	Divert	V6-P1
3	V1-P1	Nominal	V1-P1

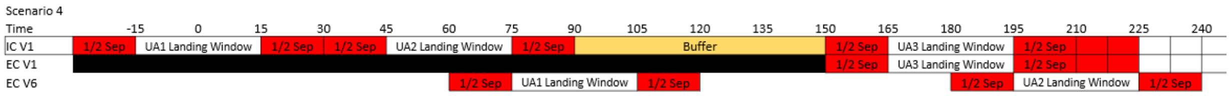

Figure 39 Scenario 4 landing timing (at vertiport 1 and vertiport 6)

The divert interaction is shown in Figure 40. In this scenario, when the vertiport manager closes the vertiport and the arrival time slot is removed, the fleet manager must decide on a new route option to go elsewhere. In this case they invoke a trial planning feature which determines options for reroutes. The fleet manager then selects an option, for example to land at vertiport 6. This new route then gets submitted to the VAS for vertiport 6 which approves or denies the planned operation. Once approved, the new flight plan is sent to the GCSO to upload to the vehicle and execute.

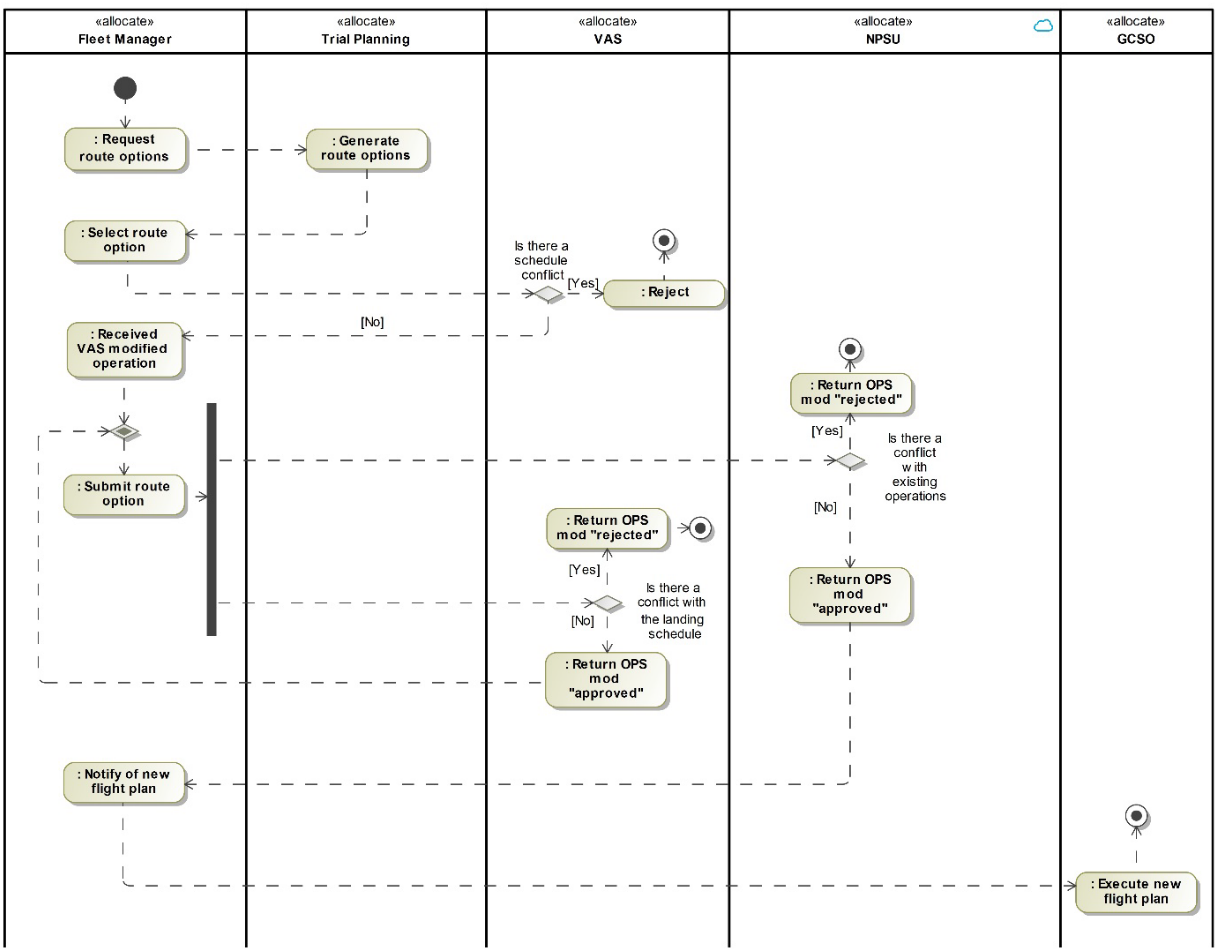

Figure 40 Divert interaction diagram

5.3.5 Scenario 5 – Significant Closure resulting in Multiple Actions

Up to four vehicles flying V1 to V1 route, also possible to run this with only the first 3 vehicles (for HF data collection). The vertiport is closed for an emergency vehicle (simulated) to land at the vertiport and pick up a patient to take to a hospital. This requires a long duration closure of the vertiport. This event occurs as vehicle 1 is on approach so it must execute a missed approach. Vehicle 1 then along with Vehicle 2, divert to Vertiport 6. Vehicles 3 and 4 slow down.

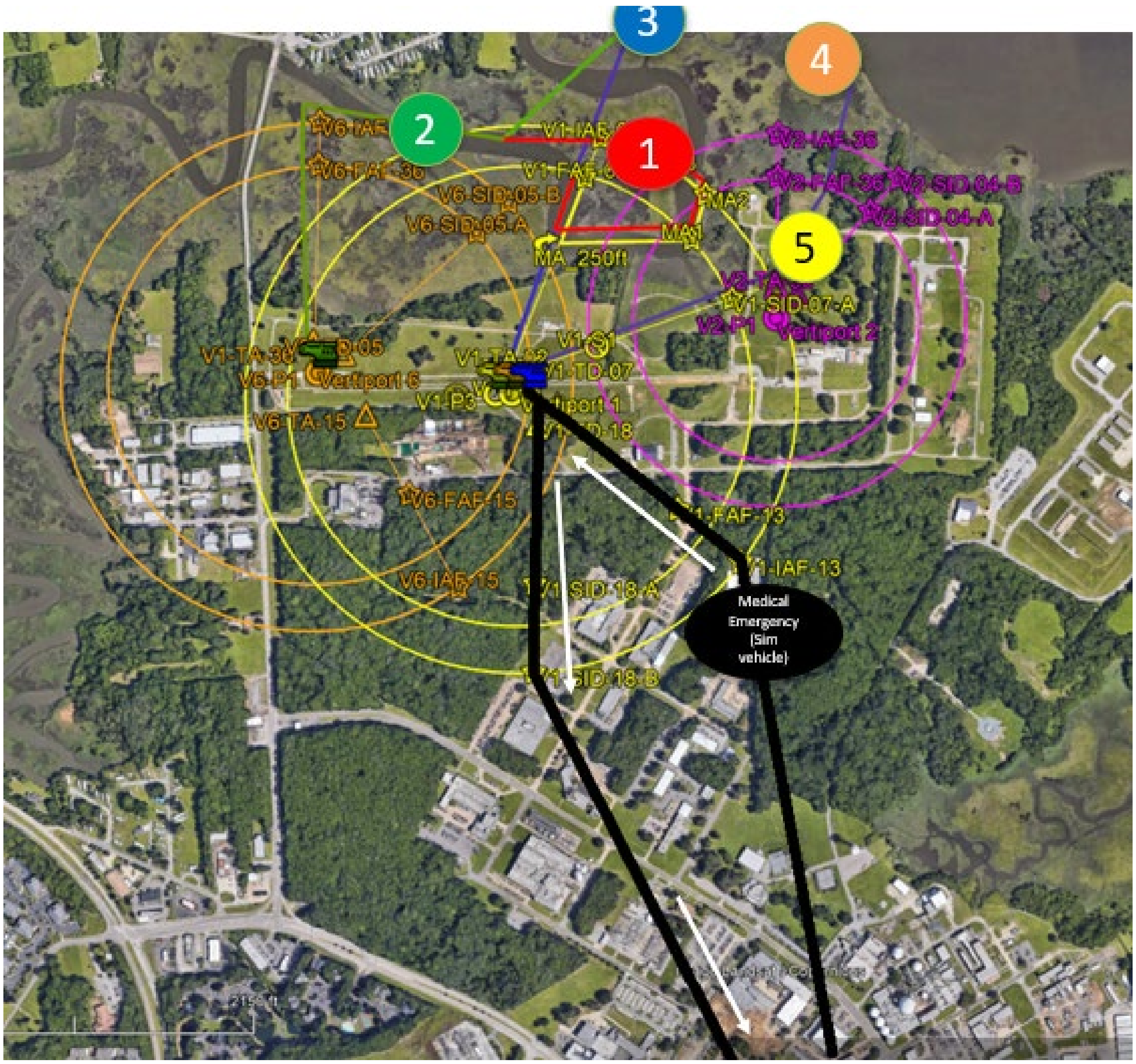

Figure 41 Scenario 5 routes

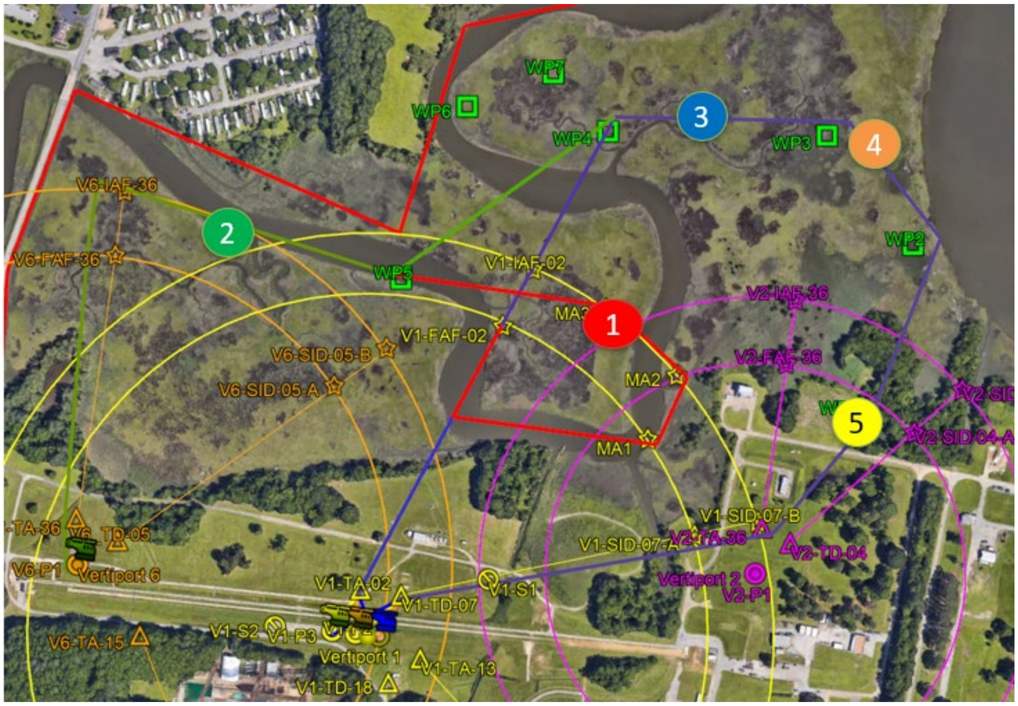

Figure 42 Scenario 5 ownship routes

Table 6 Scenario 5 overview

Vehicle	Takeoff	Contingency	Landing
1	V1-P3	MA + Divert	V6-P1
2	V1-P2	Divert	V6-P1
3	V1-P1	Speed Change	V1-P1
4	V1-P3	Speed Change	V1-P3

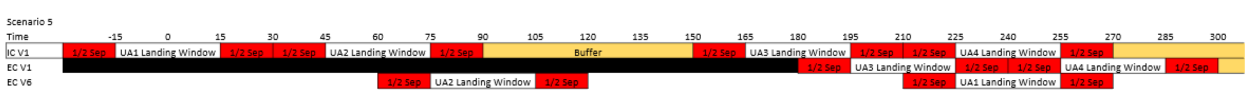

Figure 43 Scenario 5 landing times

The interaction diagram for this scenario is given in Figure 44. In this scenario when the vertiport manager closes the TLOF for an extended period of time, it may trigger multiple interactions from the previous scenarios for speed changes, missed approaches, or diverts. Depending on the action required for each of the vehicles impacted by the closure, the interaction diagrams from scenarios 2,3, and 4 will be executed depending on the type of action (ex. missed approach, divert)

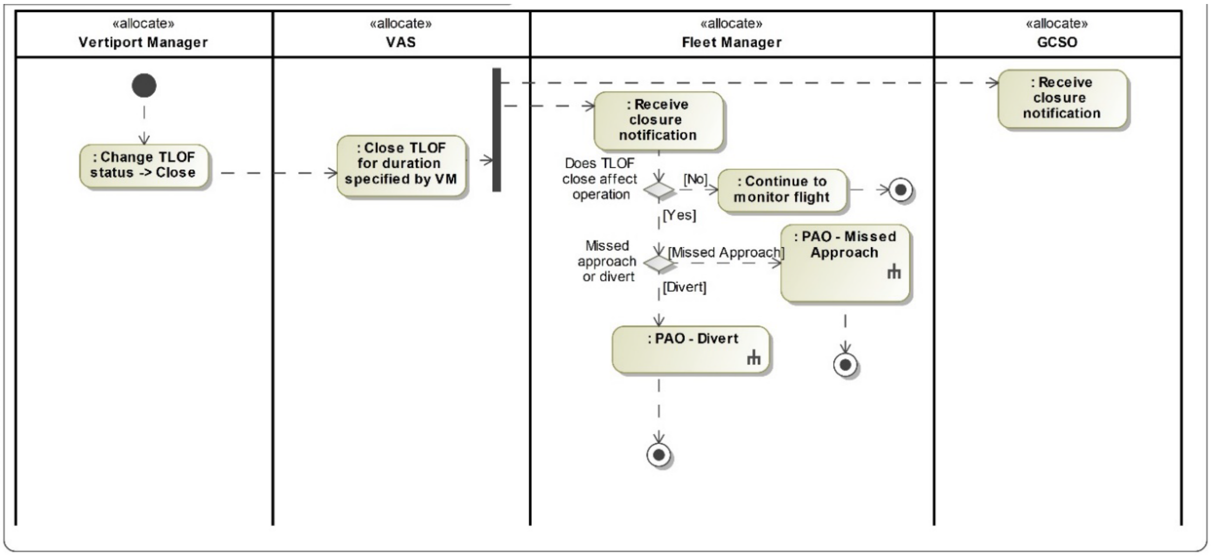

Figure 44 Multiple action interaction diagram

6. Flight Test Results

6.1 Overview

The flight tests occurred during May and June of 2023. During this time, a total of 81 individual flights were conducted over a total of 30 missions. Each mission involved flights of between 2 and 5 vehicles depending on the scenario and available crew. A total of 9 different ground control station operators were used as well as 4 vertiport managers and 3 fleet managers. Human factors data was collected on each of these individuals after each mission. A table of the missions is given below:

Table 7 Flight Test Summary

Run	Scenario	Date	UAS 1	GCSO 1	UAS 2	GCS0 2	UAS 3	GCSO 3	UAS 4	GCSO 4	UAS 5	GCSO 5	Vertiport Manager	Fleet Manager
Checkout	1	4-May	N559NU	GCSO-A	N557NU	GCSO-B							FTL	FM-A
1	3	10-May	N559NU	GCSO-A	N557NU	GCSO-B							FTL	FM-A
2	2	10-May	N559NU	GCSO-A	N557NU	GCSO-B							FTL	FM-A
3	2	10-May	N559NU	GCSO-A	N557NU	GCSO-B							FTL	FM-A
4	4	11-May	N559NU	GCSO-A	N557NU	GCSO-B							FTL	FM-A
5	4	11-May	N559NU	GCSO-A	N557NU	GCSO-B							FTL	FM-A
6	1	11-May	N559NU	GCSO-A	N557NU	GCSO-B							FTL	FM-A
7	3	16-May	N556NU	GCSO-A	N557NU	GCSO-C	N559NU	GCSO-D					VM-A	FM-A
8	2	16-May	N556NU	GCSO-A	N557NU	GCSO-C	N559NU	GCSO-D					VM-A	FM-A
9	4	17-May	N556NU	GCSO-A	N557NU	GCSO-C	N559NU	GCSO-D					VM-A	FM-A

10	1	17-May	N556NU	GCSO-A	N557NU	GCSO-C	N559NU	GCSO-D					VM-A	FM-A
11	5	17-May	N556NU	GCSO-A	N557NU	GCSO-C	N559NU	GCSO-D					VM-A	FM-A
12	3	23-May	N556NU	GCSO-E	N557NU	GCSO-F							VM-B	FM-B
13	2	23-May	N556NU	GCSO-E	N557NU	GCSO-F							VM-B	FM-B
14	4	24-May	N556NU	GCSO-E	N557NU	GCSO-F							VM-B	FM-B
15	1	24-May	N556NU	GCSO-E	N557NU	GCSO-F							VM-B	FM-B
16	5	24-May	N556NU	GCSO-E	N557NU	GCSO-F							VM-B	FM-B
17	5	25-May	N556NU	GCSO-E	N557NU	GCSO-F							VM-B	FM-B
18	5	25-May	N556NU	GCSO-E	N559NU	GCSO-F							VM-B	FM-B
19	5	25-May	N556NU	GCSO-E	N559NU	GCSO-F							VM-B	FM-B
20	1	6-Jun	N556NU	GCSO-A	N557NU	GCSO-B	N559NU	GCSO-C	N561NU	GCSO-D	N562NU	GCSO-E	VM-C	FM-C
21	1	6-Jun	N556NU	GCSO-A	N557NU	GCSO-B	N559NU	GCSO-C	N561NU	GCSO-D	N562NU	GCSO-E	VM-C	FM-C
22	1	8-Jun	N556NU	GCSO-A	N557NU	GCSO-B	N559NU	GCSO-C	N561NU	GCSO-D	N562NU	GCSO-E	VM-C	FM-C
23	1	9-Jun	N556NU	GCSO-A	N557NU	GCSO-B	N559NU	GCSO-C	N561NU	GCSO-G	N562NU	GCSO-E	VM-C	FM-C
24	1	9-Jun	N556NU	GCSO-A	N557NU	GCSO-B	N559NU	GCSO-C	N561NU	GCSO-G	N562NU	GCSO-E	VM-C	FM-C
25	2	9-Jun	N556NU	GCSO-A	N557NU	GCSO-B	N559NU	GCSO-C	N561NU	GCSO-G			VM-C	FM-C
26	3	9-Jun	N556NU	GCSO-A	N557NU	GCSO-B	N559NU	GCSO-C	N561NU	GCSO-G			VM-C	FM-C
27	3	13-Jun	N556NU	GCSO-G	N561NU	GCSO-H							VM-D	FM-C
28	2	13-Jun	N556NU	GCSO-G	N561NU	GCSO-H							VM-D	FM-C
29	1	13-Jun	N556NU	GCSO-G	N561NU	GCSO-H							VM-D	FM-C
30	1	14-Jun	N561NU	GCSO-B	N556NU	GCSO-I							VM-D	FM-C

The flight tests of each of the mission scenarios is discussed further in this section.

Of note, NASA 1 is the callsign used for the first live vehicle to takeoff, followed by NASA 2, NASA 3, NASA 4, and NASA 5. Tail numbers (N-Number of vehicle) and GCSO names or numbers were not used to keep radio communications simpler by using “NASA [1-5]” instead to communicate to the pilot manipulating the controls (PMC) of that vehicle (the ground control station operators).

6.2 Scenario 1 – Nominal Mission

The nominal scenario was flown 11 times with between 2 and 5 vehicles. The missions flown are described below as well as a discussion of key findings.

The initial checkout flight of the fully integrated system was flown with two vehicles running the nominal scenario 1. It was then flown with an increasing number of vehicles, ultimately achieving 5 vehicles. Due to crew limitations, the scenario was modified to have all vehicles takeoff from vertiport 1, instead of vehicle #2 and #4 taking off from vertiport 6.

The five vehicle’s staging for run #24 at vertiport 1 on the three vertipads is shown below as vehicle 1 was taking off.

Figure 45 Five vehicle operation

Since this was a nominal mission, all 5 vehicles remained in their cleared airspace volume along the mission route as shown on the HDV client's map display in Figure 46.

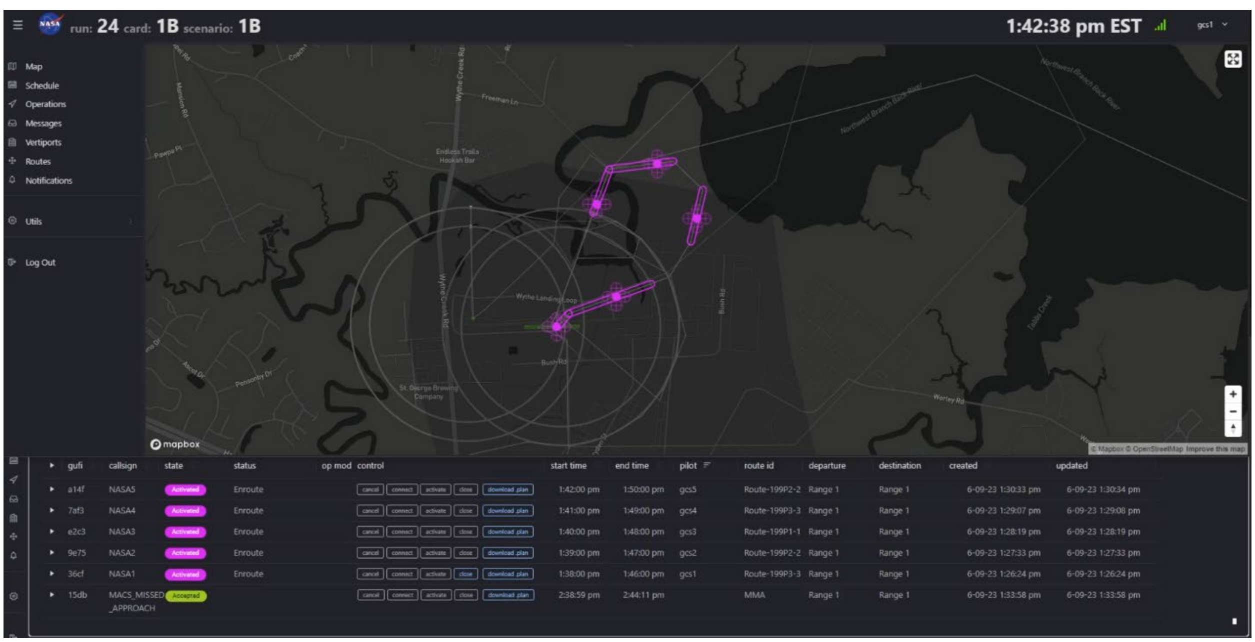

Figure 46 Five vehicle flight in HDV client

During the flight, each GCSO had situational awareness of the other vehicles through the HDV client map as well as the location of the other vehicles on their GCSO display a shown in Figure 47 below.

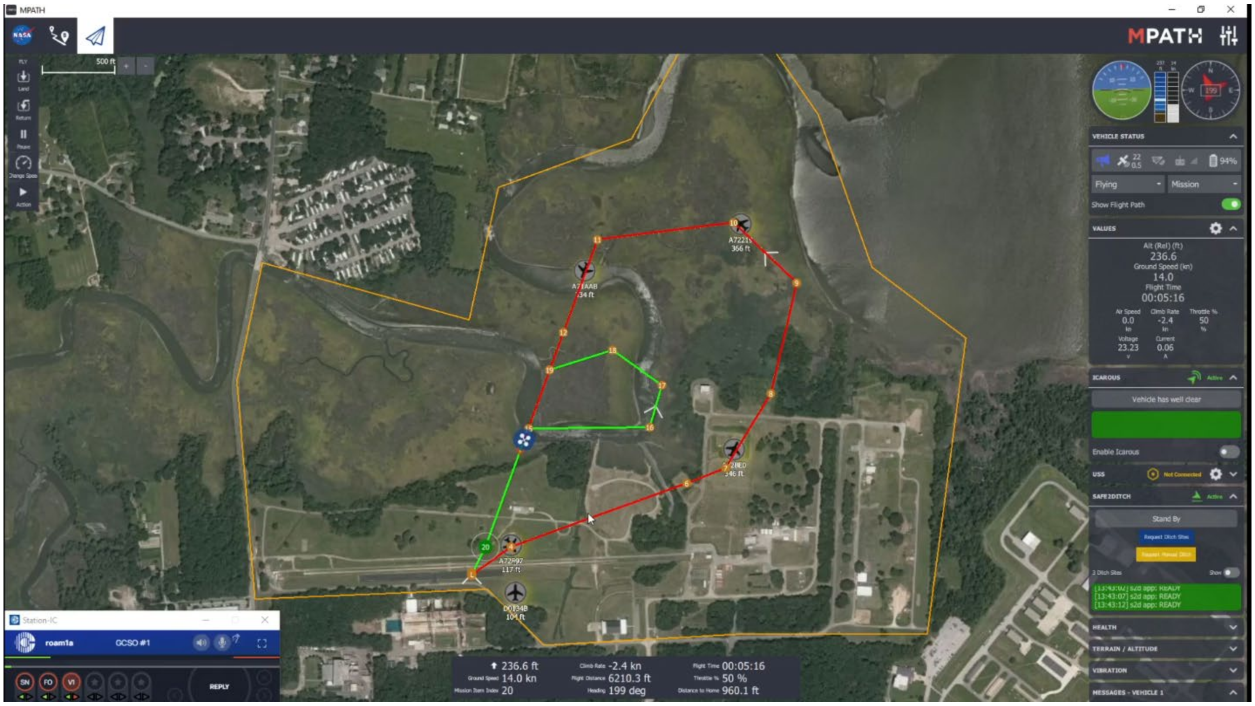

Figure 47 GCSO 1's display during 5 vehicle operation

During these missions, the capability to operate five vehicles simultaneously was proven out. The high rate temp of 60 ops/hr was also demonstrated by having a live vehicle land or takeoff every 60 seconds. With additional simulated traffic before and after the 5 live vehicles.

6.1 Scenario 2 – Emergency Traffic resulting in a Missed Approach

Scenario 2 was flown six times. Five of the six runs were completed successfully with one mission being called off due to a magnetometer warning preventing a vehicle from taking off.

The five successful runs of scenario 2 went as planned and had similar outcomes. Run #25 is described in greater detail here. This mission involved 4 vehicles.

For Run #25, the four vehicles took off at the following times with the planned arrival times in the table below:

Table 8 Run 25, Scenario 2 Departure/Arrival times

Callsign	Departure Time	Planned V1 Arrival Time
NASA 1	15:00	15:08
NASA 2	15:01	15:09
NASA 3	15:02	15:10
NASA 4	15:03	15:11

15:00 thru 15:03 – The 4 vehicles took off at their assigned takeoff times +/- 5 seconds

At approximately 4 minutes and 20 seconds into the flight, the contingency was initiated by the flight test lead.

15:04:20 - The Flight Test lead communicated to NASA #2 that there was an onboard emergency and instructed them to request they land immediately.

15:04:28 – NASA 2 makes a radio call to the fleet manager requesting expedited landing at vertiport 1.

At this time, the vehicles were located in the following positions shown in Figure 48.

Figure 48 NASA 2 declares an emergency

Since vehicle #2 declared an emergency and requested an earlier arrival time, that meant vehicle 1 had to give up its arrival time slot and give way to the emergency vehicle. Since it was already on approach at this point, just past the IAF, the option available to the fleet manager was to send it on missed approach and sequence them back in for a later arrival time.

15:04:40 – Fleet Manager verbally tells NASA 1 to execute a missed approach

15:04:44 – NASA 1 commands vehicle to fly missed approach route.

15:04:58 – Fleet Manager gives NASA 2 earlier arrival time.

15:05:02 – NASA 2 increases ground speed to meet new arrival time.

15:05:34 – NASA 1 while on missed approach route, the fleet manager issues a new arrival time slot of 15:09 (previously NASA 2's arrival time slot, that is now open).

15:06:40 - NASA 1 flies its newly approved route and rejoins the approach with a planned landing time of 15:09.

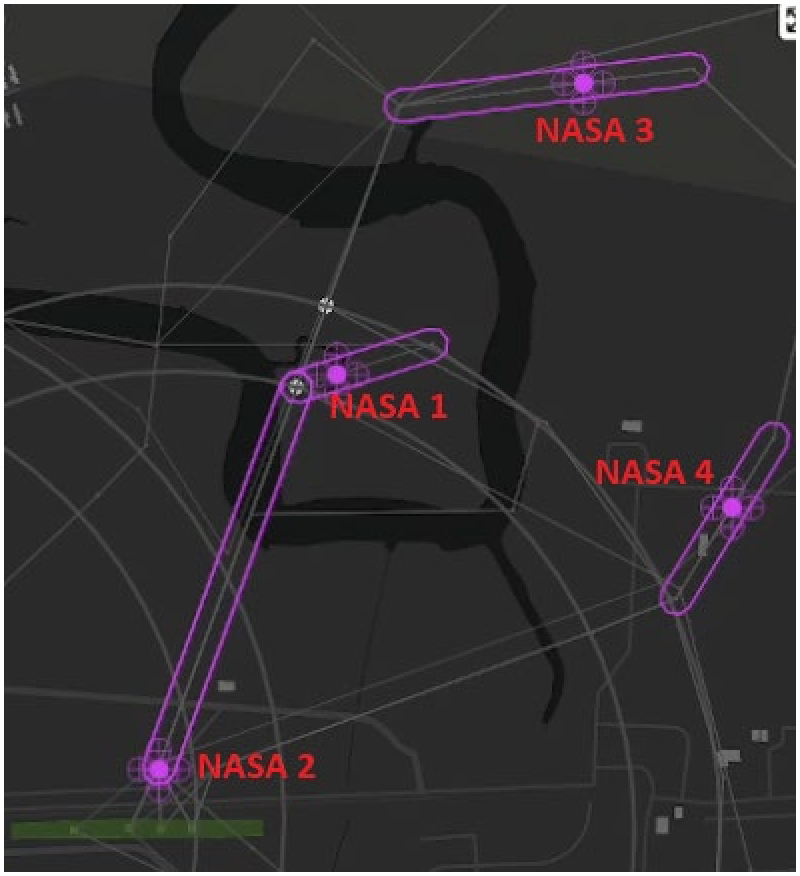

Figure 49 NASA 1 rejoining approach

15:07:50 – NASA 2 lands 1 minute 10 seconds earlier than its initial planned arrival time due to the emergency declaration and the fleet manager moving their time slot up.

15:08:50 – NASA 1 lands at vertiport 1 50 seconds behind the initial plan but 10 seconds before the newly updated arrival time which is within the expected buffer window.

NASA 3 and NASA 4 then land at their originally schedule landing times of 15:10 and 15:11 respectively.

Some of the major takeaways from this scenario were that the missed approach was executed effectively and the flow of information to determine the execution of the missed approach was effective. The verbal communication allowed for timely actions. In this case the fleet manager was acting as the focal point and decision maker and no interaction with the vertiport manager was necessary, just the fleet manager and the GCS operators.

6.2 Scenario 3 – Short Closure causing Arrival Delay

Scenario 3 was flown five times. Four of the five missions were successfully completed.

One mission was scrubbed because NASA 1's vehicle position was not showing up in the HDV client. So the fleet manager and vertiport manager had no situational awareness of NASA 1's position. This was traced back to an earlier issue on that mission where NASA 1 requested the wrong arrival time and had to request a new operation. In closing out the wrong arrival time operation for the correct one, the new mission was not activated in the HDV client.

The other four missions went as planned and the contingency scenario played out as expected. Run #26 is detailed below, which was a successful run of scenario 3 with four vehicles.

Initial planned mission takeoff and arrival times are given in the table below:

Table 9 Run 26 Scenario 3 Planned Departure/Arrival Times

Callsign	Departure Time	Arrival Time	Landing Location
NASA 1	04:10	04:17	V1 – Pad 3
NASA 2	04:11	04:18	V1 – Pad 2
NASA 3	04:13	04:20	V1 – Pad 1
NASA 4	04:14	04:21	V1 – Pad 3

Note: an open slot was pre-planned in between NASA 2 and NASA 3 which was used during the contingency.

The vehicles all took off at their assigned takeoff times.

04:13:49 - The Flight test lead notifies the Vertiport Manager for Vertiport 1 of a “simulated” hazard, an animal has run out onto Vertipad #3.

04:14:10 – Vertiport manager closes Pad 3.

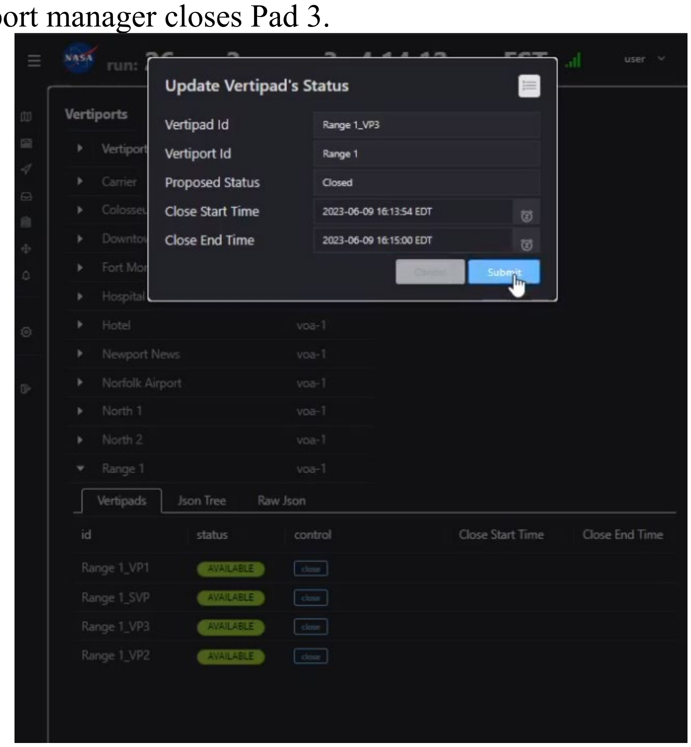

Figure 50 Vertipad closure

Vertiport 1 Pad 3 changes to a closed status in the HDV Client and notifies operators of a mission requiring replanning.

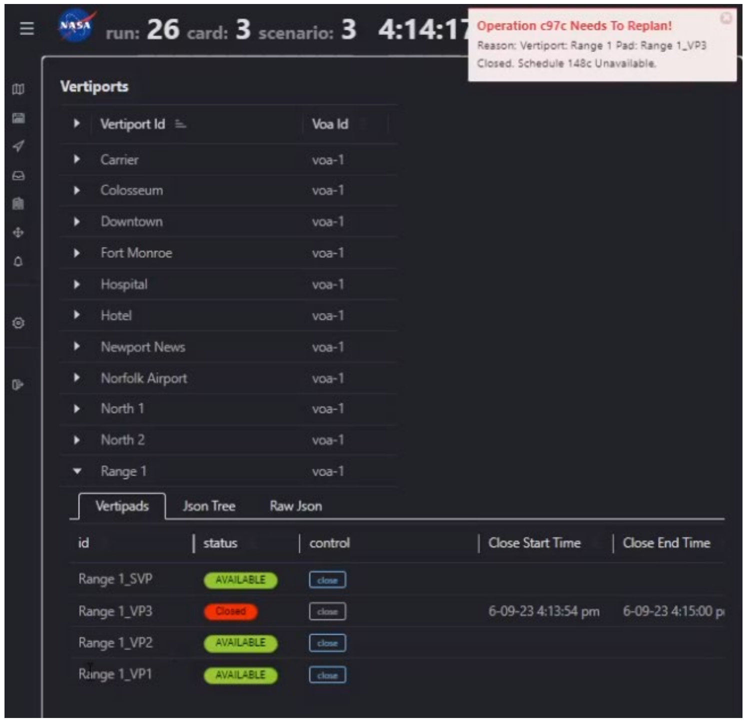

Figure 51 Arrival time no longer available, replan required

04:14:24 – Fleet manager notifies NASA 1 to slow down to 10 kts to adjust to a new landing time of 4:18 (1 minute later than initially planned).

04:14:28 – NASA 1 slows vehicle to 10 kts (from 14 kts)

04:14:34 - The flight test lead notifies the Vertiport Manger the hazard has moved to Vertipad #2

04:14:41 – The vertiport manager closes Vertipad #2 and allows Vertipad 3 to reopen at 04:15:00.

04:14:45 – Fleet manager notifies NASA 2 to slow down to 10 kts to adjust to a new landing time of 4:19 (1 minute later than initially planned).

04:15:00 – Vertiport 1 Pad #3 reopens

04:16:00 – Vertiport 1 Pad #2 reopens

04:17:54 – NASA 1 lands (54 seconds after initial planned arrival time, 6 seconds before updated arrival time)

04:18:51 – NASA 2 lands (51 seconds after initial planned arrival time, 9 seconds before updated arrival time)

Table 10 Run 26 Scenario 3 Planned and Actual Arrival Times

Callsign	Departure Time	Planned Arrival Time	Adjusted Arrival time in flight	Actual Arrival Time

NASA 1	04:10	04:17	04:18	04:17:54
NASA 2	04:11	04:18	04:19	04:18:51
NASA 3	04:13	04:20	04:20	04:19:51
NASA 4	04:14	04:21	04:21	04:21:02

Some key findings from scenario 3 are that the shifting of arrival times and executing speed changes went as planned. The flow of information through the HDV client was effective. The vertiports closing of the vertipads resulted in the fleet manager taking action and then giving commands to the GCS operators. The vehicles were able to change speed and hit their new arrival times demonstrating the capability to replan due to a contingency at the vertiport.

One additional finding is the need to have contingency buffers built into the schedule. When NASA 1 and 2 had to slow down, they shifted their arrivals into an empty slot at the vertiport. If a full schedule of arrivals with no openings was occurring at the vertiport, vehicles would have needed to divert, even for small delays like this. Thus the vertiport scheduling should include some amount of buffer to allow for minor contingencies.

6.3 Scenario 4 – Moderate Closure causing Diverts

Scenario 4 was run 4 times. It was run three times with two vehicles and once with three vehicles.

During the first run of scenario 4, (run #4), the divert path took the vehicle closer to the trees than planned due to a bug in the code generation of the divert plan file. While the vehicle had clearance, the safety pilot was uneasy about the separation and called a “knock it off.” All operators paused their vehicles and were then sequenced back in for landing at the direction of the flight test lead.

The mission was attempted again on run #5, with a modification of using a predesigned divert plan rather than using the divert plan generated by the trial planner and passed to the GCSO through the HDV client. The GCSO had a divert plan pre-saved on their desktop that they could load in real-time.

After this run, the issues were resolved with the generation of the divert plan and on Run #9 the scenario was attempted again and was carried out successfully. On this run, three vehicles were used. All vehicles took off from Vertiport 1 with planned landings at Vertiport 1.

13:00:00 – NASA 1 takes off from vertiport 1 with planned landing at Vertiport 1 Pad 3

13:01:00 – NASA 2 takes off from vertiport 1 with planned landing at Vertiport 1 Pad 2

13:02:00 – NASA 3 takes off from vertiport 1 with planned landing at Vertiport 1 Pad 1

13:04:30 – The flight test lead notified the vertiport manager of an issue at the vertiport requiring pad 3 to be closed for 2 minutes. The Vertiport manager closes vertiport 1 pad 3.

13:04:34 The fleet manager is notified of a mission requiring replanning (NASA 1’s arrival at Vertiport 1 pad 3)

13:05:01 – The fleet manager successfully finds a slot at Vertiport 6 and sends a divert command to NASA 1’s ground control station operator.

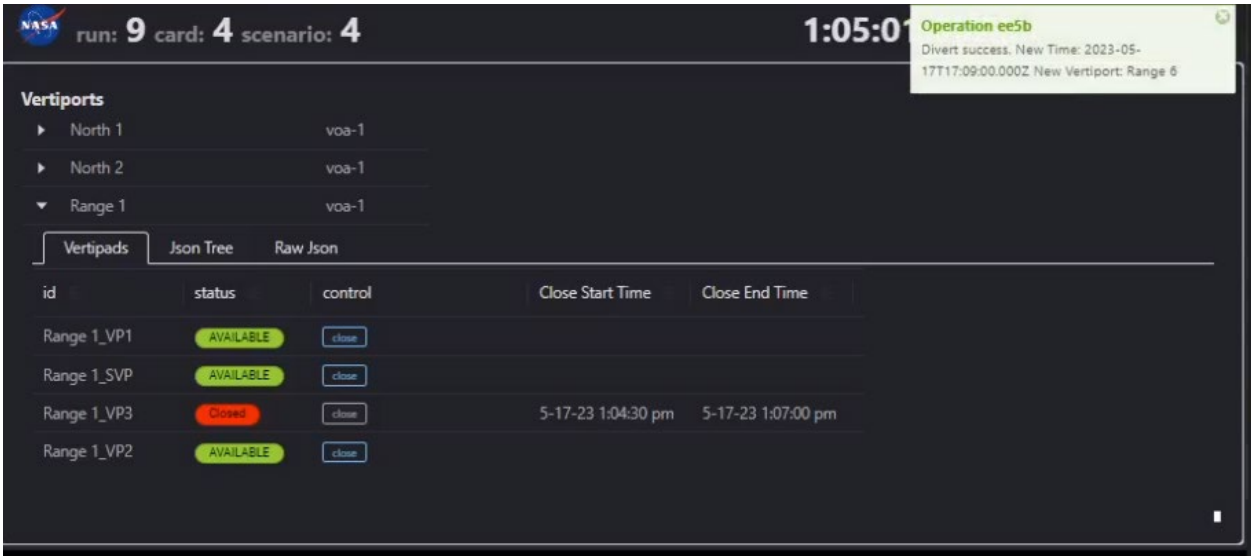

Figure 52 Divert Replan Successful

13:05:24 – NASA 1 uploads the new divert plan to the vehicle and sends the vehicle to fly it.

Figure 53 Divert Route to Vertiport 6

13:06:20 – The flight test lead notified the vertiport manager of an issue at the vertiport requiring pad 2 to be closed for 2 minutes. The Vertiport manager closes vertiport 1 pad 2.

13:06:24 The fleet manager is notified of a mission requiring replanning (NASA 2's arrival at Vertiport 1 pad 2)

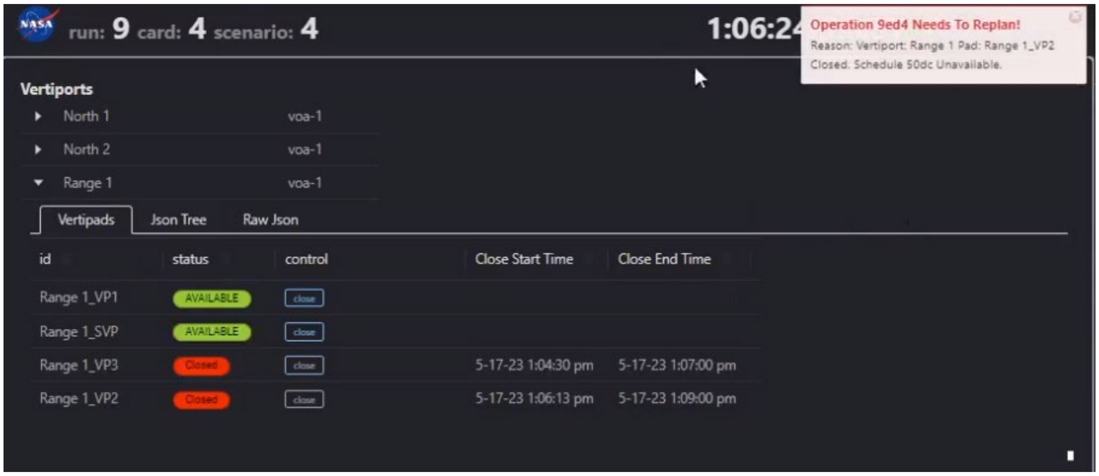

Figure 54 Vertipads closed, NASA 2 require replan

13:06:37 – The fleet manager successfully finds a slot at Vertiport 6 and sends a divert command to NASA 2's ground control station operator.

13:07:58 – NASA 2 begins flying divert plan to vertiport 6

NASA 1 goes on to land at vertiport 6, while NASA 2 is also diverting to vertiport 6.

Of note is that the time required to execute the divert maneuver for NASA 2 took longer than planned. This resulted in their aircraft flying well behind their conformance volume. The conformance volume is the magenta box on the xTM display. In Figure 55, NASA 2 can be seen starting its divert from the approach into vertiport 1 to an approach into vertiport 6. Their conformance box is well ahead and is indicating they should already by on approach into vertiport 6 when they are actually just starting to divert over.

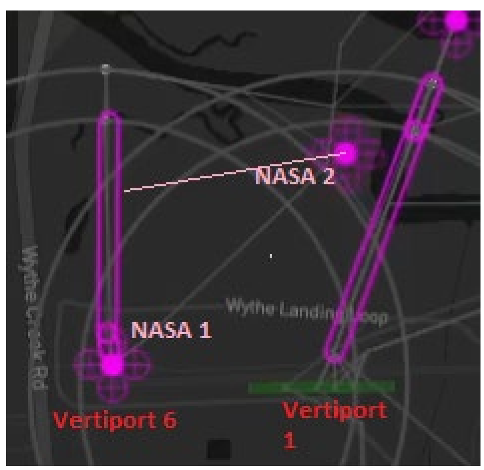

Figure 55 NASA 2 not in conformance volume of divert plan

This scenario was run one more time on run #14 and had similar results.

The key findings from this scenario was that the divert procedurally took a lot longer to execute than planned. The time it took for the fleet manager to divert the vehicle, and then the GCSO to load that divert plan and send the vehicle to another location took too long and often resulted in traffic conflicts with the vehicle behind them. More consideration on spacing must be made to account for the time it takes to execute the actions.

6.4 Scenario 5 – Significant Closure resulting in Multiple Actions

Scenario 5 was attempted five times with 4 being unsuccessful and one being partially successful. Success for this scenario was defined as all vehicles appropriately executing their contingencies and arriving at their scheduled location within 30 seconds of the scheduled arrival time, with no traffic conflicts mid flight with a loss of safe separations.

Scenario 5 was meant to be the most complex and the most taxing on the system. It involved a long closure at the vertiport resulting in multiple actions to multiple vehicles. This included closing the vertiport when NASA 1 was on approach resulting in having to execute a missed approach as well as then a divert.

On the first attempt at scenario 5, run #11, three vehicles took off from vertiport 1 nominally and were routed in to land back at vertiport 1. As NASA 1 was on approach, the vertiport was closed. This resulted in NASA 1 executing a missed approach. All three vehicles required replanning by the fleet manager due to their arrival slots at vertiport 1 being affected by the closure. While NASA 1 was flying the missed approach, the initial action by the fleet manager was to divert NASA 2 to vertiport 6. As shown below:

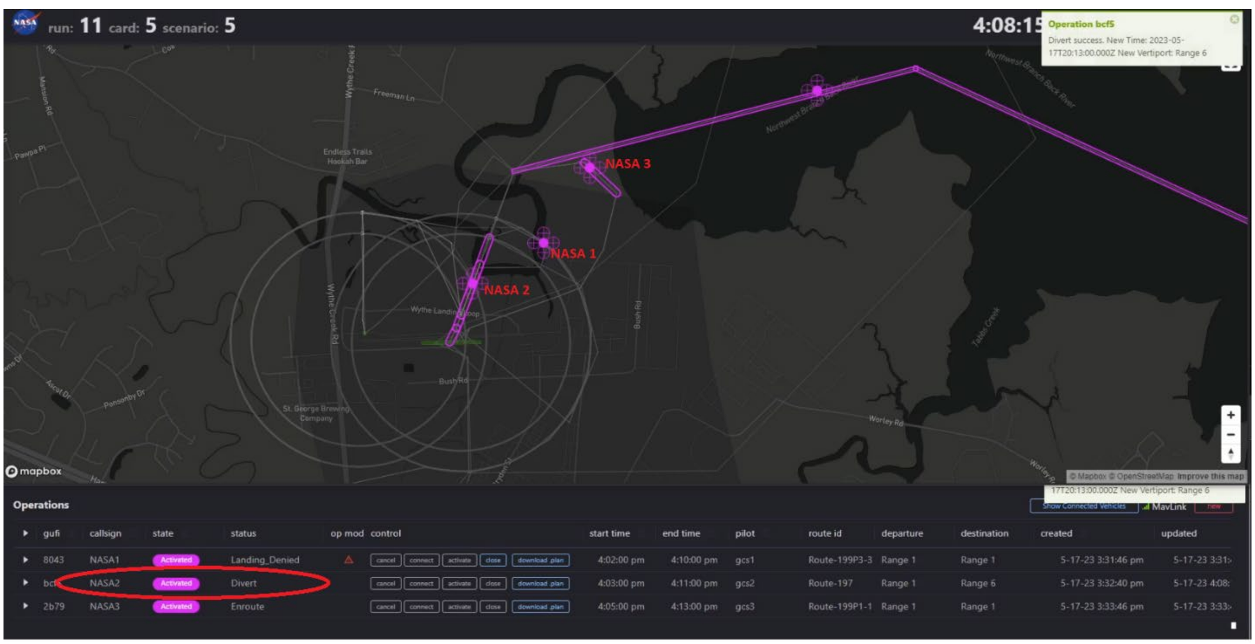

Figure 56 NASA 1 and NASA 2 positions shortly after closures

The GCSO for NASA 2 did not notice this action to divert and continued into vertiport 1.

The next action by the fleet manager was to divert NASA 1 to vertiport 6 as shown below in Figure 57:

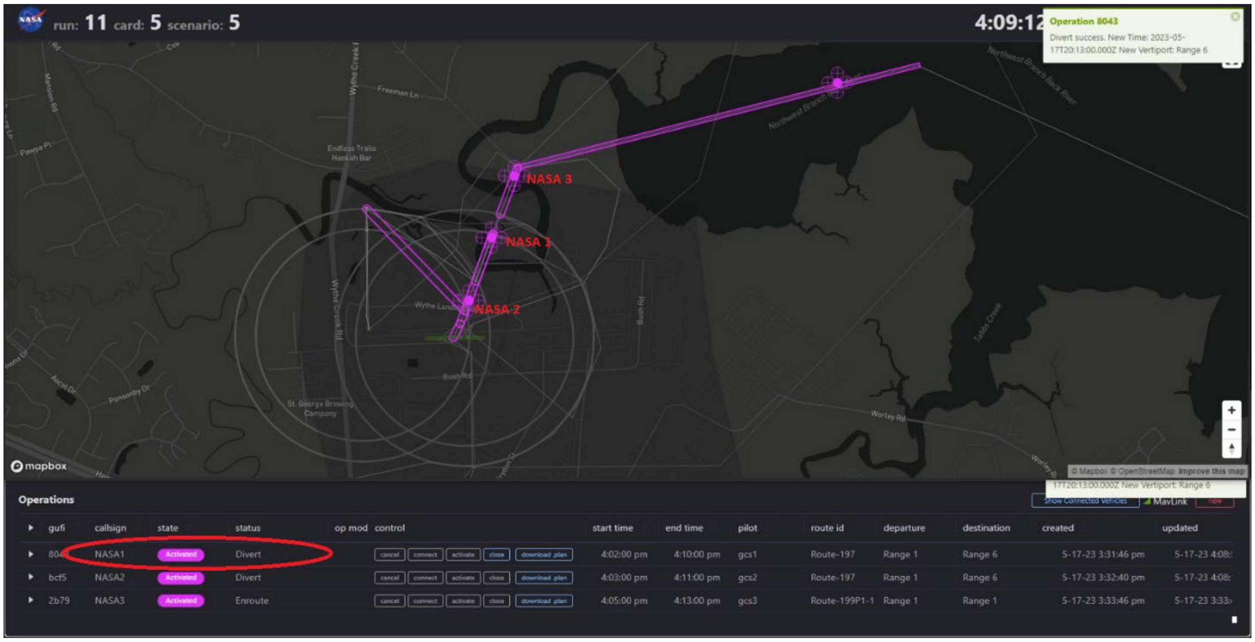

Figure 57 NASA 2 divert route

NASA 2, now at the bottom of the approach into vertiport 1 noticed the divert action from the fleet manager and paused their vehicle and started the divert to vertiport 6. This was occurring right as NASA 1 was about to also divert to vertiport 6. Since NASA 2 was so far off the planned route, they were about to divert to V6 and merge into the path of NASA 1 also diverting to V6. At this time the flight test lead called a knock it off and aborted the scenario as NASA 1 and NASA 2 were both turning and heading to the same point at the top of the approach for vertiport 6.

On the second attempt at scenario 5, run #16, the second vehicle did not takeoff due to a sensor calibration warning. The run was aborted and the vehicles were reset for another run.

On the third attempt at scenario 5, run #17, two vehicles were flown nominally. As NASA 1 was on approach, the vertiport manager closed the vertiport as planned and NASA 1 was sent on a missed approach. The fleet manager's initial action was to divert NASA 2 and let NASA 1 fly the missed approach and loop back around. The point at which NASA 2 was given the divert command was right at the IAF point. This resulted in them pausing their vehicle as they uploaded a new divert plan to vertiport 6. This took longer than expected and NASA 1 was beginning to circle back around. In Figure 58 below, NASA 2 is paused holding position as they work to upload a divert plan, right as NASA 1 is approaching. At this point the flight test lead called a "knock it off" and aborted the mission as the minimum safe separation distances were about to be breached. The primary reason for this was the longer time it took the GCSO for NASA 2 to execute the divert action, which likely indicated a longer buffer and spacing between vehicles is required.

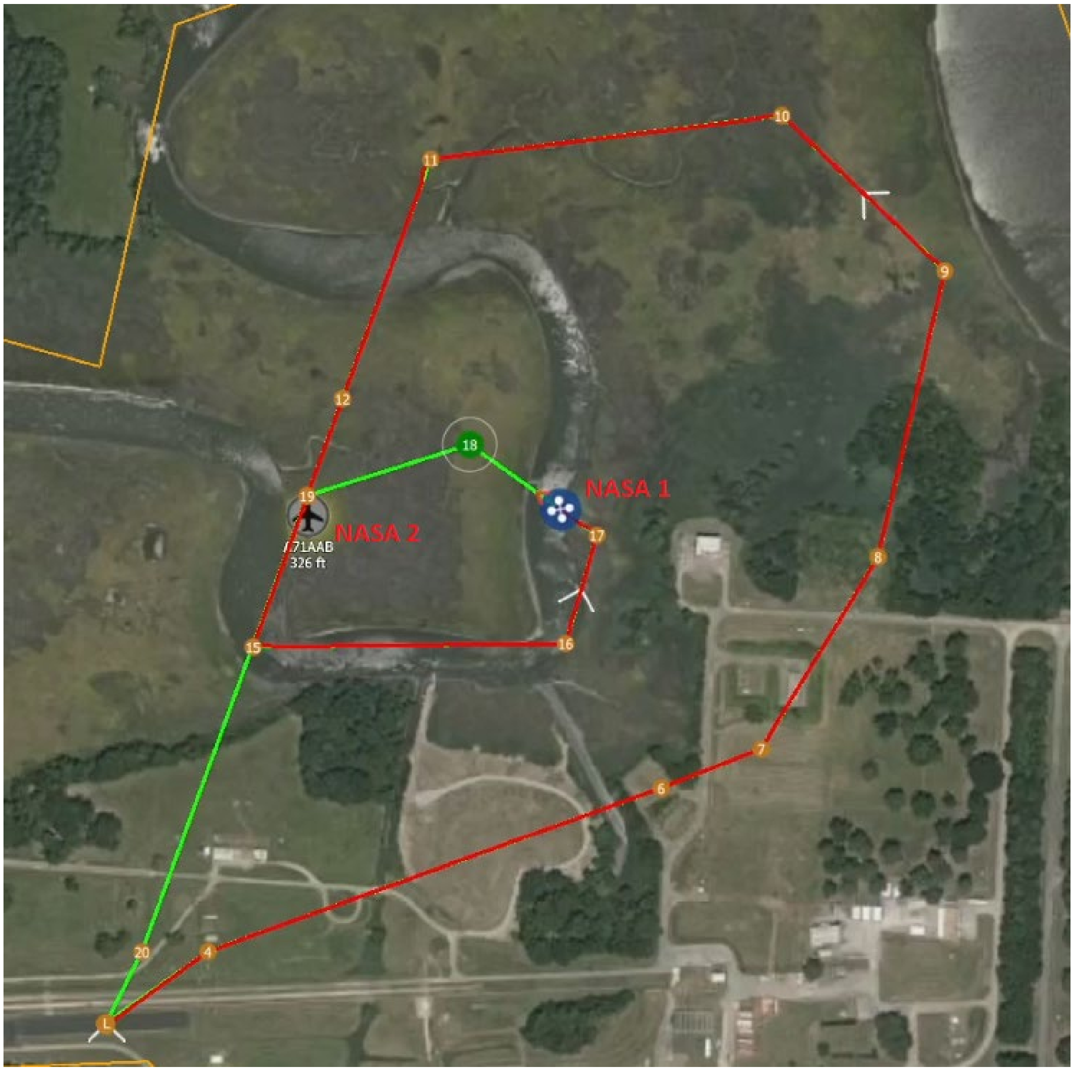

Figure 58 NASA 1 on missed approach headed towards NASA 2 holding position

On the fourth attempt at scenario 5, run #18, the second vehicle did not takeoff due to a sensor calibration warning similar to what occurred on run #16. The mission was continued for just NASA 1 which executed the missed approach and divert to a landing at vertiport 6.

Figure 59 NASA 1 completes missed approach route

Figure 60 NASA 1 is sent on divert route to Vertiport 6

On the fifth attempt at scenario 5, run #19, two vehicles partially successfully completed the mission.

The mission went as planned, NASA 1 executed a missed approach when the vertipads closed. The fleet manager diverted NASA 2 to Vertiport 6. The fleet manager then diverted NASA 1 to Vertiport 6 which resulted in a divert plan that was unexpected as shown below, where the first waypoint was extremely far east for an unknown reason.

Figure 61 NASA 1 divert plan to Vertiport 6

The divert plan took the vehicle far east for an unknown reason. NASA 1 noticed this occurring and changed course to skip ahead on the trajectory as shown below:

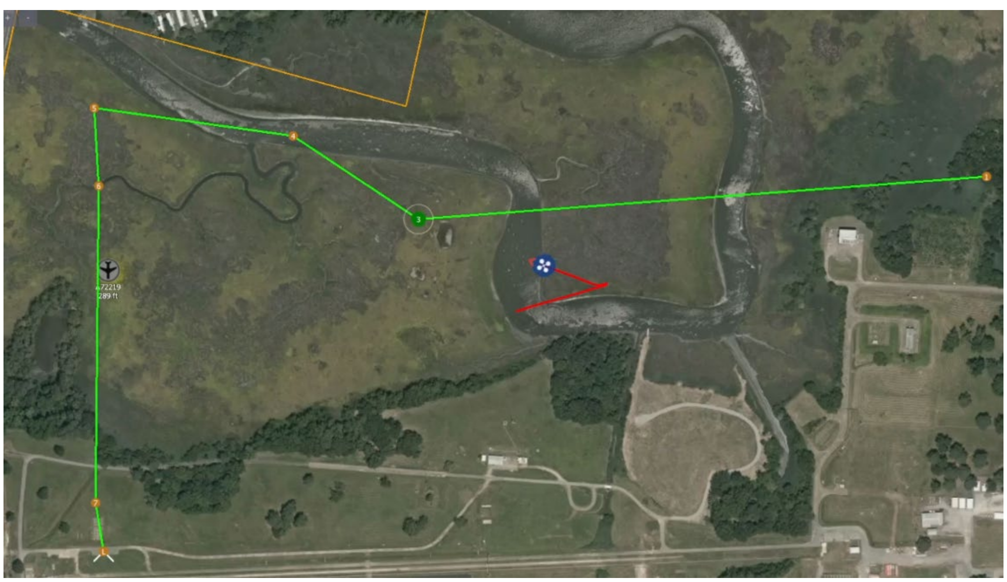

Figure 62 NASA 1 adjusted course to skip ahead on divert route

By NASA 1 skipping ahead on the divert trajectory, it resulted in them being within their conformance volume for the divert plan as shown below and resulted in them hitting their newly planned arrival time at Vertiport 6. So while the plan file that was generated for NASA 1 was in error, the arrival time and conformance volume was as expected, and by NASA 1 GCSO skipping ahead, they were able to get on their route and on schedule.

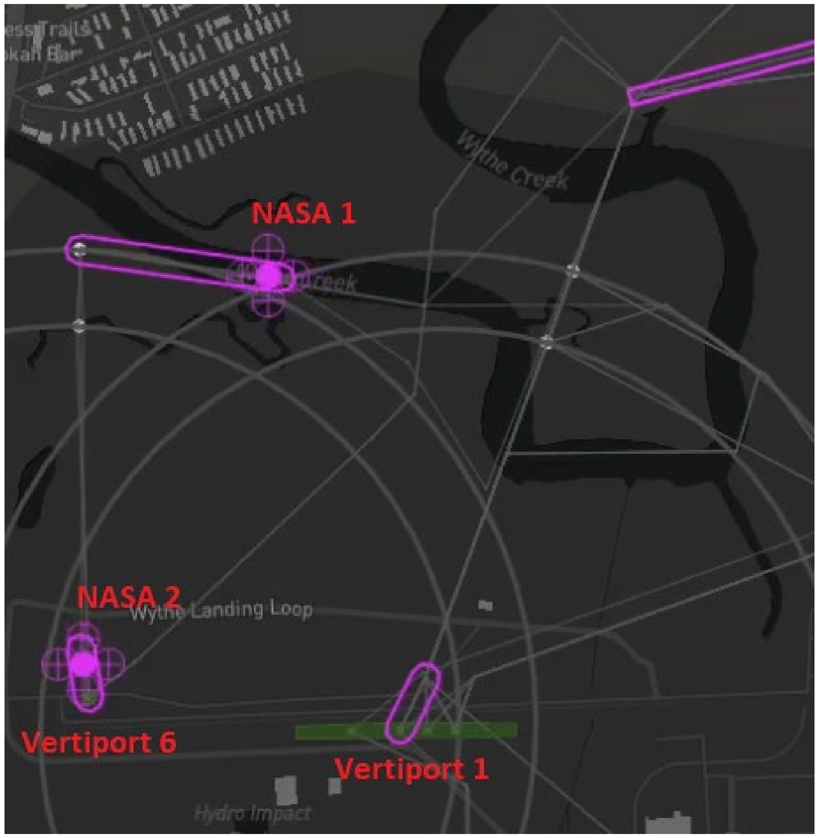

Figure 63 Conformance volumes for NASA 1 and NASA 2 on their diverts to Vertiport 6

The largest findings from this scenario are similar in nature to the ones from scenario 4 in which the divert action often took significantly longer than planned. When the fleet manager issues the divert action in the HDV client, it is often not immediately noticed by the GCSO, and in some cases such as attempt #1 of Scenario 5, a significant amount of time passed before it was realized that they needed to divert. Better cueing to the GCSO that they need to divert is needed, as well as likely more buffer in the schedule to allow the GCSO to do the actions required to send the vehicle on a divert route.

6.5 Human Factors Results

Usability human factors data were collected on the operators for the roles of GCSO, VM, and FM. As UAM operations are in their infancy, the corresponding research regarding roles, responsibilities, and task structures are limited and undefined. One strength of this data set was collecting valuable data on human cognition and performance within a high-fidelity operational environment. This research complied with the American Psychological Association Code of Ethics and received approval by the Institutional Review Board at NASA.

During the test missions, GCSOs, FMs, and VMs served as participants and completed several questionnaires about the five scenarios, including the NASA-TLX [21] , SART [22], and a Perceived Risk of Scenarios questionnaire, each given at the end of each scenario. Additionally, participants filled out a series of pre- and post-experiment questionnaires about their trust in the onboard automated systems, their workstations, and display elements based on prior research [23]. After the end of the experiment, participants filled out a system usability questionnaire on the HDV client [24]. In addition, researchers engaged in informal qualitative interviews with the participants.

6.5.1 Vertiport Manager

A detailed study of the Vertiport Manager role based on the human factors data collected during these tests is provided in ref [25]. The primary findings are listed below:

Insight 1: VMs need time to make decisions and time demand is a primary factor for vertiport management.

- Time demand and time pressure were one of the most frequently reported issues for the VMs

Insight 2: VMs require time progression information about an aircraft's mission state and their intent.

- One important goal for the VM was to verify that the current operations were going as expected. By a glance, the VMs wanted to know what an aircraft was intending to do, what vertiport it was going to, what vertipad it was scheduled for, and where the aircraft was on its mission path including a timer of when it was expected to land.

Insight 3: Role ambiguity and lack of training increased uncertainty and error.

- VMs received a quick brief about their role, task, and responsibilities as set by prior concepts of operations for a vertiport manager [15]. However, the VMs were not explicitly trained on their role. The ambiguity of their role in the operations and lack of training contributed to errors in monitoring, response time, and the omission or commission of incorrect interactions with their displays.

Insight 4: Trust and knowledge of the procedure helped the VMs manage uncertainty.

- The VMs relied on their knowledge of the procedures and intent of the aircraft to manage their uncertainty. For example, in one incident an aircraft was not descending as the VM expected it to do. But, when the VM realized the aircraft was performing a missed approach and intending to fly over the vertiport, they were able to determine if it was a threat requiring a closure of the vertiport or not.

Insight 5: Procedures, checklists, and training are required for determining separation, safety, and decision making.

- The VM is primarily a safety role. Their ability to serve as a resiliency factor within vertiport operations is reliant on their ability to notice errors when they occur and make appropriate and effective decisions. To make these decisions, they require a series of procedures and/or checklists that serve as the criteria for decision making. Additionally, training to build the VM's expertise in the operations and procedures could facilitate better performance in noticing anomalies and making better decisions.

Insight 6: Communication can support sensemaking for off-nominal events.

- When an off-nominal event occurred, the visual displays did not always provide information that could help a VM understand why it had occurred. VMs listened to the pilots' communications to improve their understanding of why the off-nominal events occurred and how the situation was going to unfold.

Insight 7: Communication between the VM and the GCSO can foster better coordination.

- VMs preferred the ability to communicate with a GCSO to coordinate mission efforts. In one scenario, a vehicle was set to land at a vertipad that had recently closed but was awaiting an imminent reopening. The GCSO engaged in a divert a few seconds before the vertipad reopened, an unnecessary action that would have been resolved through better communication.

Insight 8: VMs want the ability to close all vertipads within a vertiport at once.

- In the current setup, each vertipad had to be closed sequentially. However, there may be events where an entire vertiport must be closed at once and this closure is urgent, creating the need for a "close-all" button.

Insight 9: Providing additional vertipad states can provide useful information to the VM.

- VMs requested more information about the vertipad states outside of open and closed. Providing the VMs with additional states for each vertipad may offer useful information to help facilitate their sensemaking, decision making, and planning among other macrocognitive activities.

Insight 10: Vertiport and airspace monitoring without an active role can increase boredom and make the task more difficult.

- VMs reported maintaining attention was difficult and boring when their task was to monitor a nominal operation with no interactions. The addition of audio communications allowed them to become more engaged in the operations. Additionally, including more active monitoring features, such as marking traffic, was desired.

Insight 11: Understanding ground movements were of equal or greater priority to understanding air movements

- Low awareness for ground movements, personnel, and grounded aircrafts were one of the primary concerns for the VMs.

Insight 12: Different phases of the operation had different informational requirements, potential hazards, and response options to conflicts.

- Vertiport operations have different phases that can be categorized by factors such as spatial location to the vertiport, temporal demands of mission, and the state of the mission to list a few. Based on the vehicle's location within each phase of operation, the VM will sample different information and anticipate different hazards.

Insight 13: Monitoring and noticing both spatial and time separation is integral for vertiport operations.

- Two of the most important tasks reported by the VMs were to maintain an awareness of both spatial and temporal separation between the aircraft.

Based on the results of these tests, a simplified task model was developed and recommendations for the vertiport manager role are detailed in Reference [25].

6.5.1 Fleet Manager

A detailed analysis of the data collected in relation to the fleet manager role can be found in ref [16]. Some of the main findings are that the fleet manager typically had a higher situation awareness of the airspace and operations than the GCSO and VM. The vertiport managers had awareness of the vertiport, and the GCSOs each had awareness of their individual aircraft; however, the fleet manager has a higher level awareness of the entire fleet operation.

During the HDV testing, some communication was done digitally through the HDV client and others through verbal communication. Triggering a divert for example was communicated digitally through the HDV client were as a GCSO requesting an operation was done through verbal means. While verbal communication resulted in less workload and was less error prone than digital communication, there are scalability issues and thus the necessitates the drive towards digital communications. One key find in relation to this is given below:

"Analysis of operator communication exchanges indicated that the design of an interface-based communication platform must ensure that notifications are salient to the operators and persist long enough for them to respond. They should contain relevant information that is specific to the task the operator must complete and provide additional information once the task has been completed, or any follow-up steps that are required to complete the task." Ref [16]

Additional analysis on the Fleet manager and their interaction with the HDV client tool are given in Ref [16] as well as a discussion on the role of the fleet manager based on the implementation during HDV and limitation of that role. The HDV implementation of the fleet manager is likely a first iteration that needs to evolve further. The fleet manager likely will need additional tools to be able to operate on a M:N level and where they can replan multiple operations simultaneously or shift blocks of aircraft. Additional research is needed to further develop the concept of the fleet manager within the UAM ecosystem. The fleet manager is likely to evolve to be predominately supervisory in nature, even in the off-nominal events where autonomy is assisting the operator to reduce workload.

7. Conclusions

The High Density Vertiplex project successfully developed a UAM ecosystem prototype with representative vehicles, airspace management, ground control, fleet management, and a vertiport automation system. A comprehensive flight test campaign was completed using sUAS as surrogates for more expensive and less risk tolerant aircraft. Usability HF results were acquired for the UAM Ecosystem Prototype and the various envisioned operators.

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