High Density Vertiplex: Scalable Autonomous Operations Flight Test Overview

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The NASA High Density Vertiport project has completed a multi-aircraft flight test of a scalable autonomous vertiport prototype system. These tests included end to end system integration testing of hardware and software, operational procedure testing of defined roles and responsibilities within a vertiport environment, and human factors data collection. This paper provides an overview of the flight test setup , scenarios, and summary results.

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I. Introduction

The Advanced Air Mobility (AAM) concept is helping usher in a new age in aviation that holds the potential to change the way people commute, cargo is transported, public good missions are carried out, and many other aspects affecting 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. The High Density Vertiplex (HDV) sub-project is a part of NASA's Airspace Operations and Safety Program (AOSP) and currently part of the AAM project. HDV is tasked to develop, integrate, and assess autonomous technologies and architectures that support envisioned Urban Air Mobility (UAM) Ecosystem operations. 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 low risk surrogates for larger proposed UAM aircraft to accelerate the prototyping effort, ensure safety, and greatly mitigate costs. 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 [2]. Following this initial prototype, HDV performed multiple iterations of testing, including both simulated and live-flight operations, producing a number of novel findings and insights in the field of UAM [3, 4, 5, 6]. This paper will describe the operations under test, the test planning, and test results from the SAO flight test campaign.

II. Goals and Objectives

The goal of SAO for HDV is to develop and evaluate concepts, prototypes, procedures, and technologies supporting operations at high-density from a vertiport. From this goal, three objectives were derived which were:

1. Connect fleet management tools and airspace management services to UAS ground control stations.
2. Develop and test a vertiport automation system.
3. Demonstrate vehicle, airspace, and vertiport automation technologies supporting dense operations at a vertiport.

III. HDV Test Environment

In 2023, HDV conducted flights tests in support of its second phase called Scalable Autonomous Operations (SAO) that features a prototype 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 VAS and Vertiport Manager were also located within the ROAM facility controlling a prototype vertiport at the CERTAIN Range. 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 live and virtual flight operation tempos equivalent to 60 operations per hour, contingency scenarios were presented to the operations team, such as 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.

The execution of the HDV SAO flight test required three research facilities: 1) the ROAM UAS Operations Center at NASA Langley Research Center, 2) NASA Langley's CERTAIN test range and 3) the AOL facility at NASA Ames Research Center.

A diagram of the ROAM facility is shown below comprising of two rooms, one (ROAM I) for test management and airspace monitoring including a Flight Test Lead (FTL), a Range Safety Officer (RSO), Airspace Monitor (AM), Radar Operator (RO), a Vertiport Manager (VM), and a ROAM Operator. The second room (ROAM II) was for the Ground Control Station Operators (Fig. 1). ROAM I was equipped with six workstations, a forward videowall, and a communication system that supported the FTL, RSO, RO, VM and AM. The workstations provided each role displays they needed to perform their tasks including Integrated Airspace Displays (IAD), access to checklists and to the HDV client. The forward video wall allowed for each role to maintain situational awareness of the operation by providing workstation feeds from ROAM II, the IAD, the checklists of the current operation and test card information for the current run (Fig. 2). ROAM II supported up to five Ground Control Station Operators (GCSOs) connected to 5 sUAS vehicles via remotely connected 900 MHz transceivers and LTE cellular connections (Fig. 3). Communication between ROAM-I, ROAM-II, and field crew was maintained using a Clear-Com communication system, which provided seven channels for communication. The seven channels included a safety channel, a flight operations channel, and an individual channel for each GCSO. For an in-depth discussion of ROAM see Reference [7].

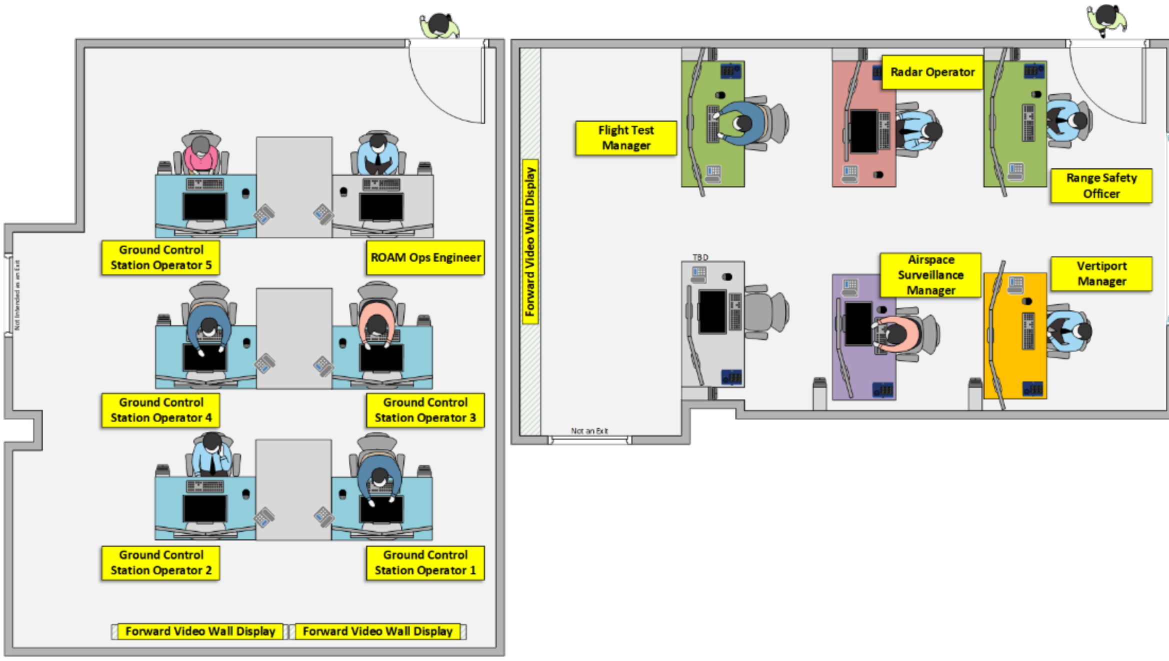

Fig. 1 Plan view diagram of ROAM Facility.

Fig. 2 ROAM UAS Operations Center (ROAM-I) during Flight Test Operations.

Fig. 3 Ground Control Station Operator within the ROAM UAS Operations Center (ROAM II).

An example configuration of the ground control station (GCS) is shown in Fig. 3. The GCS contained three monitors. The top left screen contained a communications display, any procedural checklists, and a testing display used to facilitate the test. The top right screen showed the HDV client interface, which has information on routing and scheduling information from the fleet manager. HDV client is a software prototype that is used for the various roles that interact with the traffic management functions for the test [8]. The bottom head-ups display showed the vehicle control application also known as the Measuring Performance for Autonomy Teaming with Humans (MPATH) GCS software. MPATH, seen in Fig. 4 is an application developed by NASA for controlling Micro Air Vehicle Link (MAVLink) enabled sUAS and is a modified version of QGroundControl [3].

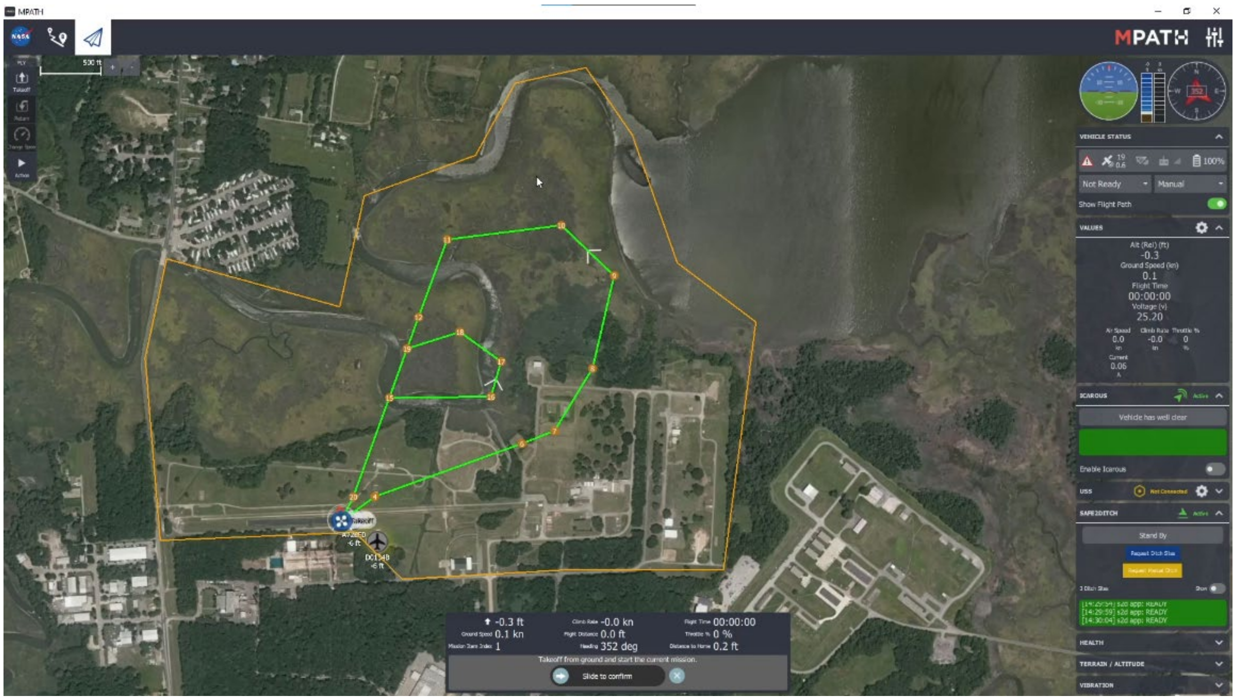

Fig. 4 MPATH Display

Another critical role within these operations was that of the VM. The VM within ROAM controlled up to three vertipads at the CERTAIN flight range. The VM's workstation contained three monitors displaying relevant information to facilitate the VM to monitor and manage their vertipads (Fig. 5). The left display contained a three-dimensional visual display of the vertiports operational area called UAS Mission Analysis Tool (UMAT) (Fig. 6). UMAT is a mission planning software tool that supports high accuracy 3D environmental modeling and geographic data visualization. The middle screen displayed a list of vehicle arrival and departure times and a live map displaying vehicle positions through the HDV client software (Fig. 7). In addition, they used the HDV client software to close and open the vertiport or specific vertipads and assign estimated times of closure. On the right screen, VMs monitored a live video feed of the vertipad, real-time weather display, and a testing display used to facilitate configurations and data collection tools.

Fig. 5 Example configuration of the Vertiport manager workstation.

Fig. 6 UMAT 3D Visual Display

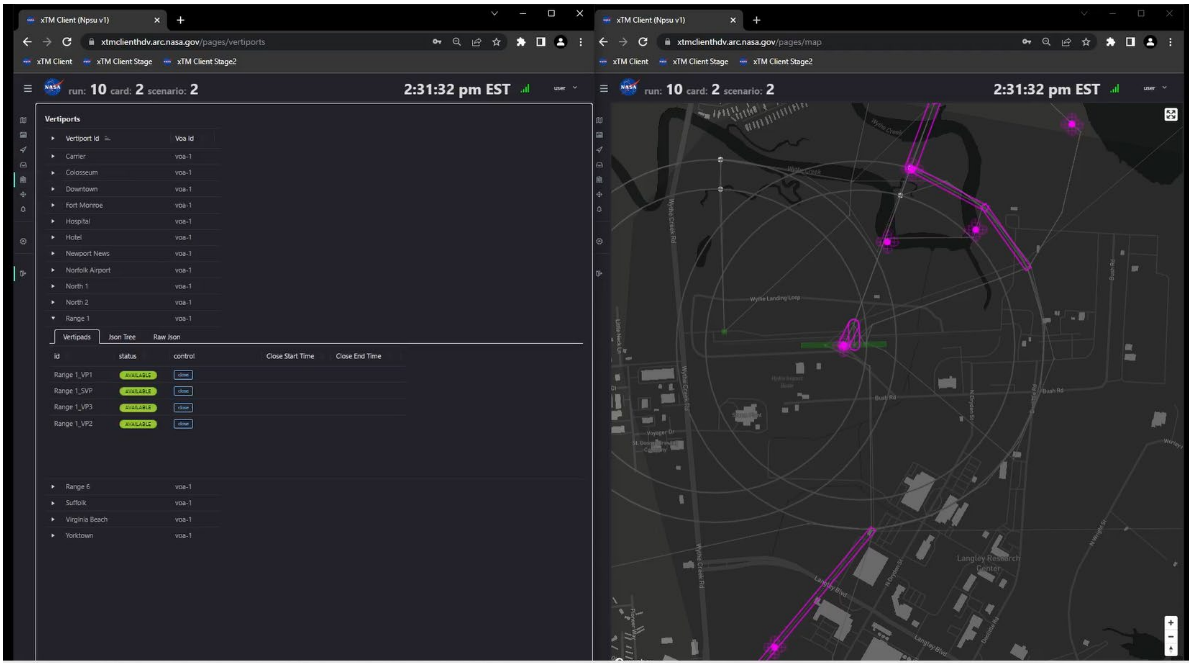

Fig. 7 HDV client display for vertiport managers.

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NASA Langley's CERTAIN test range is comprised of government property within Class D airspace (Fig. 8), intended for research flight testing activities. This airspace is utilized through a Certificate of Authorizations with the Federal Aviation Administration and a Letter of Agreements with Langley Air Force Base. Infrastructure has been established to support communications and monitoring of air operations. This equipment included airspace surveillance sensors, command and control radios, vertipad video, and radio communications for field personnel (Fig. 9).

Fig. 8 NASA Langley Designated Flight Range – CERTAIN.

Fig. 9 CERTAIN Flight Range and Infrastructure

The AOL lab at NASA Ames provided a location for the Fleet Manager (FM) to operate and interact with the GCSOs and VM [9] (Fig.10). The FM controlled the routing and scheduling of the vehicles. Through the HDV Client, each vehicle is assigned time dependent trajectory specification when their operation is assigned, which is visualized as volumes of airspace that they are scheduled to fly through at a specific period of time. This information is then passed back to the GCSO through the HDV Client and displayed at their station giving them the ability to monitor 4D flight path conformance.

Fig. 9 AOL facility located at NASA AMES Research Center

IV. Live and Simulated Vehicles

During operations, the goal was to test a high volume of traffic operations, with the objective being 60 operations per hour, at a vertiport. In this case, an operation is considered either a takeoff or a landing. To accomplish this goal, traffic was simulated at 60 ops per hour and 5 simulated vehicles were replaced with live vehicle flights. All operations were nominally equally spaced in time.

The live test vehicles were Alta 8 Pro multirotor vehicles (Fig. 11). The vehicles weighed about 30 lbs 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) [10] that provided autonomous detect and avoid (DAA) functionality along with Safe2Ditch [11] that provided emergency landing/contingency management capability. The resulting vehicle capabilities is considered to be technologically similar to envisioned UAM aircraft.

Fig. 11 Alta 8 Pro

V. Vertiplex Range

All flight tests were conducted at the CERTAIN range outlined in Fig. 12. Three prototype vertiports were established, Vertiport 1 (yellow), Vertiport 2 (purple), and Vertiport 6 (orange). Vertiport 1 was the primary vertiport used and is the vertiport that was managed by the VAS and Vertiport Manager (Fig. 13). For the SAO testing, the other vertiports were assumed empty and utilized for takeoffs and diverts depending on the test scenario. Each vertiport was developed for the following procedures: Take-Off, Outbound Taxi, Departure, Holding, Approach, Inbound Taxi, and Landing. In Fig. 13, Vertiport 1 specifications are shown which include: Vertipads, Taxi Points, Departure Points, Approach Points, Missed Approach Points and a Traffic Holding Orbits.

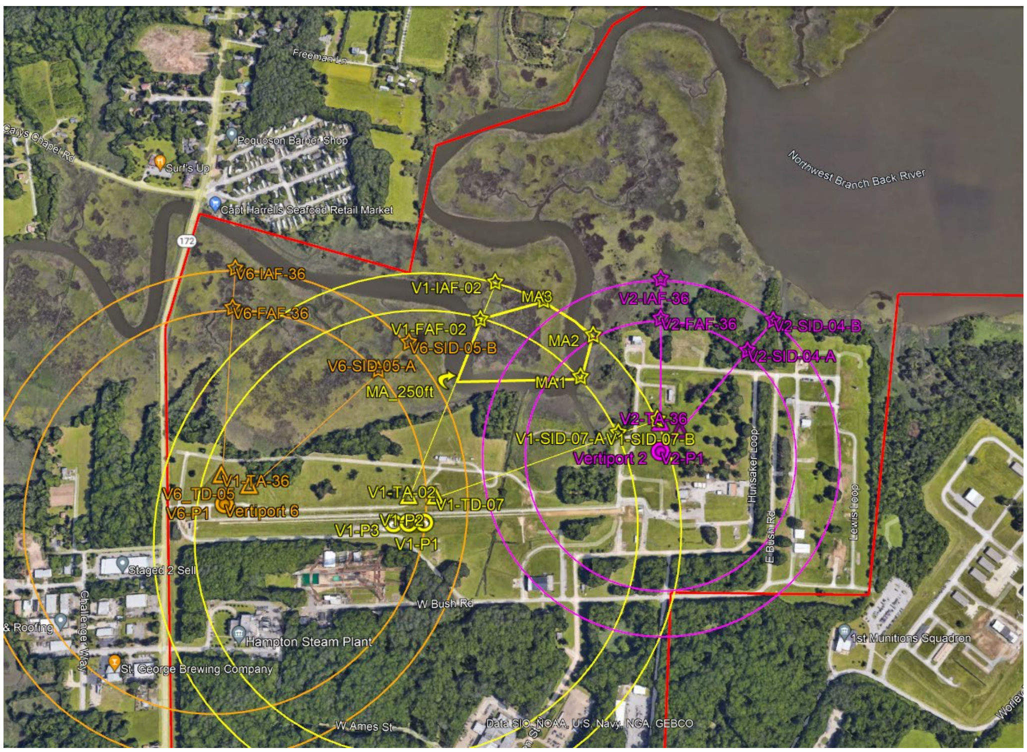

Fig. 12 Flight range and vertiport layout

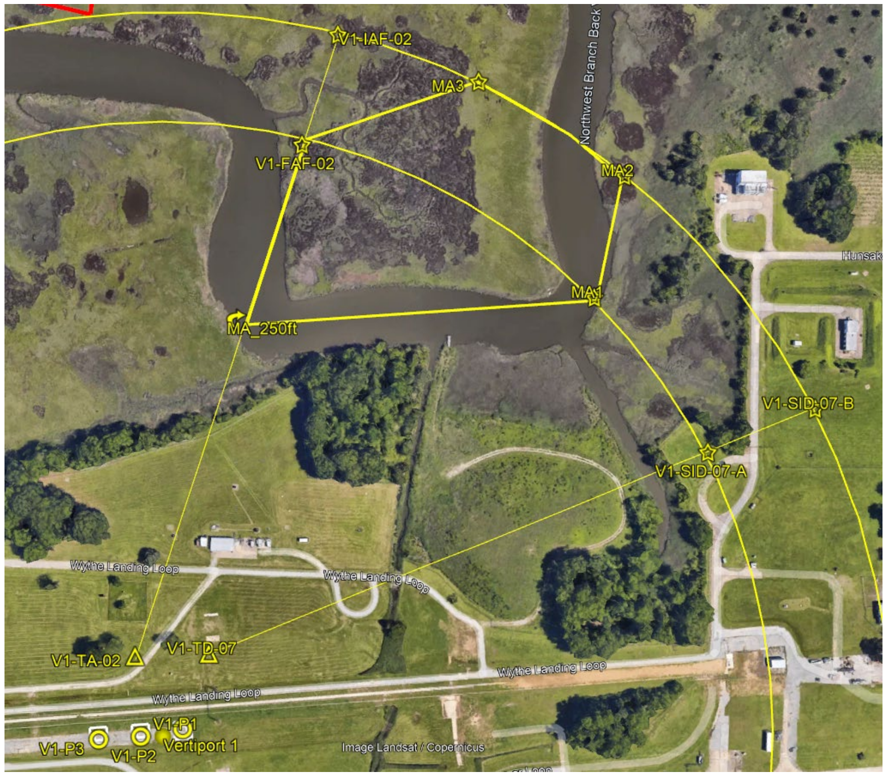

Fig. 13 Vertiport 1 geographic markers.

VI. Contingency Scenarios

During each test mission, the participating GCSOs, VMs, and FMs were presented with five unique scenarios, each of which represented different potential vertiport operation scenarios. The scenarios were defined by the required actions of the GCSOs from the FM, which may be caused by the VM closing the vertipads. The five scenarios are described in the following way:

1. Nominal

The nominal case represented a scenario where no issues were encountered during the operation. The only actions required by the GCSOs were those used in typical operations, which included uploading flight plans, ensuring successful takeoff of the vehicle, monitoring systems during flight, and landing the vehicle.

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 time slot than originally intended. A missed approach can occur for various reasons, such as a vertipad closure, a vertipad being occupied longer than expected by a previous arrival, or the need for expedited landing of an aircraft with an emergency.

3. Speed Change

For the speed change scenario, the vertiport was required to be closed for a short amount of time. For HDV SAO testing, simulated wildlife was detected on the vertipads, requiring closure by the VM.

The FM instructed the GCSOs to slow their vehicles to allow for the vertipads to reopen before the vehicles request to land at the vertiport.

4. Divert

When the divert scenario was executed, the vertiport was closed for much longer than the speed change scenario, prompting the FM to send the aircraft to another vertiport when replanning the operation. Once the vertiport was closed, the FM interacted with the HDV client's trial planning feature which allowed them to generate a new trajectory towards a nearby vertiport to avoid the closure.

5. Combination of Missed Approach, Divert, and Speed Change

The final scenario presented a situation where a combination of a missed approach, speed changes and diversions were required by the GCSOs. The scenario included a long shut down of the vertiport due to an incoming emergency vehicle landing at vertiport 1 for a medical pickup, which required all operations at the vertiport to stop during that time. This scenario was the most complicated and was intended to simulate a worst-case scenario, as it required more actions than any other scenario executed in the SAO flight test.

VII. Flight Test Results

Two main types of data were collected, data on system performance and human factors data. System performance data was used for analysis about how well the HDV UAM system performed, including analysis of traffic densities during operations. Flight testing achieved 5 simultaneous live aircraft remotely piloted with flight plans generated by a fleet manager. During nominal scenarios including five aircraft operating out of vertiport 1, which included vertiport manager oversight, 60 seconds separation for departures were accomplished providing a 60 operations/hour traffic tempo during the most complex flight test runs.

Human factors (HF) data acquired included situational awareness, workload, trust, and overall system evaluation responses during this usability study. A total of 15 participants supported the flight test experiments. These included three VMs, three FMs, and nine GCSOs selected from NASA's professional staff. A total of 5 unique scenarios (Nominal (N), Missed Approach (MA), Speed Change (SC), Divert (D), and Combination) with various numbers of live and simulated aircraft were conducted, all requiring different actions and interactions by the various participants. A summary of all of the test runs in SAO can be seen in Table 1.

Table 1 Flight Test Run Summary

Test Scenario	Single Aircraft Test Runs	Two Aircraft Test Runs	Three Aircraft Test Runs	Four Aircraft Test Runs	Five Aircraft Test Runs
1 - N	0	4	2	2	3
2 – MA	2	2	2	1	0
3- SC	0	2	2	1	0
4 – D	0	3	1	0	0
5 – SC, MA, D	3	2	1	0	0

Out of all of the data collected during this phase of the project, one example metric that was important is the aircrafts' flight profile during the test runs. One example chosen to demonstrate an aircraft's flight profile during a scenario with a short duration vertiport closure of 60 seconds is described below. In Fig.

14 and Fig. 15, the altitude and velocity profile of a vehicle flying into vertiport 1 is shown. In the figures, the star denotes the planned landing time per the preflight scheduled route, at approximately 7 minutes after takeoff. During the flight, approximately 3 minutes after takeoff (noted by the black vertical line), the VM noticed a simulated hazard on the vertipads and closed the vertiport for 60 seconds. This closure resulted in the FM updating the scheduled route to result in a new arrival time 60 seconds later. The updated arrival time and schedule was sent to the GCSO as a slowdown command where they slowed the vehicle from 14 knots to 10 knots to arrive at the newly scheduled arrival time. This flight profile example demonstrates the full functionality of the systems and human agents working together to accomplish this mission and responding to a contingency situation that included the VM closing the vertiport along with the subsequent vehicle response.

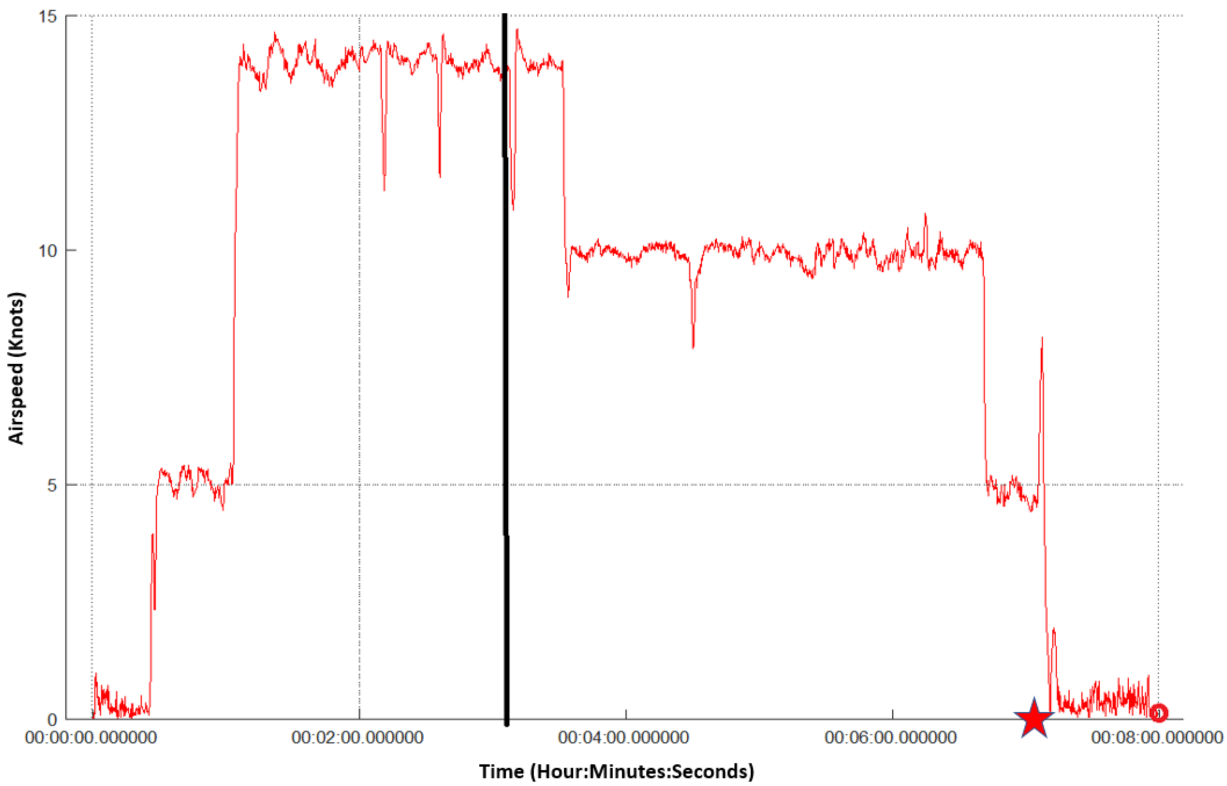

Fig. 14 Airspeed change during speed change scenario

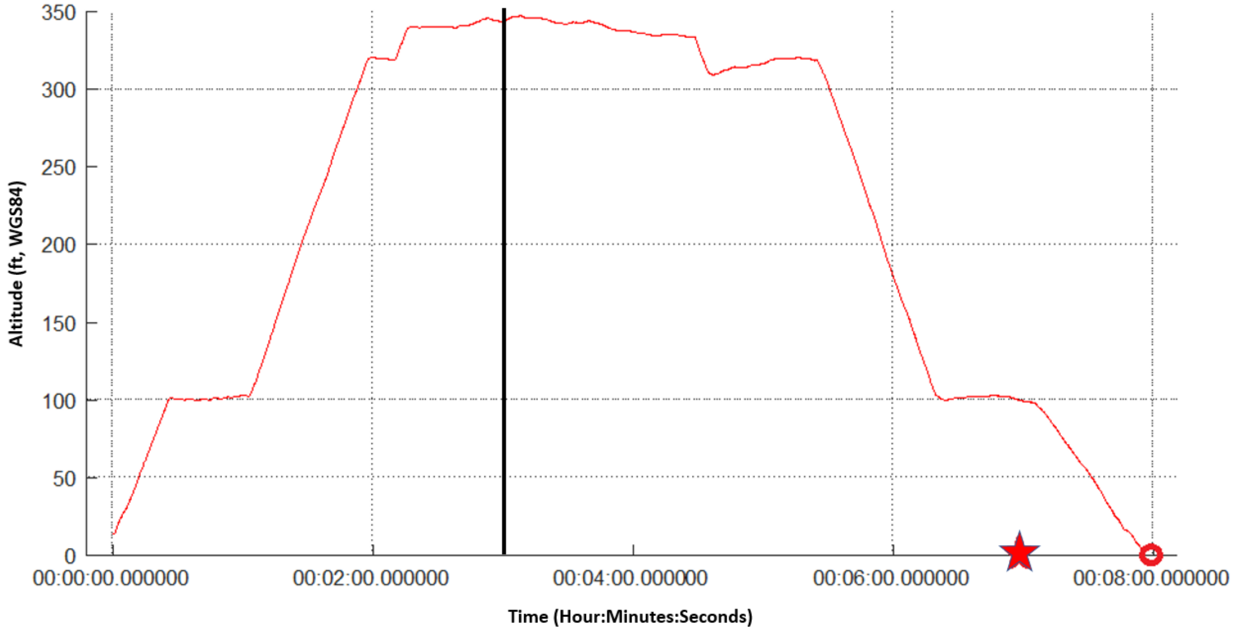

Fig. 15 Altitude during speed change scenario.

The second set of data collected was human factors data on the GCSO, VM, and FM. One strength of this work was collecting valuable data on human cognition and performance within a high-fidelity operational environment. As UAM operations are in their infancy, the corresponding research regarding roles, responsibilities, and task structures are limited and undefined. HDV has had success in exploring the roles of the GCSO and FM prior, leading to information regarding the gaze patterns of GCSOs [4], usability assessment of vertiport scheduling tool [6], and cognitive and procedurally analyses of humans within this multi-agent system requiring great interaction between the human and automation [5]. During this test cycle, GCSOs, FMs, and, additionally, VMs served as participants and completed several questionnaires about the five scenarios, including the NASA-TLX [12], SART [13], 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 [14]. After the end of the experiment, participants filled out a system usability questionnaire (PSSUQ) on the HDV client. In addition, researchers engaged in informal qualitative interviews with the participants. Some of the data collected are discussed in detail in [8, 15]. For an in-depth overview of fleet management capabilities within a UAM environment see [8]. For an in-depth overview of the cognitive and task elements of vertiport management within a UAM environment see [15].

In addition to the test data collected, the HDV sub-project also achieved a significant milestone in the field of UAM. Specifically, the HDV sub-project successfully performed real, no visual-observer beyond visual line of sight (NOVO-BVLOS) sUAS flights at NASA's CERTAIN test range following the UAM vertiport operation testing. Within the NOVO-BVLOS operations, neither the vehicle nor the airspace is monitored using direct human observation. A series of ground-based sensors including radar and ground-based ADS-B and FLARM provided complete awareness of the operational airspace and redundant vehicle positions. One objective of the NOVO-BVLOS flights is to support NASA technology transfer essential to sUAS Part-135 operators to enable package delivery and surveillance applications. Through coordinated simulations, flight testing, and safety risk assessments [16] [17], operational credit for a series of enabling sUAS technologies was acquired. NASA's ICAROUS software provided autonomous detect and avoid functionality and was part of the overall system to maintain well clear from other air traffic. NASA's Safe2Ditch system provided remote landing contingency management and contributed to mitigating ground risk. NASA's ability to transfer these technologies significantly benefitted from the NOVO-BVLOS flights. In addition, the documentation and dissemination of the integrated test and evaluation environment established for the NOVO-BVLOS flights is another significant contribution to sUAS Part-135 operations. These flights will be included in a future report.

IX. Summary

The HDV sub-project completed the SAO flight tests and successfully conducted NOVO-BVLOS vertiport flights, 5 simultaneous multi-aircraft flights, and 60 operations per hour from a vertiport. A rapid prototyping and assessment approach was applied to acquire critical results regarding a UAM Ecosystem that included representative: 1) Onboard Autonomous Systems, 2) Ground Control and Fleet Management Systems, 3) Airspace Management Systems, and 4) the VAS. Unique results related to VAS and VMs were acquired that will greatly facilitate development in support of future envisioned UAM operations. sUAS were employed as low risk surrogates for larger proposed UAM aircraft to accelerate the prototyping effort, ensure safety, and greatly mitigate costs. Usage of sUAS also generates results applicable to the sUAS operational expansion, such as beyond visual line of sight (BVLOS) operations. Lastly, No Visual Observer BVLOS (NOVO-BVLOS) operations in Class D airspace were performed that will greatly facilitate expansion of commercial sUAS operations and enable NASA technology transfer. Results are currently being analyzed and will be provided in future NASA and/or conference reports.

X. References

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