

Initial Development and Integration of a Vertiport Automation System for Advanced Air Mobility Operations

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The High Density Vertiplex Sub-Project, as part of NASA's Advanced Air Mobility (AAM) Project, has been developing a reference Vertiport Automation System (VAS) to support the management of arrival and departure operations in the terminal area of a vertiport or network of inter-connected vertiports known as a vertiplex. The VAS is potentially a key element of an integrated AAM architecture that will enable greater levels of coordination and predictability for vertiport users through its integration and sharing of information, and greater control of vertiport resources for managing operators. This paper provides an overview of the VAS and a description of an initial implementation that has been integrated into a broader reference architecture as part of ongoing research. Examples from recent simulations are presented with an outline for next steps and considerations.

I. Introduction

Advanced Air Mobility (AAM) is at the forefront of ushering in a new age in aviation that holds potential for changing the way that people and cargo move, where and when they move, what types of vehicles will be in the air, and transforming the way that cities and infrastructure adapt to accommodate new operations and modes of transportation. NASA has been a key research entity and contributor to the development of the AAM concept and the research, testing, and community building that has taken place thus far. There are many different areas in AAM that NASA is currently active in. This document will focus on a particular element identified as a critical piece of AAM infrastructure known as vertiports and the systems needed to manage their operations.

NASA is currently engaged in dedicated research into vertiport operations through its AAM Project through a particular Sub-Project referred to as High Density Vertiplex (HDV). This effort's technical challenges is to develop a

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reference automation architecture for vertiports that will enable operations to scale to the density levels envisioned for future environments. Through the development of the HDV Concept of Operations and accompanying architecture documents, a key component of this architecture was identified as the Vertiport Automation System (VAS) [1, 2]. This paper will focus on an initial implementation and efforts underway to integrate a VAS with other systems that are part of the overall system of systems that HDV has established as part of its continuing series of simulation and flight activities.

II. Vertiports

Within the AAM operational environment, vertiports are the locations and supporting infrastructure that the vehicles arrive and depart from. As such, operations at these vertiports -from pre-flight planning to surface movements to approaches and takeoff and touchdowns- are highly impactful on the efficiency and scalability of area operations. Given the importance of vertiports and their management on the flow of AAM operations, there has been dedicated research and considerable discussion on the topic. Figure 1 provides a high-level description for the types of facilities that may accommodate arrival and departure operations.

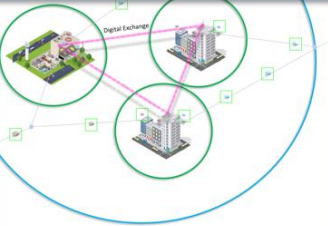
Vertistop	Vertiport	Vertihub	Vertiplex
 A facility intended solely for takeoff and landing of VTOL aircraft and rotorcraft to drop off or pick-up passengers or cargo.	 An identifiable ground or elevated area, including any buildings or facilities thereon, used for the takeoff and landing of VTOL aircraft and rotorcraft.	 A vertiport with infrastructure for maintenance, repair, and overhaul operations for the fleet, parking spaces for longer-haul vertical takeoff and landing aircraft, and a centralized operations control system.	 A localized geographic area covering several vertiports whose arrival and departure operations are highly interdependent. Resources within a Vertiplex can be flexibly allocated among the associated vertiports

Fig. 1 Types of vertiport facilities.

III. Vertiport Automation System

The VAS is the system collective 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 to support high-density operations. The VAS will have a highly automated scheduling tool capable of vertiport pad allocation and 4D surface trajectory sequencing or other vertiport resource assignments, leveraging vertiport ground-based sensor infrastructure and information shared from supporting stakeholders. The VAS manages ground-based scheduling, sequencing, and movement across the vertiport surface, provides aircraft with surface movement four-dimensional (4D) surface trajectories (latitude, longitude, height above vertiport surface, and time), and assures that the 4D trajectories are clear of obstacles and other traffic. The VAS also provides a standard interface for other services (e.g., Provider of Services for UAM (PSU)) to access vertiport information about resource availability, aircraft servicing, and any other vertiport-supplied resources.

IV. Vertiplex Operations: Actors, Roles, and Environment

Achieving high-density AAM operations will require complex interactions between multiple actors and integrated systems. To give some insight into the actors that are envisioned to interact with the VAS, the following high-level descriptions are provided for context:

Flight Crew and Aircraft: The two entities are considered as one dependent upon the level of automation and pilot configuration. The HDV concept generally assumes a further term level of maturity in which the important factor with respect to vertiport operations is the execution of aircraft maneuvers and adherence to procedures regardless of whether they are carried out by a flight crew in the loop or via onboard automation (or a combination of the two along a spectrum).

Fleet Manager: The Fleet Manager maintains a fleet-level view of operations and, at varying levels from supervisory to direct, engages in the planning, staging, operational execution, and overall monitoring of operations in support of company/fleet objectives. This role involves interaction with multiple systems to ensure safe and efficient operations.

Airspace Services: A number of services may be available in the future to provide services for the management of AAM airspace. The primary service envisioned is the PSU, which will be a key interfacing system for the Fleet Manager and Vertiport Manager roles for common situation awareness and resource scheduling/management. In this paper, the PSU will be referred to as the NASA PSU (NPSU) given the implementation that HDV is using for internal testing.

Vertiport Manager: The Vertiport Manager, a public or private operator of a vertiport, is responsible for managing ground-to-air operations at the vertiport, ranging from landside management to monitoring vertiport airside surface conditions. The vertiport manager will primarily serve as a supervisor of the VAS and associated services to monitor overall operational flow and resource management while being vigilant of risks and hazards and prepared to respond appropriately. The vertiport manager also may need to step in for communications with aircraft, flight crews, PSUs, or fleet operators on an ad hoc basis if equipment at the vertiport or on aircraft is not operating as expected, or if communication is time-critical to diverting an aircraft.

The environment envisioned for the above actors and supporting systems is shown visually in Fig. 1 where there is the assumption that there will be, in places, high density arrival and departure operations at a vertiport in an urban setting. Underlying the operations depicted in Fig. 2 are a complex system of systems that communicate and exchange data to manage resources at the vertiport, manage fleet operations, execute autonomous flights, and provide situation awareness for planning purposes and a common operating picture.



Fig. 2 Conceptual view of future high density vertiport operations.

V. Architecture and Implementation

The following section will describe the HDV architecture that has been implemented as part of the research and testing strategy. The overall reference architecture will be described first followed by more targeted discussion.

A. Reference Architecture

The primary technical challenge that the HDV Sub-Project is endeavoring to meet is the development of a reference automation architecture to enable scalable operations in a vertiport environment (to include one or multiple vertiports). As part of addressing that challenge, a reference architecture has been developed and implemented to the extent of being able to test concept elements using complex scenarios in real time through distributed simulation and live flight activities using small Uncrewed Aircraft Systems (sUAS) as surrogates for larger UAM vehicles. The architecture is expansive to include the necessary components to facilitate testing of the interactions, roles, and procedures of the system actors and the supporting systems with respect to airspace management, aircraft, flight crew, fleet management, and vertiport management. A more detailed presentation of the larger architecture that has been implemented as part of HDV research will be included as part of forthcoming publications. For the purposes of this paper, the Vertiport Automation System and its key interfacing systems will be the focus of discussion.

B. Component Connectivity and Information Flow

The VAS is a system that is responsible for management of vertiport resources through the integration of multiple data sources and data exchanges with inter-connected systems through standard protocols. As part of the UAM ecosystem that has been integrated for HDV research, one of the primary systems to exchange data with the VAS is referred to as the HDV Client. The client component maintains connections with multiple systems to serve the backend capabilities needed for processing operational data and feeding frontend user interfaces depending on role and configuration. The following is an initial description of the connectivity details between the VAS and the HDV Client that provides services to support fleet and vertiport management needs.

1. VAS and HDV Client Connectivity

The connection protocols between the different systems of focus for this paper are shown in Fig. 3. The VAS and HDV Client communicate via Socket.IO, a library that provides an abstraction layer on top of WebSocket secure protocol, making it easier to create real-time applications. It allows for bi-directional communication between a client and a server in a way that is much more efficient and responsive than traditional HTTP-based approaches. The HDV Client uses a combination of communication protocols to connect with various systems. To update the operator in real-time, it connects to the operator's browser using GraphQL's WebSocket secure protocol. To submit operation requests and operation updates from the operator, it interacts with NPSU's RESTful API over HTTPS protocol. To receive aircraft positions and status updates, it subscribes to the NPSU's Async API over WebSocket Secure protocol. All the data transmitted between different systems are in JSON format, which is a lightweight data-interchange format.

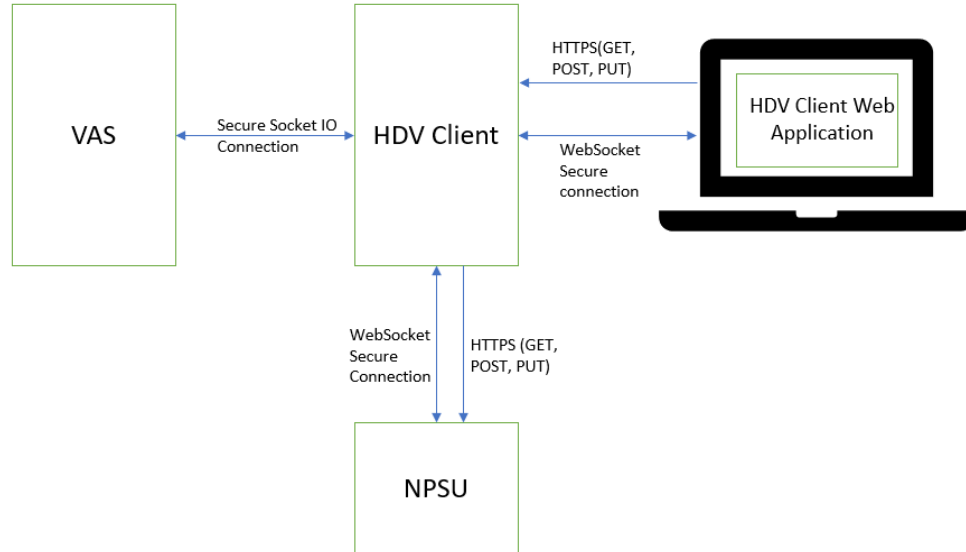


Fig. 3 Connection protocols between VAS, NPSU, and HDV Client.

2. VAS and HDV Client Communication

After the successful authentication between VAS and HDV Client systems, a bi-directional channel initiates where both systems can send/receive data using Socket IO events as shown in Fig. 4. During the initial connection,

handshaking, and authentication, information regarding the specific VAS being connected to is provided such as the VAS ID, list of vertiport IDs it operates, etc. For the initial implementation of the VAS, a single instance was established for managing the primary vertiport. However, a need exists for multiple VAS to be available for connection as the concept and HDV development plans anticipate interactivity between vertiports and their supporting systems from a gate-to-gate perspective as well as divert scenarios where inter-VAS schedule and capacity coordination is needed. The inclusion of VAS and vertiport IDs enables the future establishment of a network of inter-connected vertiports and associated VAS.

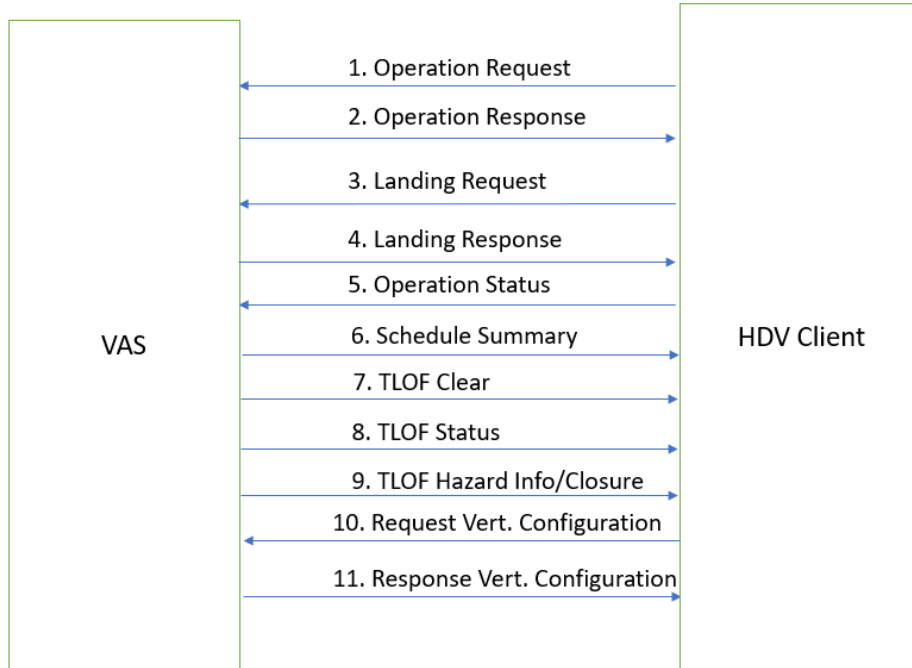


Fig. 4 List of events between Vertiport Automation System and HDV Client over Socket IO.

The messages included in the initial implementation of the VAS are provided below. Additional message sets will be added as more requirements are identified and the concept evolves. At the moment, the included messages are related to operations requests, landing requests, and status tracking. The following provides details for each respective message type:

- 1) Operation Request: This event is the primary means to request a reservation for an arrival or departure schedule on a vertiport. It can also be used to close a TLOF and to cancel a reservation schedule on a vertiport. The data members of the operation request event are displayed in Table 1.

Table 1. Interface for Operation Request

Member	Datatype	Description
topic	string	This is a unique Socket.IO event name to publish and subscribe to this message. For example: 'vas/operation/request'
type	int	1. Arrival 2 Departure 3. Cancel 4. Swap 6. Closure
reservation_id	string	Unique id for this reservation request
time	int	This is the epoch-based time in seconds for the beginning of the reservation
end_time	int	This is the epoch-based time in seconds for the ending of the reservation
guifi	string	Unique identifier for an NPSU operation
tlof_id	string	Unique identifier for an TLOF

- 2) Operation Response: The VAS will publish this event in response to an arrival or departure reservation request. If the requested time is not available, then the next available time will be sent. If the arrival/departure time is available, the message is returned as requested along with the end time which will be set to indicate the end of the period allocated for the schedule slot. The data payload of the operation response event is displayed in Table 2.

Table 2. Operation Response Data Payload

Member	Datatype	Description
topic	string	This is a unique Socket.IO event name to publish and subscribe to this message. For example: 'vas/operation/response'
type	int	1. Arrival 2. Departure 3. Cancel 5. Unable 6. Closure
reservation_id	string	Unique id for the reservation request
time	int	This is the epoch-based time in seconds for the beginning of the reservation
end_time	int	This is the epoch-based time in seconds for the ending of the reservation
gufi	string	Unique identifier for an NPSU operation
tlof_id	string	Unique identifier for an TLOF

- 3) Landing Request: This event is a request for landing approval for an aircraft at the landing vertiport. The presumption is the arrival was scheduled and the operation is verified to be scheduled to land, the TLOF is clear, and no hazards exist. The data payload of the landing request event is displayed in Table 3.

Table 3. Landing Request Data Payload

Member	Datatype	Description
topic	string	This is a unique Socket.IO event name to publish and subscribe to this message. For example: 'vas/landing/request'
type	int	2. Approach_Request 5. Landing_Clearance
gufi	string	Unique identifier for an NPSU operation
tlof_id	string	Unique identifier of a landing TLOF pad

- 4) Landing Response: When a landing approval request is received from the HDV Client, VAS responds by dispatching this event to indicate the approval status. The data payload of the landing response event is displayed in Table 4.

Table 4. Landing Response Data Payload

Member	Datatype	Description
topic	string	This is a unique Socket.IO event name to publish and subscribe to this message. For example: 'vas/landing/response'
type	int	2. Approach_Request 5. Landing_Clearance
gufi	string	Unique identifier for an NPSU operation
tlof_id	string	Unique identifier of a landing TLOF pad
cleared	string	This identifies if the clearance is approved or not. It can have either 'approved' or 'unable' value.

- 5) Operation Status: The HDV Client uses this event to transmit the current status of an active operation to VAS based on the phase of flight or approval status. The data payload of the operation status event is displayed in Table 5.

Table 5. Operation Status Data Payload

Member	Datatype	Description
topic	string	This is a unique Socket.IO event name to publish and subscribe to this message. For example: 'vas/operation/status'
status	int	1. Enroute 2. Approach_Request 3. Approach_Approved 4. Approach_Denied 5. Landing_Clearance 6. Landing_Denied 7. Cleared_to_land 8. Missed_Approach 9. Divert 10: Unknown
gufi	string	Unique identifier for an NPSU operation

- 6) Schedule Summary: This event message contains the scheduled arrivals/departure reservations. This summary is shared periodically with all connected client systems.

Table 6. Schedule Summary Event Data Payload

Member	Datatype	Description
topic	string	This is a unique Socket.IO event name to publish and subscribe to this message. For example: 'vas/schedule'
reservations	array	List of reservations where each reservation should have reservation ID, start-time, end-time, reservation type, tlof_ID, and gufi.

- 7) TLOF Clear: This message is transmitted in real-time by the VAS when the status of a TLOF changes from being occupied (e.g., by an arrival taxi delay or object detected) to being clear and ready for the next arrival or departure. The data payload of the TLOF clear event is displayed in Table 7.

Table 7. TLOF Clear Event Data Payload

Member	Datatype	Description
topic	string	This is a unique Socket.IO event name to publish and subscribe to this message. For example: 'vas/tlof_status/clear'
cleared	string	- approved - unable
tlof_id	string	Unique identifier for an TLOF

- 8) TLOF Closure and TLOF Hazard Info: These messages are shared immediately with all the connected HDV Clients upon their transmission. The HDV Client uses these real-time messages to not only cancel the reserved schedules on a particular TLOF but also inform all the landing vehicle operators subsequently. The payloads used for this event is shown in Table 1 and Table 2 with type 6 (closure).
- 9) TLOF Status: The VAS publishes this event periodically and whenever the status of one of the TLOFs changes. The data payload of the TLOF status event is displayed in Table 8.

Table 8. TLOF Status Event Data Payload

Member	Datatype	Description
topic	string	This is a unique Socket.IO event name to publish and subscribe to this message. For example: 'vas/tlof_status'
vertiport_id	string	Unique identifier for a vertiport
tlofs	array	List of TLOF along with respective IDs and current status

- 10) Request Vertiport Configuration: After establishing the initial connection to VAS, the HDV Client publishes this message to retrieve all vertiport configurations from the VAS in real-time (Table 9).

Table 9. Request Vertiport Configuration Data Payload

Member	Datatype	Description
topic	string	This is a unique Socket.IO event name to publish and subscribe to this message. For example: 'vas/configuration'
vertiport_id	string	Unique identifier for a vertiport

- 11) Response Vertiport Configuration: This message is sent in response to the Vertiport configuration request from an active HDV client, which contains a list of TLOFs and their dimensions, arrival, and landing procedures, vertiport operational area dimensions, and additional information needed to create and update the user interface on the HDV Client system (Tables 10 and 11).

Table 10. Response Vertiport Configuration Data Payload

Member	Datatype	Description
topic	string	This is a unique Socket.IO event name to publish and subscribe to this message. For example: 'vas/configuration/response'
vertiports	array	List of vertiport's configuration defined in Table 11

Table 11. Data Payload for Vertiport Data

Member	Datatype	Description
vertiport_id	string	Unique identifier for a vertiport
lat	number	This is the latitude of the vertiport.
lng	number	This is the longitude of the vertiport.
alt	number	This is the altitude of the vertiport.
minimum_operation_time	number	In development
volume_radius_meters	number	In development
volume_height_meters	number	In development
operations_area_radius_meters	number	In development
operations_area_height_meters	number	In development
iaf	array	Initial Approach Fix coordinates
faf	array	Final Approach Fix coordinates
voa_radius	number	Vertiport Operation Area Radius
vpv_radius	number	Vertiport Volume Radius
procedures	object	List of procedures at a vertiport
tlofs	object	List of TLOFs where each TLOF will have ID, lat, lng, alt, dimension, and status.

3. Data flow between VAS, HDV Client, and NPSU

This section will discuss the data flow between the systems of focus by taking a base nominal operation submission as an example and detailing the steps by which the operation is processed. Submitting an operation requires communication between three core systems: VAS, NPSU, and HDV Client, as illustrated in Fig. 5.

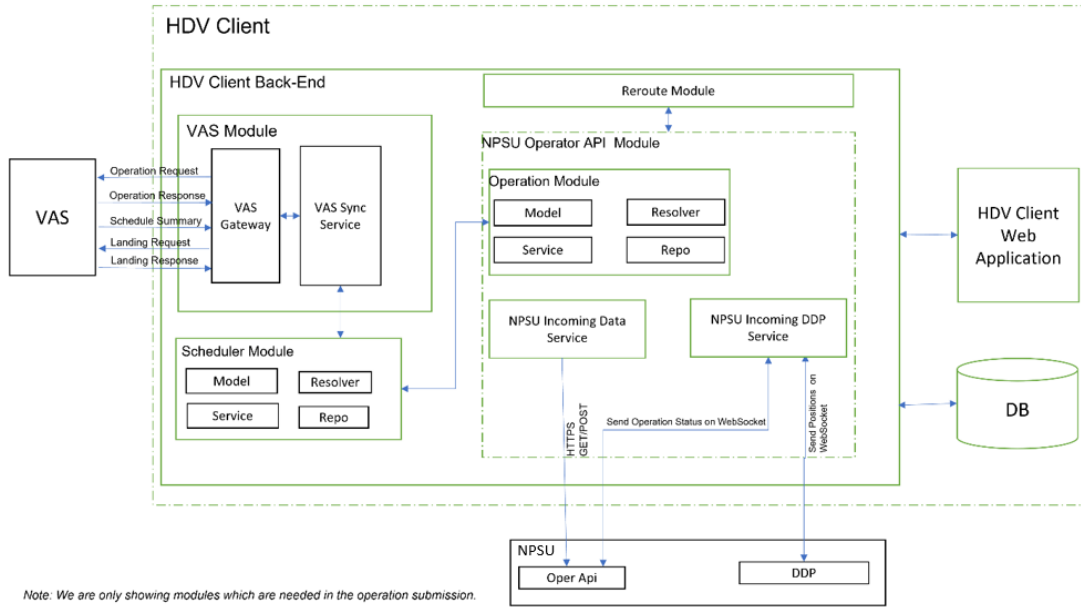


Fig. 5 A base nominal operation submission data flow.

The following data flow represents a simple nominal sequence of steps from operation proposal/request, to enroute flight, and to final approach:

- 1) UAM Operation Proposal: Fleet Manager submits UAM operation from HDV Client’s web application to the back-end server in the fleet management configuration.
- 2) Arrival/Departure Slots Reservation: The HDV Client’s back-end server publishes two operation requests (Arrival, Departure) to VAS. The request structure is defined in Table 1.
- 3) UAM Operation Submission to NPSU: After VAS approves the arrival/departure requests, the HDV Client submits an operation to the NPSU.
- 4) Operation Acceptance and Updates: If the operation submission meets acceptance criteria, the NPSU accepts the operation and sends state updates whenever a change is triggered. The HDV Client receives these operation updates in real-time and publishes it to the VAS using the “Operation Status” message as displayed in Table 5.
- 5) Landing Clearance: When a vehicle approaches the Initial Approach Fix (IAF) of the landing vertiport’s operation area, the HDV Client publishes a landing request to VAS. If the approval criteria are met, the operator prepares for landing after receiving approval from the VAS.

VI. Initial Simulation Integration

In addressing the technical challenge of developing a reference automation architecture for scalable vertiport operations, the HDV Sub-Project has followed a development and testing approach involving a series of progressively more complex scheduled work packages. Each of the scheduled work packages involves two primary events designed to test the integration of systems, services, and technologies that are part of the overall architecture as well as the procedures and specific concept elements encompassed by the defined goals and objectives. The first event of any work package is a large-scale, distributed simulation involving research facilities at NASA Ames Research Center in California and NASA Langley Research Center in Virginia. The simulation event is an initial check out of the architecture elements under test, the scenarios and procedures, participant, and researcher roles, as well as the data output functionality necessary for collection, visualization, and analysis. Successful completion of simulation is meant to serve as a checkout in preparation for culminating flight tests where all elements tested in simulation are brought forward and integrated with live flights of multiple aircraft that are also connected to the representative AAM ecosystem developed as part of the HDV research effort [3-8]. The following is a brief description of the facilities used in support of the simulation and flight test activities as well as the current implementation and application of the systems and components discussed thus far.

A. Facilities

1. Remote Operations for Autonomous Missions (ROAM)

Located at NASA Langley Research Center, the ROAM Operations Center serves as a simulation and flight coordination facility (Fig. 6). Data collection is also conducted within the facility with the flight crews and, as of the current work package, the Vertiport Manager participants. In transitioning to the subsequent flight testing, the ROAM facility will host additional Ground Control Station (GCS) operators, a Range Safety Officer (RSO), and the overall Flight Test Manager. Surveillance feeds of surrounding air traffic and live camera feeds are also available within ROAM for situation awareness during testing in addition to weather and spectrum monitoring.



Fig. 6 Remote Ops for Autonomous Missions: NASA Langley Research Center.

2. Airspace Operations Laboratory (AOL)

Located at NASA Ames Research Center, the AOL facility serves as the Fleet Management center where the roles and responsibilities of the Fleet Manager are performed (Fig. 7). The AOL also provides integrated airspace and data views on multiple displays, and serves as simulation control for the simulated UAM fleet as part of the scenario and simulated operations environment.



Fig. 7 Airspace Operations Laboratory: NASA Ames Research Center.

3. Autonomous Vehicle Applications Laboratory (AVAL)

Located at NASA Ames Research Center, the AVAL facility provides a research environment that will provide vertiport status information and observational HDV client workstations for the Fleet Manager and vehicle GCS (Fig. 8).



Fig. 8 Autonomous Vehicle Applications Laboratory: NASA Ames Research Center.

B. HDV Client Interfaces

The HDV Client has a browser-based web application which contains multiple displays that are accessible to users based on their roles and authorities. In this section the views available to Fleet Manager and Vertiport Manager positions will be presented.

1. User interface for Fleet Manager (FM)

a. Schedule Table View

This display provides a list of schedule slots available on departure and destination vertiports as shown in Fig. 9. A Fleet Manager uses this display to assign new operations to available flight crew and keeps track of already booked schedule slots.

departure	destination	departure	arrival	routeId	gufi	pilot	assign
Range 6	Range 1	6:49 pm	6:54 pm	Route-195P1-3			assign
Range 6	Range 1	6:49 pm	6:54 pm	Route-195P1-2			assign
Range 1	Range 1	6:49 pm	6:55 pm	Route-199P3-3			assign
Range 1	Range 1	6:49 pm	6:55 pm	Route-199P2-2			assign
Range 1	Range 1	6:49 pm	6:55 pm	Route-199P2-1			assign
Range 1	Range 1	6:49 pm	6:55 pm	Route-199P1-1			assign
Range 1	Range 1	6:49 pm	6:55 pm	Route-199P1-2			assign
Range 1	Range 1	6:49 pm	6:56 pm	Route-198			assign
Range 1	Range 6	6:49 pm	6:56 pm	Route-197B			assign
Range 1	Range 6	6:49 pm	6:56 pm	Route-197			assign
Range 1	Range 6	6:49 pm	6:57 pm	Route-196			assign

Fig. 9 Schedule table view for Fleet Manager.

To assign an operation, the FM selects the ‘assign’ button from the dropdown menu and selects the available flight crew to which the operation plan will be sent to via the client. After choosing the flight crew, the operation submission dialog opens for additional interaction, which is discussed in the next section.

b. Operation Submission Dialog

The operation submission dialog contains the volume definitions and trajectory data along with other UAM-specified data elements to be sent to the NPSU for processing. As shown in Fig.10, the dialog also contains pilot and route information which was assigned by the Fleet Manager while scheduling the operation.

Fig. 10 Operation submission dialog to assign operations to available operators.

In the dialog box, most of the data gets auto-filled based on the Fleet Manager’s route and schedule slot selection. After reviewing all the information in the dialog, the Fleet Manager can submit the operation to VAS and NPSU.

c. Operations Table View

The operations table shows all the active and closed operations as shown in Fig. 11. There are various columns displayed on the operations view such as gufi, callsign, state, status, controls, pilot id, route id, start-time, and end time of the operation. The operation’s state is color-coded so that the Fleet Manager can easily notice the current state (rejected, accepted, active, non-conforming, contingent, and closed) of an operation.

gufi	callsign	state	status	op mod	control	start time	end time	pilot	route id
79de	N1171L	Accepted		cancel	connect	activate	close	download plan	Route-75
1140	UAS_S61	Closed		cancel	connect	activate	close	download plan	Route-196
30f9	UAS_S51	Closed		cancel	connect	activate	close	download plan	Route-197
ec3d	UAS_S31	Closed		cancel	connect	activate	close	download plan	Route-198
ab4b	UAS_S1A	Closed		cancel	connect	activate	close	download plan	Route-199
d211	UAS_S51	Rejected		cancel	connect	activate	close	download plan	Route-197
7302	UAS_S31	Accepted		cancel	connect	activate	close	download plan	Route-198
11be	UAS_S1A	Closed		cancel	connect	activate	close	download plan	Route-199
2065	UAS_S61	Closed		cancel	connect	activate	close	download plan	Route-196
b74b	UAS_S51	Closed		cancel	connect	activate	close	download plan	Route-197
ebef	UAS_S31	Closed		cancel	connect	activate	close	download plan	Route-198
2d23	UAS_S1A	Closed		cancel	connect	activate	close	download plan	Route-199
5724	UAS_S1A	Closed		cancel	connect	activate	close	download plan	Route-199
2662	TES	Accepted		cancel	connect	activate	close	download plan	Route-198
39af	test	Closed		cancel	connect	activate	close	download plan	Route-198
6860	N1171L	Accepted		cancel	connect	activate	close	download plan	Route-75

Fig. 11 Operations table view for Fleet Managers to monitor all assigned operations.

As shown in Fig. 11, there is a control button titled ‘download .plan’ present on each operation row. The flight crew to which an operation is assigned by the Fleet Manager can download the flight plan via this control button and subsequently use the downloaded plan for upload to the aircraft’s GCS for flight execution according to the established schedule.

d. Map view

The map view provides situational awareness for all the active operations in real-time as shown in Fig. 12. Fleet Manager uses this view to make sure the active operations are following conformance rules set by the NPSU. All the volumes and trajectories are also color-coded based on the operation state so that Fleet Managers can easily keep track of active operations during high traffic density. Additional features of the map view include highlighting of vertiport status and message alerting for additional situation awareness and response formulation.

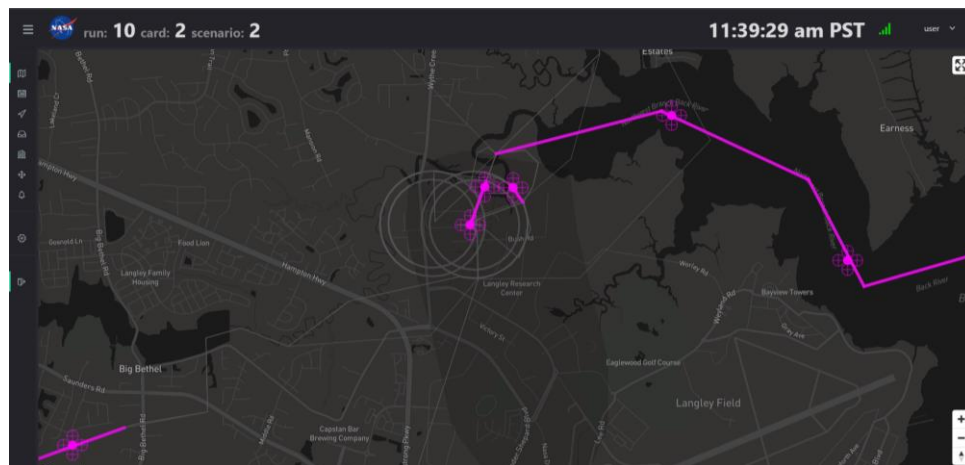


Fig. 12 Map view for Fleet Manager.

e. Aircraft’s Data Display

On the map view, a Fleet Manager can also see the information for an active aircraft by clicking on the vehicle icon as shown in Fig.13. After clicking on the vehicle icon, a popup appears near the aircraft’s icon which provides telemetry data as well as the current state of the operation.

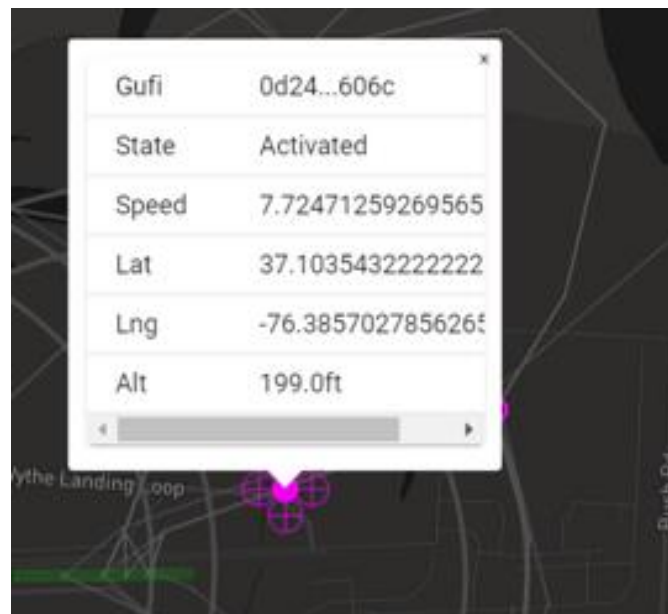
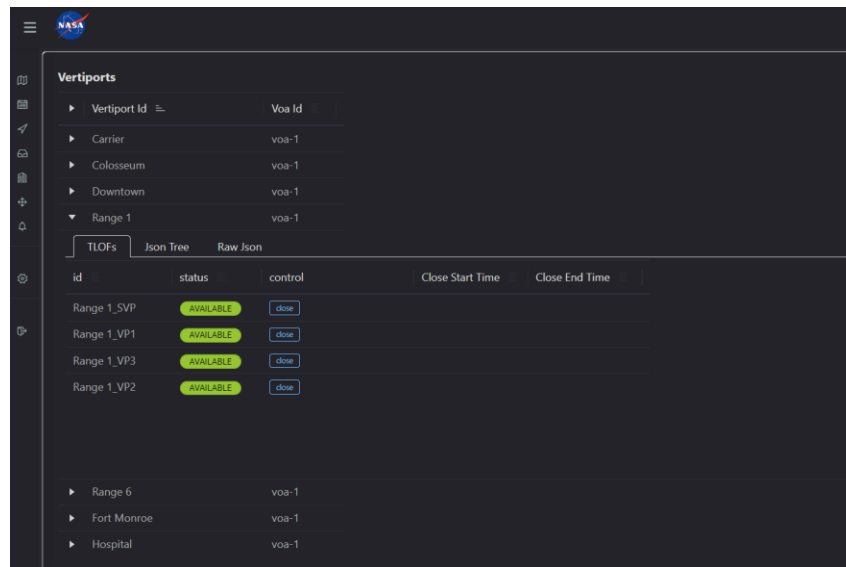


Fig. 13 An aircraft’s real-time telemetry data display

2. User interface for Vertiport Manager (VM)

a. Vertiports Display

On the vertiports page, VM can see the list of vertiports and the status of their associated TLOF in real-time. Five columns of data are provided for each TLOF: id, status, control, close start time, and close end time as shown in Fig. 14. In the control column, VM can click on the ‘Close’ button to open a dialog box to update the TLOF status. The TLOF’s status update dialog is discussed in the next section.



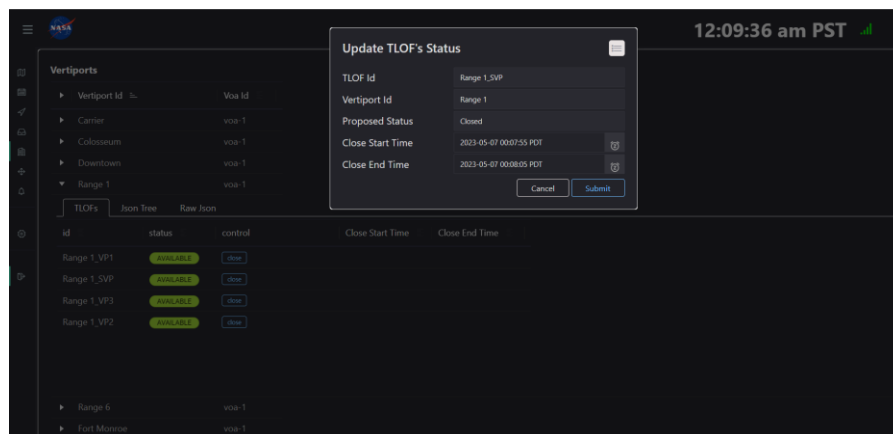
The screenshot shows the 'Vertiports' section of the interface. It features a tree view on the left with expandable categories: Vertiport Id, Carrier, Colosseum, Downtown, Range 1, Range 6, Fort Monroe, and Hospital. The main area displays a table of TLOFs (Takeoff and Landing Operations Facilities) with columns for id, status, control, Close Start Time, and Close End Time. The table lists several TLOFs, all with a status of 'AVAILABLE' and a 'close' button in the control column.

id	status	control	Close Start Time	Close End Time
Range 1_SVP	AVAILABLE	close		
Range 1_VP1	AVAILABLE	close		
Range 1_VP3	AVAILABLE	close		
Range 1_VP2	AVAILABLE	close		
Range 6				
Fort Monroe				
Hospital				

Fig. 14 Vertiports and TLOFs view for vertiport manager.

b. Update TLOF Status Dialog

After VM clicks on the ‘close’ button, the TLOF Status Update dialog opens. In this dialog, three inputs are auto filled: TLOF Id, Vertiport Id, and Proposed State. The other two fields can be updated by VM to schedule a TLOF closure time through the VAS as shown in Fig 15.



The screenshot shows the 'Update TLOF's Status' dialog box. It contains the following fields: TLOF Id (Range 1_SVP), Vertiport Id (Range 1), Proposed Status (Closed), Close Start Time (2023-05-07 00:07:55 PST), and Close End Time (2023-05-07 00:08:05 PST). There are 'Cancel' and 'Submit' buttons at the bottom. The background shows the same Vertiports Manager interface as in Fig. 14.

TLOF Id	Vertiport Id	Proposed Status	Close Start Time	Close End Time
Range 1_SVP	Range 1	Closed	2023-05-07 00:07:55 PST	2023-05-07 00:08:05 PST

Fig. 15 Update TLOF’s status dialog for vertiport manager.

The VM submits the TLOF closure request to VAS and receives confirmation. The TLOF closing and opening time get scheduled in the VAS system and it automatically opens the TLOF after the scheduled close time ends. Closure of a TLOF is communicated to the FM and flight crews, which provides awareness for planning purposes (e.g., missed approach or divert decisions).

c. VAS Network Display

The VAS Network Configuration page shows all the connected VAS and their vertiport lists. As shown in Fig. 16, the VAS 'range1-vas' is responsible for listening to all the events of vertiport ID 'Range 1'. In the initial implementation, the VM needs to make sure that the VAS is connected to the HDV Client and that it is listening to events for the appropriate vertiports. Such configurations can be streamlined with additional considerations that are under review as testing and development continues.

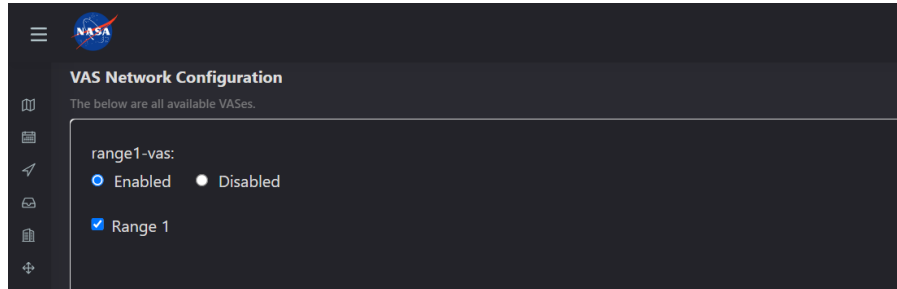


Fig. 16 VAS network view where VM can see the VAS connection status.

C. Environment

1. Airspace design and traffic simulation

To establish the environment that will serve as the foundation for the simulation and the associated operations that are consistent with the HDV concept, a high-level view of the airspace and its structures has been developed, as shown in Fig. 17 and Fig. 18. These will be adapted and tailored to support live flight testing of the scenarios. The airspace structures presented in Fig. 17 represented by the concentric circles are representations of the HDV concept of operations in which the Vertiport Operations Area (VOA) and Vertiport Volume (VPV) have been defined [1]. Routes and procedures have also been developed and instantiated as represented by the inter-connecting grey lines leading to and from the vertiports represented in green.

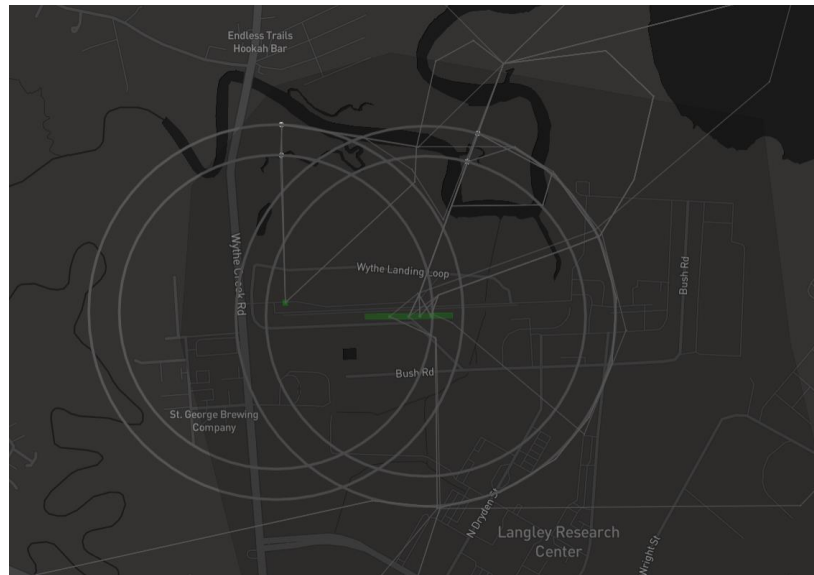


Fig. 17 Airspace design with VOA and VPV represented as circles with green vertiports in center.

Traffic scenarios were created to provide the targeted levels of density needed to address the HDV research objectives defined for the current work package. Multiple routes from disparate vertiports in the area were designed to feed into the primary vertiport of focus. Figure 18 presents a view of simulated fleet traffic departing from the primary vertiport located at NASA LaRC's CERTAIN range as well as feeding to the vertiport from the surrounding areas. All operations in view were scheduled through the VAS and supervised by the Fleet Manager in communication with the flight crews, Vertiport Manager, and NPSU.

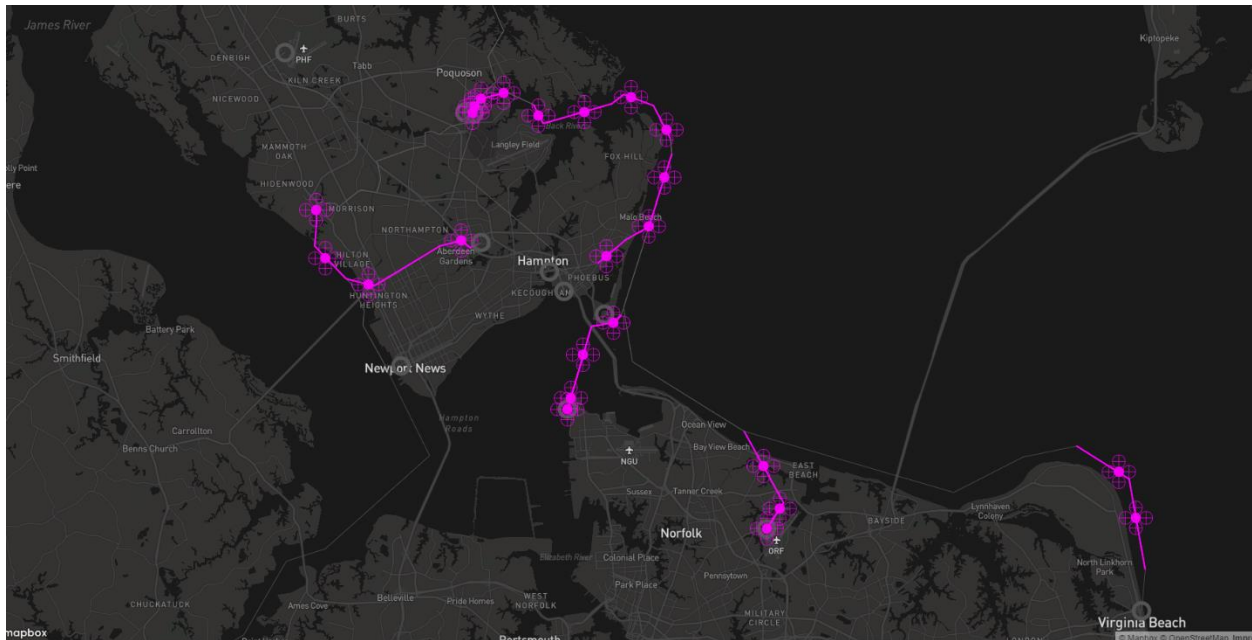


Fig. 18 Simulated traffic of multiple arrival/departure streams to and from vertiports in NASA LaRC area.

2. Vertiport airspace design

In this section, the airspace design and structures associated with vertiport operations are discussed.

a. Vertiport Operations Area (VOA) and Vertiport Volume (VPV)

The VOA is an airspace construct that represents the outer threshold of a vertiport that requires dedicated coordination once the aircraft is inside. In Fig. 19, the outer ring around the vertiport signifies the VOA boundary whereas the inner ring around the vertiport signifies the VPV. The VPV is tightly coupled with the vertiport's geographic location, and traffic cannot flow through the volume unless approved by the Vertiport Manager via the VAS. Operations within the VPV require direct coordination between vehicle and fleet operator with the vertiport for management of terminal operations.

b. Initial Approach Fix (IAF) and Final Approach Fix (FAF)

An aircraft begins its descent into the arrival stream of a vertiport starting at the IAF. From the IAF, aircraft will continue their approach towards the landing TLOF following the FAF. In Fig. 19, the point on the outer VOA ring represents the IAF and the point on the inner VPV ring is at the location denoted by the FAF. When an aircraft reaches the IAF, the HDV Client sends the approach request to VAS on behalf of the Fleet Manager. When the aircraft reaches the FAF, the HDV Client sends the landing approval (or rejection depending on situation) for the respective aircraft. After a successful response from VAS, the HDV Client informs the landing approval to the Fleet Manager, Vertiport Manager, and flight crew.

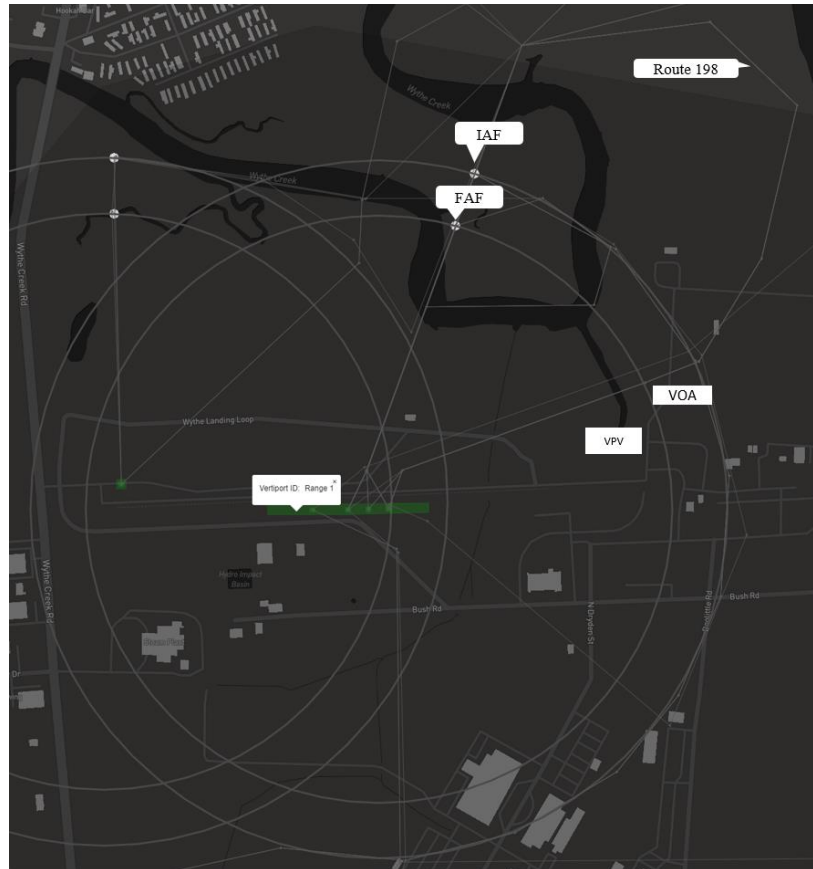


Fig. 19 Vertiport design with VOA/VPV rings, IAF, and FAF.

c. Touchdown and Lift-off (TLOF)

A TLOF is the physical area at the vertiport in which aircraft land or takeoff from. As shown in Fig. 20, there are four TLOFs represented as grey squares on the vertiport surface. The locations drawn on the map view shown in Fig. 20 map to the physical locations at the flight test range from which live vehicles will be operated from. During operations, the status of each TLOF is displayed using red to signify a ‘closed’ status and green to signify ‘available’.

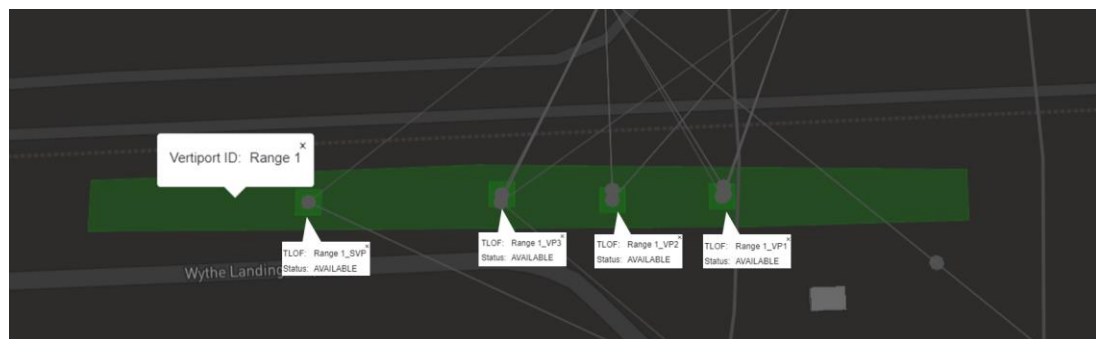


Fig. 20 Four TLOFs located on Vertiport ID “Range 1” at the flight test range.

D. Walkthrough of Arrival Operation

In this section, a walkthrough of a nominal procedure starting from Fleet Manager scheduling an operation to the landing of an aircraft at the landing vertiport is presented.

1. Schedule

a. Operation Scheduling

The FM assigns an operation (gufi: ...606c) to flight crew GCS1, as shown in Fig. 21. The operation departs from 'Range 1' at 11:07AM and lands to the same vertiport, also called 'Range 1', at 11:14AM following a loop (Route-198) shown in Fig. 19. As soon as the FM submits the operation, the HDV Client sends a message to VAS to reserve arrival and departure schedule slots, which will be discussed in the next section.

Schedule							
departure	destination	departure	arrival	routeld	gufi	pilot	assign
Range 1	Range 1	11:07 am	11:14 am	Route-198	606c	GCS1	
Range 6	Range 1	11:40 am	11:45 am	Route-195P1-3			<button>assign</button> ▼
Range 6	Range 1	11:40 am	11:45 am	Route-195P1-2			<button>assign</button> ▼
Range 1	Range 1	11:40 am	11:46 am	Route-199P3-3			<button>assign</button> ▼
Range 1	Range 1	11:40 am	11:46 am	Route-199P1-1			<button>assign</button> ▼
Range 1	Range 1	11:40 am	11:46 am	Route-199P1-2			<button>assign</button> ▼

Fig. 21 Fleet Manager assigns an operation (gufi: 606c) to pilot GCS1.

b. Arrival/Departure Slot Scheduling with VAS

The HDV Client submits a request for a departure schedule slot to VAS using the Operation Request API via socket IO. The operation request/response data elements are displayed in Table 1 and Table 2 respectively.

In Fig 22, on the left panel, the VAS receives an operation request from HDV Client with type 2 (Departure) and on the right panel, the VAS sends the response back to the HDV Client with the same information confirming that the departure of the operation (gufi:...606c) has been scheduled at TLOF ID 'Range 1_VP1'.

```
[mock-vas] Info 2023-03-16 11:05:59
Got "vas/operation/request" for Departure (2):
{
  "topic": "vas/operation/request",
  "type": 2,
  "flight_id": "NNumber",
  "reservation_id": "81abc8fb-242e-4bd6-949a-c70d0c63e827",
  "time": 1678990020,
  "end_time": 1678990080,
  "tlof_id": "Range 1_VP1",
  "gufi": "0d24633d-aac1-4765-92ef-93530ee7606c"
} { context: undefined } - {}

[mock-vas] Info 2023-03-16 11:05:59 Emitted vas/operation/response
[mock-vas] Info 2023-03-16 11:05:59 {
  "type": 2,
  "flight_id": "NNumber",
  "reservation_id": "81abc8fb-242e-4bd6-949a-c70d0c63e827",
  "time": 1678990020,
  "end_time": 1678990080,
  "tlof_id": "Range 1_VP1",
  "gufi": "0d24633d-aac1-4765-92ef-93530ee7606c",
  "topic": "vas/operation/response"
} { context: undefined } - {}
```

Fig. 22 Departure schedule slot request/response with VAS

In Fig 23, on the left panel, the VAS receives an operation request from HDV Client with type 1 (Arrival) at the TLOF 'Range 1_VP1'. On the right panel, the VAS sends the response to the HDV Client with confirmation that the arrival of the operation (gufi:...606c) has been scheduled at 'Range 1_VP1'.

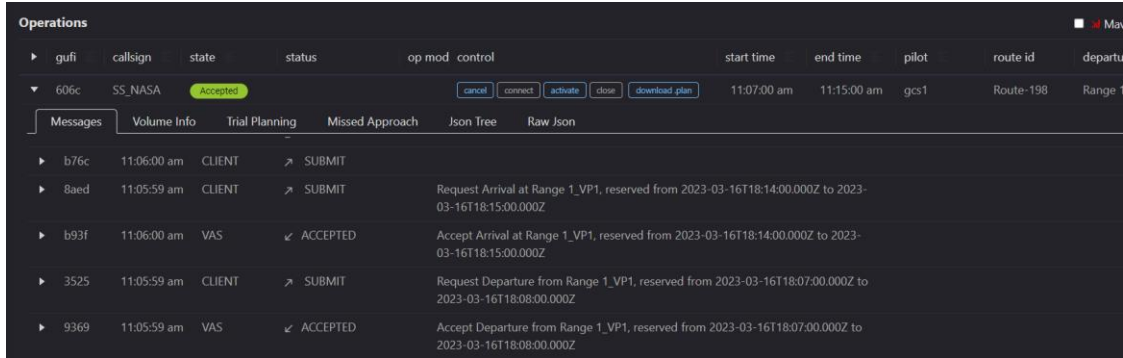
```
[mock-vas] Info 2023-03-16 11:05:59
Got "vas/operation/request" for Arrival (1):
{
  "topic": "vas/operation/request",
  "type": 1,
  "flight_id": "NNumber",
  "reservation_id": "e2abb3ad-f670-402d-8771-12f0a3c640ae",
  "time": 1678990440,
  "end_time": 1678990500,
  "tlof_id": "Range 1_VP1",
  "gufi": "0d24633d-aac1-4765-92ef-93530ee7606c"
} { context: undefined } - {}

[mock-vas] Info 2023-03-16 11:05:59 {
  "type": 1,
  "flight_id": "NNumber",
  "reservation_id": "e2abb3ad-f670-402d-8771-12f0a3c640ae",
  "time": 1678990440,
  "end_time": 1678990500,
  "tlof_id": "Range 1_VP1",
  "gufi": "0d24633d-aac1-4765-92ef-93530ee7606c",
  "topic": "vas/operation/response"
} { context: undefined } - {}
```

Fig. 23 Arrival schedule slot request/response with VAS

Under the Messages tab for gufi (...606c), as shown in Fig. 24, both the Fleet Manager and the flight crew (GCS1) can view the communication between the fleet system and VAS. After successfully scheduling the slot

with VAS, the HDV Client submits the proposed operation to NPSU for final approval. Once the NPSU accepts the operation, the state of the operation changes to ‘Accepted’ as shown in Fig 24.



gufi	callsign	state	status	op mod	control	start time	end time	pilot	route id	departu
606c	SS_NASA	Accepted				11:07:00 am	11:15:00 am	gcs1	Route-198	Range 1

gufi	time	from	to	action	details
b76c	11:06:00 am	CLIENT		SUBMIT	
8aed	11:05:59 am	CLIENT		SUBMIT	Request Arrival at Range 1_VP1, reserved from 2023-03-16T18:14:00.000Z to 2023-03-16T18:15:00.000Z
b93f	11:06:00 am	VAS		ACCEPTED	Accept Arrival at Range 1_VP1, reserved from 2023-03-16T18:14:00.000Z to 2023-03-16T18:15:00.000Z
3525	11:05:59 am	CLIENT		SUBMIT	Request Departure from Range 1_VP1, reserved from 2023-03-16T18:07:00.000Z to 2023-03-16T18:08:00.000Z
9369	11:05:59 am	VAS		ACCEPTED	Accept Departure from Range 1_VP1, reserved from 2023-03-16T18:07:00.000Z to 2023-03-16T18:08:00.000Z

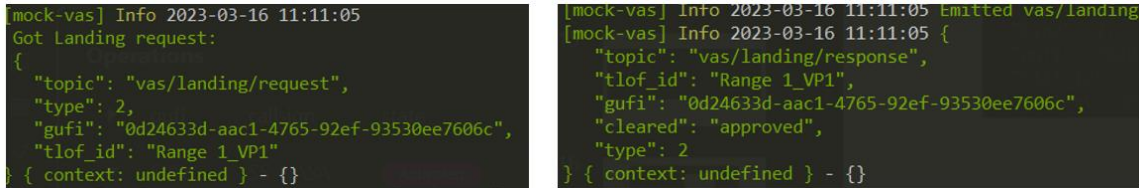
Fig. 24 Departure and Arrival scheduling messages on the operations page.

2. Approach

When an aircraft enters the VOA region of the landing vertiport, the HDV Client sends a landing request to VAS via Socket IO, based on the aircraft's current location (IAF or FAF). The data structure of landing request/response is defined in Table 3 and Table 4.

a. An Aircraft approaching to Initial Approach Fix (IAF)

In Fig. 25, on the left panel, the HDV client sends a landing request with type 2 (Approach_Request) to VAS via socket IO when aircraft enters the VOA at the IAF point. On the right panel, VAS sends the response to the HDV Client, confirming the approach request for the aircraft with gufi 0d24...606c.



```
[mock-vas] Info 2023-03-16 11:11:05
Got Landing request:
{
  "topic": "vas/landing/request",
  "type": 2,
  "gufi": "0d24633d-aac1-4765-92ef-93530ee7606c",
  "tlof_id": "Range 1_VP1"
} { context: undefined } - {}
```

```
[mock-vas] Info 2023-03-16 11:11:05 Emitted vas/landing
[mock-vas] Info 2023-03-16 11:11:05 {
  "topic": "vas/landing/response",
  "tlof_id": "Range 1_VP1",
  "gufi": "0d24633d-aac1-4765-92ef-93530ee7606c",
  "cleared": "approved",
  "type": 2
} { context: undefined } - {}
```

Fig. 25 Approach request(left)/response(right) with VAS.

b. Final Approach Fix (FAF) coordination with VAS

In Fig. 26, on the left panel, the HDV client sends a landing request with type 5 (Landing_Clearance) to VAS via socket IO when the aircraft enters the VPV at the FAF point. On the right panel, VAS sends the response to the HDV Client, confirming that the aircraft, with gufi 0d24...606c, is approved to land at TLOF ‘Range 1_VP1’.



```
Got Landing request:
{
  "topic": "vas/landing/request",
  "type": 5,
  "gufi": "0d24633d-aac1-4765-92ef-93530ee7606c",
  "tlof_id": "Range 1_VP1"
} { context: undefined } - {}
```

```
[mock-vas] Info 2023-03-16 11:11:18 {
  "topic": "vas/landing/response",
  "tlof_id": "Range 1_VP1",
  "gufi": "0d24633d-aac1-4765-92ef-93530ee7606c",
  "cleared": "approved",
  "type": 5
} { context: undefined } - {}
```

Fig. 26 Landing clearance request (left) and response from VAS (right).

3. Operation Status

To have adequate coordination between the Fleet Manager, Vertiport Manager, and flight crew, the operation status plays a key role. The HDV Client transmits an operation status to VAS via ‘Operation Status’ message over the socket IO. Table 5 displays the data structure of this event.

In the following sequence, the status update message protocol of a simulated operation with the callsign SS_NASA and gufi ending in ‘606c’ will be stepped through. In Fig. 27, the status is ‘Enroute,’ which indicates that the aircraft is in flight and outside of the VOA of the arrival vertiport. From a data perspective, the status implies that the HDV

Client has started receiving the aircraft's position data from the NPSU. On the left side of Fig. 27, the HDV Client updates the web application and transmits the 'Enroute' status to VAS, which is shown on the right side.

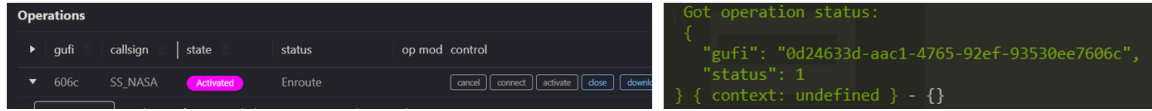


Fig. 27 (a) Enroute status of aircraft when outside the VOA threshold.

In Fig. 27 (b), the operation status is 'Approach_Request' which indicates that the aircraft is entering into the VOA region at the IAF point of the landing vertiport. The HDV Client calculates the distance between the aircraft's current position and the landing vertiport's IAF coordinates. When the aircraft is within a defined distance to the VOA, an approach request to VAS is initiated followed by an update of the status on the web application user interface.

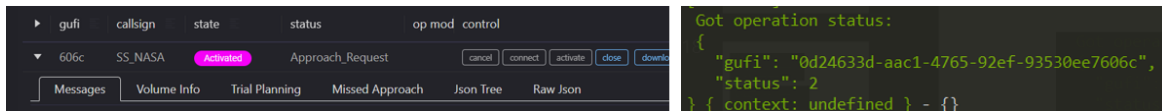


Fig. 27 (b) Approach_Request: Aircraft approaches the IAF point of a landing vertiport.

In Fig. 27 (c), the operation status is 'Approach_Approved' which implies that the VAS has approved the aircraft's approach request. After the approach request is approved by VAS, the aircraft can continue its path for entry to the VPV region of the landing vertiport. In other test scenarios, an aircraft's approach request also gets denied, which will be discussed in future publications.

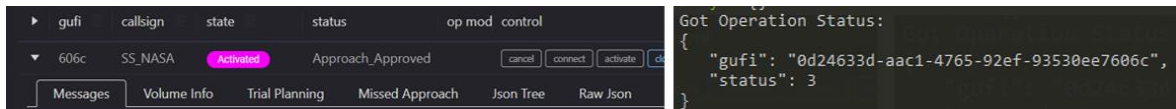


Fig. 27 (c) Approach_Approved: VAS approves approach request.

In Fig. 27 (d), the operation status is 'Landing_Clearance' which indicates that the aircraft was approved for entry into the VPV region at the FAF point of the landing vertiport. The HDV Client calculates the distance between the aircraft's current position and the landing vertiport's FAF coordinates. When the aircraft is within a set distance, a landing clearance request is sent to the VAS, which then updates the status on the HDV web application to reflect the change.

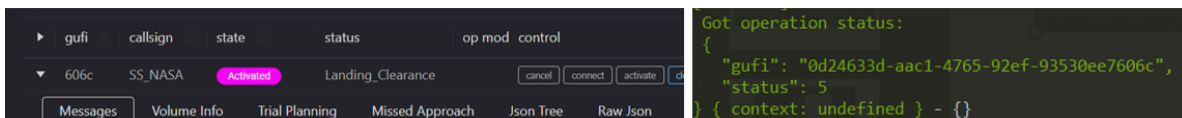


Fig. 27 (d) Landing_Clearance: When the aircraft approaches the FAF point of a landing vertiport.

In Fig. 27 (e), the operation status is 'Cleared_to_land' which implies that the VAS has approved the aircraft's landing approval request. After the aircraft receives approval by the VAS, it can prepare to land on the assigned TLOF pad. In future test scenarios, an aircraft may not receive landing approval and will require further coordination.

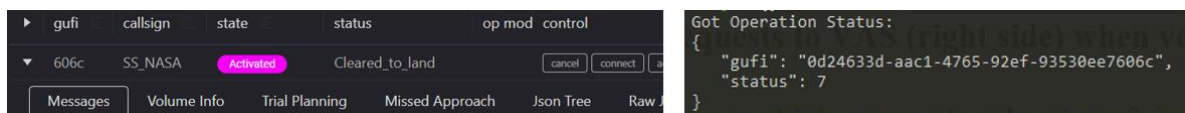


Fig. 27 (e) Cleared_to_land: VAS approves the landing request.

VII. Next Steps and Considerations

In this paper, the initial development and integration of the VAS with the broader architecture established as part of the ongoing research effort under the HDV Sub-Project has been presented. Further development and refinements are in progress. Next steps in the development of the VAS are to transition the integration testing from local systems to externally accessible systems in line with the needs of planned testing in the near future. The first set of upcoming tests are part of what is referred to as the Scalable Autonomous Operations (SAO) work package, which will involve the first instance of a VAS to be deployed and integrated in test. The progression of the SAO testing will first involve distributed simulation with multiple inter-connected facilities between the NASA Ames and Langley Research Centers along with cloud-accessible client and airspace service systems. A culminating flight test will build upon the initial simulation activity and will involve live flights (with small UAS as surrogate aircraft) and data integration from fielded sensors at the flight range vertiports and surrounding area for surveillance. The SAO activity itself is part of a broader research portfolio that builds upon each stage to include more complex system and actor interactions and to eventually incorporate representative UAM vehicles. Follow-on publications will discuss advances in the development and testing of the reference architecture and more detailed updates on the VAS software and Fleet Management development.

VIII. Conclusion

The HDV Sub-Project has been addressing the technical challenge of developing a reference automation architecture to support scalable operations in vertiport environments. The research effort has been steadily progressing in the implementation of the architecture with key components established early to support Fleet Management capabilities as well as flight crew interactions in large-scale distributed simulation and live, virtual, constructive flight testing with surrogate small UAS. More recently, the addition of a Vertiport Automation System to manage scheduling and vertiport management through a human Vertiport Manager has been developed and implemented. This advancement is a milestone for the HDV effort as it paves the way for dedicated research into more complex interactions between multiple vertiports and their stakeholders from an end-to-end perspective as well as contingency management handling in larger scale, dense environments. Further development is in progress to establish the networks of VAS, which will be incorporated in future testing. The progress thus far, however, has provided a strong foundation for future research and its potential for further integration into the larger transportation system.

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- [1] NUAIR (2021) High-Density Automated Vertiport Concept of Operations. https://ntrs.nasa.gov/api/citations/20210016168/downloads/20210016168_MJohnson_VertiportAtmtnConOpsRprt_final_corrected.pdf
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- [6] Gaug, N. and Tang, A., “Lightweight Surveillance and Target Acquisition Radar, Characterization for High Density Vertiplex Beyond Visual Line of Sight Operations,” 41st Digital Avionics Systems Conference, Portsmouth, VA, 2022.
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