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Concept, Design, & Implementation of a Remote Vehicle Operations Center for Autonomous Missions

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November 2024

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Space Administration

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List of Acronyms

4G LTE	Fourth Generation Long-Term Evolution
AAM	Advanced Air Mobility
ADDS	Aviation Digital Data Services
ADS-B	Automatic Dependent Surveillance – Broadcast
ACERO	Advanced Capabilities for Emergency Response
AFCM	Automated Flight Contingency Management
AMIO	AAM Mission Integration Office
AMP	Air Mobility Pathfinders
AOA	Advanced Onboard Automation
AOL	Airspace Operations Lab
AOSP	Aviation Operations and Safety Program
ARC	Ames Research Center
ARMD	Aeronautics Research Mission Directorate
AS	Autonomous Systems
ASI	Airspace Systems Integration
ASM	Airspace Surveillance Manager
ATC	Air Traffic Control
ATIS	Automated Terminal Information System
ATM-X	Air Traffic Management – Exploration
ATOL	Air Traffic Operations Laboratory
ATOL Ops	ATOL Operations
AVAL	Autonomous Vehicle Applications Laboratory
BVLOS	Beyond Visual Line of Sight
CAS	Convergent Aeronautics Solutions
CERTAIN	City Environment for Range Testing Autonomous Integrated Navigation
CFR	Code of Federal Regulations
COA	Certificate of Authorization
COVID-19	Coronavirus Disease 2019
ER-ARB	Eastern Region Airworthiness Review Board
eVTOL	electric Vertical Takeoff and Landing
EVLOS	Extended Visual Line of Sight
FAA	Federal Aviation Administration
FM	Fleet Manager
FLARM	Flight Alarm
FTM	Flight Test Manager
GCS	Ground Control Station
GCSO	Ground Control Station Operator
GIS	Geographic Information System
GPS	Global Positioning System
HDV	High Density Vertiplex
HHITL	Hardware- and Human-In-The-Loop
HITL	Human-In-The-Loop
IAD	Integrated Airspace Display
IASP	Integrated Aviation Systems Program
ICAO	International Civil Aviation Organization
ICAROUS	Independent Configurable Architecture for Reliable Operations of Unmanned Systems
IEEE	Institute of Electrical and Electronics Engineers
IOC	Initial Operating Capability
IoT	Internet of Things

IP	Internet Protocol
IRB	Institutional Review Board
ISA	Interagency Services Agreement
ISM	Industrial, Scientific, and Medical
JSON	JavaScript Object Notation
KIAS	Knots Indicated Airspeed
KLFI	ICAO code for Langley Air Force Base
LaRC	Langley Research Center
LMS	Langley Management System
LPR	Langley Procedural Requirement
LSTAR	Lightweight Surveillance and Target Acquisition Radar
LVC	Live, Virtual, and Constructive
MACS	Multi Aircraft Control Systems
MaRERA	Multi-aircraft Remote Emergency Response Assessment
METAR	Meteorological Aerodrome Report
MOSAIC	Mission Operations & Autonomous Integration Center
MPATH	Measuring Performance for Autonomy Teaming with Humans
MS	Microsoft
MQTT	Message Queuing Telemetry Transport
NAII	NASA Advisory Implementing Instruction
NASA	National Aeronautics and Space Administration
NexRAD	Next Generation Weather Radar
NOP	NASA Operations Planner
NOTAM	Notice to Airmen
NPD	NASA Policy Directive
NPR	NASA Procedural Requirement
NUAIR-CLIN	Northeast UAS Airspace Integration Research Alliance – Contract Line Item Number
NWS	National Weather Service
O365	(Microsoft) Office 365
OTA	Over-the-Air
PAO	Prototype Assessment Operation
PIC	Pilot-In-Charge / Pilot-In-Command
POV	Point of View
PSU	Provider of Services to UAM
RADAR	Radio Detection and Ranging
RAM	Revolutionary Aviation Mobility
RBO	Role-Based Ontology
RD&T	Research, Development, and Technology
RO	Radar Operator
ROAM	Remote Operations for Autonomous Missions
ROE	ROAM Operations Engineer
RSD	Research Services Directorate
RSO	Range Safety Officer
S2D	Safe2Ditch
SAO	Scalable Autonomous Operations
SD	Simulation Director
SDAB	Simulation Development & Analysis Branch
SIVL	UAS Systems Integration and Validation Lab
SP	Safety Pilot
SSP	Software Security Plan
STEReO	Scalable Traffic Management for Emergency Response Operations

sUAS	Small UAS
TACP	Transformative Aeronautics Concepts Program
TAF	Terminal Area Forecast
TC	Test Coordinator
TCP	Transmission Control Protocol
TRL	Technology Readiness Level
TTT	Transformative Tools and Technologies
TWP	Technical Work Package
UAM	Urban Air Mobility
UAS	Uncrewed Aerial Systems (NASA)
UAS	Unmanned Aircraft System (FAA, Industry)
UASOO	Uninhabited Aerial Systems Operations Office
UMAT	UAS Mission Analysis Tool
UML	UAM Maturity Level
USS	UAS Service Provider
VAS	Vertiport Automation System
VHF	Very High Frequency
VLOS	Visual Line of Sight
VM	Vertiport Manager
VMD	Vertiport Manager Display
VNP	Visitors / Non-Participants
VO	Vertiplex Operations
VO	Visual Observer
VoIP	Voice Over Internet Protocol
VSC	Vehicle Service Crew
WAHLDO	Wide-Area Hazard Locator for Drone Overflight
WMO	World Meteorological Organization
Wx	Weather
XRD	eXtended Range Datalink
xTM	eXtensible Traffic Management
xTMO	xTM Operator

Abstract

The National Aeronautics and Space Administration is supporting research to develop a prototype remote vehicle operations center at Langley Research Center to explore current and future advanced air mobility operations using small uncrewed aerial systems vehicles as surrogates for future, larger-scale passenger carrying vehicles. The prototype facility known as the Remote Operations for Autonomous Missions (ROAM) Uncrewed Aerial Systems (UAS) Operations Center is being used to explore different roles and responsibilities of remote operators managing multiple autonomous vehicles, with the goal of exploring human-autonomy teaming concepts that enable m:N operations (i.e., m operators managing N vehicles). ROAM has developed into a world-class research, development, and technology (RD&T) environment that can support both the collection of human factors data and the command and control of remote vehicles in beyond visual line of sight conditions. ROAM provides a key capability to enable full end-to-end hardware- and human-in-the-loop simulation testing, connecting with simulated small-UAS and creating a seamless Live-Virtual-Constructive (LVC) environment. This report describes the development of the ROAM UAS Operations Center from concept through design, culminating in the current implementation at NASA's Langley Research Center.

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1. Introduction

As part of its work with the aviation community to identify and address challenges for advanced air mobility concepts, the National Aeronautics and Space Administration (NASA) initiated the Advanced Air Mobility (AAM) Project within the Integrated Aviation Systems Program (IASP) of the Aeronautics Research Mission Directorate (ARMD). AAM was a broad mission that spans the ARMD portfolio and was managed through the AAM Mission Integration Office (AMIO). The NASA Critical Commitment of the AMIO was defined as follows:

> Based on validated operational concepts, simulations, analyses, and results from National Campaign demonstrations and other simulated and actual vehicle testing in the High Density Vertiplex[1] (HDV) and Automated Flight Contingency Management (AFCM) subprojects, the AAM Mission will deliver aircraft, airspace, and infrastructure system and architecture requirements to enable sustainable and scalable medium density advanced air mobility operations.

There were three areas of focus within the overall NASA AAM Mission portfolio: vehicle development and operations, airspace design and operations, and community integration. The AAM project was concluded in 2023, but many of its core concepts and aspirations continued to live on within the Air Traffic Management Exploration (ATM-X) and Air Mobility Pathfinders (AMP) Projects under the Aviation Operations and Safety Program (AOSP) within ARMD.

The HDV subproject, along with the other AAM sub-projects, National Campaign and AFCM, and other NASA research projects in ARMD, were working to advance the three areas of focus identified in the AAM Mission portfolio. The Critical Commitment flowed down to the AAM Project Office which traced to their goal to develop and implement an environment to accelerate AAM development and operational adoption concepts, including developing and demonstrating key automation functions, and delivering validated system architectures and requirements to the benefit of the AAM ecosystem. AAM operations are envisioned to include passenger transport, local and regional cargo transference, inspection and surveillance events, and emergency response activities [1].

From its onset, the HDV subproject was responsible for the development and maturation of automation technologies and architectures that serve AAM community infrastructure needs supporting AAM operations. To this end, HDV focused on the development and testing of concepts, requirements, software architectures, and technologies needed for the terminal environment around vertiports. Specifically, the subproject focused on how automation can increase safety, efficiency, and scalability of flight operations in these environments. Although HDV technologies, requirements, and architectures are relevant to broad AAM operations, the HDV subproject has focused on use cases that are specific for urban operations, which are closely aligned with Urban Air Mobility (UAM) operations.

To reach this goal, the HDV subproject aimed to deliver validated concepts, requirements, software architectures, and technologies needed for the terminal environment around vertiports [2]. A significant facet of this work entailed standing up a remote uncrewed aerial systems (UAS) operations center that would eventually enable a crew of human operators to remotely manage multiple highly automated small-UAS (sUAS) in Beyond Visual Line of Sight (BVLOS) conditions. The remote vehicle operations center

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[1] A *Vertiport* is defined as an identifiable ground or elevated area, including any buildings, or facilities thereon, used for the vertical takeoff and landing of an aircraft. A *High Density Vertiport* is qualitatively defined as a vertiport that supports an increasing number of aircraft movements at or near vertiport capacity. High density refers to the average aircraft movements at a vertiport needed to support UAM Maturity Level 4 operations. A *Vertiplex* is defined as multiple vertiports in a local region with interdependent arrival and departure operations.

developed under the HDV subproject is known as the Remote Operations for Autonomous Missions (ROAM) UAS Operations Center[2].

The purpose of this document is to outline the conceptual needs, design, and implementation of a remote vehicle operations center for vehicle types that support flight operations of sUAS and future UAM vehicles at NASA's Langley Research Center (LaRC). The system overview outlines the high-level requirements and needs of the operations center. The design methodology, called the Role-Based Ontology (RBO) is detailed, including the as-designed system as an outcome. Digital Services and Software that are used within the Network Architecture Design are presented followed by the roles and responsibilities of personnel and their interconnectivity within the complex system-of-systems. The report concludes with descriptions of the current, as-built implementation of the remote vehicle operations center, and highlights data collection activities that have been successfully completed at LaRC.

2. Background

Many of the AAM mission types envision electric Vertical Takeoff and Landing aircraft (eVTOL), and therefore vertiports (i.e., "identifiable ground or elevated area, including any buildings, or facilities thereon, used for the vertical takeoff and landing" of an aircraft) [3] become an important operational component to consider. Key barriers for UAM operations in the vertiport domain include:

1. A lack of standardization around required technologies and performance levels to enable high tempo and throughput to support UAM business cases around vertiports.
2. Mature concepts, procedures, and technologies supporting automated approach and landing, automated merging and spacing, and automated contingency decision making for eVTOL operations in vertiport environments.
3. Required data information exchange among the aircraft, airspace service provider, and the vertiport systems to support increasingly dense operations.

A derived barrier also exists in the development of evaluation and testing practices necessary for demonstrating that automated mitigations warrant satisfactory means of compliance to existing or future safety regulations. This is particularly true for the use of automation to support Visual Line of Sight (VLOS) and BVLOS operations for UAS vehicles. It is critical to address these barriers to ensure that the industry is ready to support UAM Maturity Level 4 (UML-4) operations[3].

Within the AAM mission portfolio, the HDV subproject addressed these barriers by designing concepts, procedures, and technologies focused on UAM operations while leveraging subscale sUAS testing to assess suitability and verify requirements around UAS and vertiport automation architectures. The HDV subproject used a "crawl, walk, run" approach to build-up complexity in the operational environment and integrate the aircraft-airspace-vertiport automation technology needed to support three main use cases: (1) automated landing, (2) automated merging and spacing, and (3) automated contingency decision making.

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[2] This facility also carries the name of NASA LaRC CERTAIN Research Command Center.

[3] UML-4 consists of medium density and medium complexity operations with collaborative and responsible automated systems. At UML-4, medium density is characterized as hundreds of simultaneous operations over a single metropolitan area or region. Medium complexity includes low-visibility operations, aircraft operating near one another in high-density routes, and operations to/from high-throughput aerodromes. There are also automated systems that do not require human oversight or mitigation of potential failures for some functions. These collaborative and responsible automated systems enable humans to have roles that differ from those performed by humans in the traditional aviation system and it is anticipated that UAM aircraft at UML-4 will utilize a network of third-party providers of services to UAM (PSUs) to manage scheduling of routes and provide automated, tactical deconfliction, in addition to other services.

HDV focused development on technology gaps associated with the use cases (e.g., auto-land capability and vertiport automation) and leveraged other ARMD technologies or industry technologies to support integration and build-out of the environment necessary for vertiport testing. HDV testing planned to increase the operational complexity with each schedule packages culminating in the integrated automation systems assessment of sub-scale (or full scale[4]) eVTOL aircraft flying into multiple nearby vertiports with interdependent arrival and departure operations (i.e., Vertiplex). The HDV vertiport automation technology was expected to increase in maturity level to support requirements development and operations in a future National Campaign activity.

Critical to the success of subprojects like HDV at NASA, a facility like the ROAM UAS Operations Center provides a controlled research environment to conceptualize, integrate, and evaluate systems of technologies that deliver on the desired goals. The following subsections outline the direct purpose of the remote vehicle operations center with statements on the initial goals, objectives and expected research capabilities.

2.1 Purpose

The ROAM UAS Operations Center at LaRC has a twofold purpose:

1. To conduct human-in-the-loop (HITL) experiments that explore different roles and responsibilities of remote operators managing multiple increasingly autonomous vehicles, with the goal of exploring human-autonomy teaming concepts [4-6] that enable *m:N* operations (i.e., *m* operators managing *N* vehicles).
2. To enable multi-vehicle sUAS flight operations from a remote location under BVLOS conditions. ROAM facilitates BVLOS flight operations of sUAS vehicles using a live, virtual, and constructive (LVC) environment.

Use cases tested within the facility focus on sUAS operations (e.g., package and food delivery, emergency response, and surveillance and reconnaissance) and passenger-carrying operations (e.g., UAM). As BVLOS operations in the National Airspace System become more common, it is important to understand how humans can effectively team with technology in a manner that supports user business models highlighted in these use cases.

The overarching design considerations for the operations center are to relocate existing field operators to the remote vehicle operation center, produce a shared situational awareness environment for participating personnel, and to provide the ability to pursue advanced vehicle operations and control supporting AAM and other various research activities. The remote operations center is envisioned to provide a user training environment, flight operations planning and briefing environment, and a research facility for simulated and live operations of sUAS vehicles. Live vehicle flight operations are conducted on the designated flight range at LaRC called the City Environment for Range Testing Autonomous Integrated Navigation (CERTAIN)[5]. A part of flight operation considerations is safety of flight for the vehicle, the local airspace, and people on the ground below and near the vehicle's flight path. Safety considerations and constraints are driven by project requirements and existing NASA policies, procedures, and regulations.

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[4] Full-scale eVTOL aircraft refers an electric aircraft that is capable of vertical takeoff and landing and capable of carrying weight equivalent to at least one passenger.

[5] CERTAIN is a designated flight range at LaRC that allows for flight operations in a wide array of environments. By utilizing the Center's buildings and landscape, operations in the CERTAIN range can be used to study the difficulties of autonomous flight in challenging scenarios. The AAM-HDV subproject plans included the buildup of test infrastructure, sensors, radio communication, and cloud-based services to demonstrate an automated vertiport environment.

2.2 Goals, Objectives, and Research Capabilities

The goals for the development of ROAM UAS Operations Center are:

1. Enable full end-to-end hardware- and human-in-the-loop (HHITL) simulation testing with live and simulated sUAS.
2. Provide a more comprehensive, permanently configured, environmentally controlled area to perform research activities involving vehicle control, coordination, and communication with other sUAS test elements.
3. Enable the testing of human-autonomy teaming concepts and technologies with live sUAS operations.
4. Enable the conduct of research to evaluate UML-4 and greater remote supervisory operations with sUAS as a proxy.

The objectives initially defined for the ROAM UAS Operations Center are:

1. Conduct VLOS and BVLOS research flight operations on the NASA LaRC CERTAIN range with multiple sUAS using the ROAM UAS Operations Center.
2. Create a shared situational awareness environment for all required personnel within the ROAM UAS Operations Center.
3. Define roles and responsibilities for personnel within the ROAM UAS Operations Center conducting VLOS and BVLOS research operations on the CERTAIN range.

Some of the expected research capabilities of the ROAM UAS Operations Center can be defined as:

1. Provide a simulation and training environment for sUAS research flight operations on the NASA LaRC CERTAIN range.
2. Support live research flight operations on the NASA LaRC CERTAIN range.
3. Enable integrated human factors data collection during training, simulation, and flight activities.
4. Enable future remote operations (*m:N*) within a live/virtual/constructive environment.
5. Provide conduit for continuous integration of human-autonomy teaming technologies with simulated and live flight operations.

2.3 Milestones

Throughout its development, the ROAM UAS Operations Center supported multiple milestones for both the AAM-HDV and Transformative Tools and Technologies Revolutionary Aviation Mobility Autonomous Systems (TTT-RAM AS) Human-Autonomy Teaming Foundational Research activity subprojects. These subproject milestones have included systems integration completion, simulation data collection, and flight testing of remote vehicles under various conditions of line of sight.

3. Remote Vehicle Operations Center Overview

An initial system description and boundary diagram for the remote vehicle operations center is presented in Figure 1 and locates the ROAM UAS Operations Center at the middle of the data and voice flow for the conduct and simulation of sUAS vehicles at LaRC. In simplest terms, ROAM is an information hub that permits users of the facility to perform roles integral to BVLOS sUAS operations. ROAM aggregates information from multiple services in the system (e.g., a Provider of Services to UAM (PSU) located at NASA's Ames Research Center (ARC), surveillance, a Vertiport Automation System (VAS), video, and weather), and generates information (e.g., either simulated or live vehicle command and control) that is transmitted throughout the system. Spanning across all locations is the service providing the voice communications.

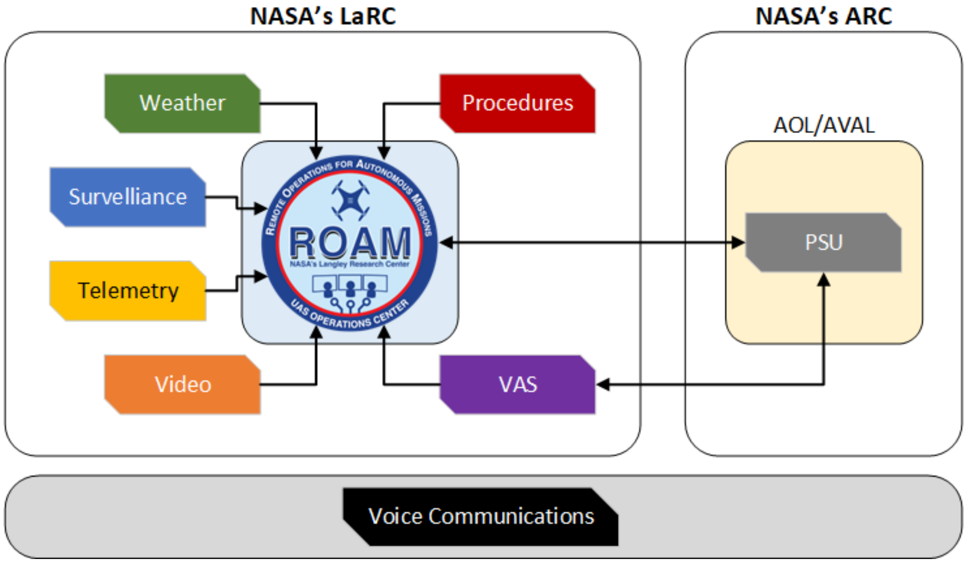

Figure 1: Conceptual System Description and Boundary Diagram

3.1 Stakeholders

The following lists the primary and interested parties at NASA that have a direct and indirect stake in the development and success of the ROAM UAS Operations Center.

Primary:

- AOSP-AAM-HDV – Vehicle & Vertiport System Integration & Flight Operations Technical Work Packages
- Transformative Aeronautics Concepts Program (TACP)-TTT-RAM-Autonomous Systems-Human-Autonomy Teaming Foundational Activity

Interested parties:

- TACP-CAS (Convergent Aeronautics Solutions) Scalable Traffic Management for Emergency Response Operations (STEReO)
- AOSP Advanced Capabilities for Emergency Response (ACERO)
- NASA LaRC CERTAIN Range
- NASA LaRC UAS Systems Integration and Validation Lab (SIVL)[6]
- NASA ARC Airspace Operations Lab (AOL) and Autonomous Vehicle Applications Lab (AVAL)[7]

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[6] SIVL is managed by the Systems Development and Analysis Branch at LaRC and is located within Building Complex 1268. SIVL maintains hardware-in-the-loop vehicles for simulation with representative research payloads and command and control links for real-time connection to ground control systems in the ROAM UAS Operations Center during simulation data collection activities for subprojects like AAM-HDV.

[7] The AOL and AVAL are located at ARC and directly supports the integration of systems and software connected to the AAM-HDV subproject. Prototyping tools for airspace management automation technologies, the ROAM UAS Operations Center connects with these facilities and shares vehicle telemetry data from LaRC in real-time allowing for the management of fleet operations. These facilities also provide simulation capabilities and controls for fleet traffic and host the PSU that is external to ROAM.

- NASA LaRC Mission Operations & Autonomous Integration Center (MOSAIC)[8]
- NASA LaRC Research Services Directorate (RSD)
- NASA Eastern Region Airworthiness Review Board (ER-ARB)
- NASA LaRC Aeronautics Research Directorate

3.2 NASA Langley Designated Flight Range

Established in 2015, the CERTAIN flight range was designated as a mix of operating areas, from rural operations up to more densely populated areas typical of an urban environment, intended for research flight testing activities at LaRC. The CERTAIN range (see Figure 2) started as a small area on the northern part of the LaRC campus (designated as CERTAIN I in Figure 2) and has steadily increased in size and capabilities since its initial inception. Currently, the CERTAIN range covers the entire LaRC campus and includes the Class D airspace up to 400 feet above ground level. Infrastructure has been established within CERTAIN to support the flight operations of sUAS for various NASA research programs and includes equipment for airspace surveillance sensors, vehicle command and control, video streaming of vertiport locations, and radio communications for field personnel. Several designated vertiport areas are equipped with dedicated power and NASA LaRC Enterprise Network (LaRCnet) services, with more coverage planned to provide greater coverage. More information on the CERTAIN range, the airspace characterization, and how it integrates into the established safety case for BVLOS flight operations at LaRC is presented in Reference [7]. To manage flights of sUAS in varying degrees of line of sight from the operators, a facility like the ROAM UAS Operations Center is required to provide the collocation of information and resources. Conversely, a remote vehicle operations center like ROAM needs an established flight range with infrastructure to perform research into such areas as increasingly autonomous vehicles, human-autonomy teaming, and vertiport operations.

As depicted in Figure 2, the CERTAIN range is made up of four individually designated areas of increasing size – CERTAIN I, II, III, and IV. CERTAIN I and northern portions of CERTAIN II are rural in nature that are unpopulated or have very low numbers of workforce populating buildings. The middle portion of CERTAIN II is exemplarily of an industrial park or college campus with more concentrated population, parking lots, walkways, and buildings. The southern portion of CERTAIN II and CERTAIN III are more urban in nature with buildings between two and five stories. Finally, CERTAIN IV includes the hangar ramp areas and taxiway that leads to the runway of Joint Base Langley-Eustis (Langley Air Force Base [KLFI[9]]). Tower control for the local airspace is located at KLFI, south-southeast of CERTAIN.

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[8] MOSAIC is the Mission Operations & Autonomous Integration Center for the CERTAIN Smart Center at LaRC.

[9] KLFI is the International Civil Aviation Organization (ICAO) airport identifier code for Langley Air Force Base, Hampton, Virginia, USA. LaRC and Langley Air Force Base share a common property line between facilities.

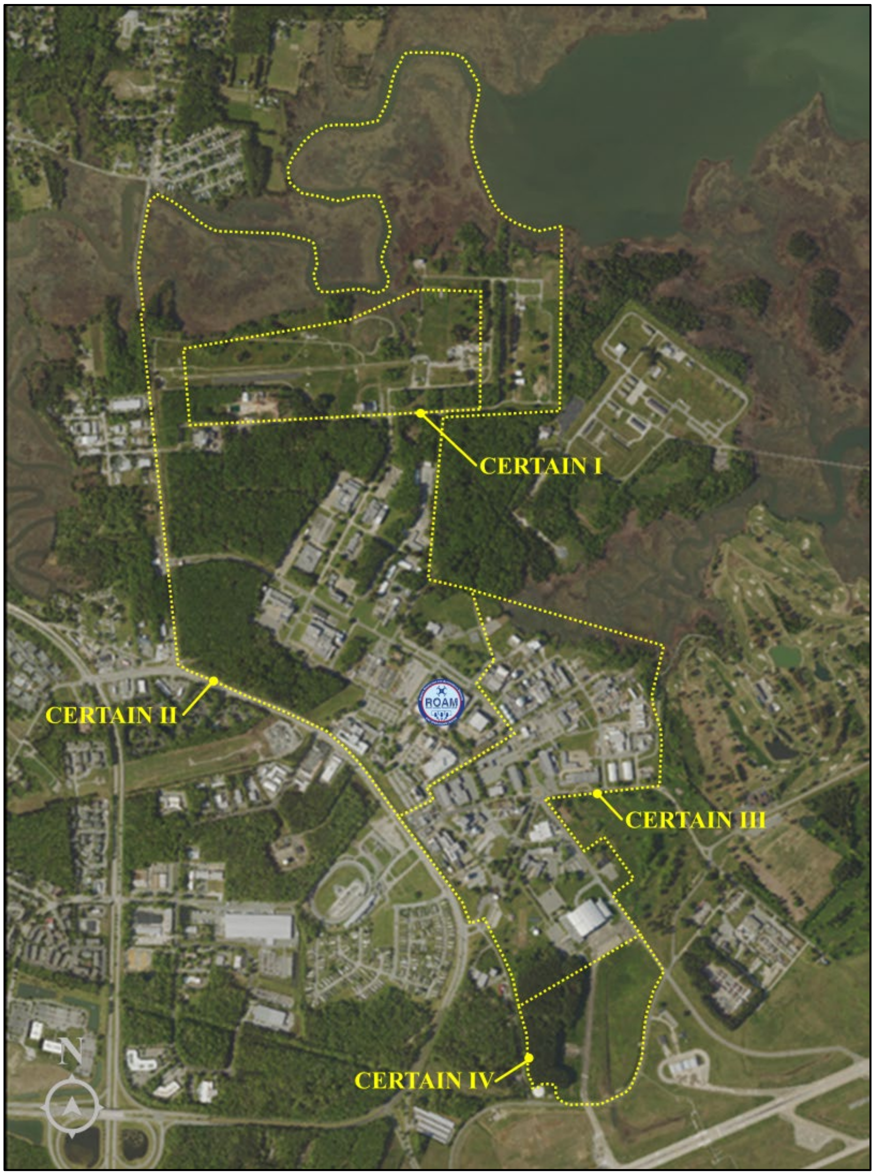

Figure 2: NASA Langley Designated Flight Range – CERTAIN

3.3 Operations Center Functions and Features

For the initial vision of the ROAM UAS Operations Center, it needed to support the intended Goals, Objectives, and Research Capabilities of the identified stakeholders. Initially, five potential high-level functions were identified, which formed the basis of the Concept of Operations for the ROAM UAS Operations Center. The functions were defined to be broad in scope and subsequently defined the role of the operations center. The operations center role would support the primary stakeholders (as described in Section 3.1), the needs of the AAM-HDV use cases, and other CERTAIN research flight operations. By decomposing these functions into individual use cases for ROAM, multiple categories of features were identified that further detailed stakeholders' expectations for the design of the remote vehicle operations center. Figure 3 presents the conceptualized high-level function and features of ROAM.

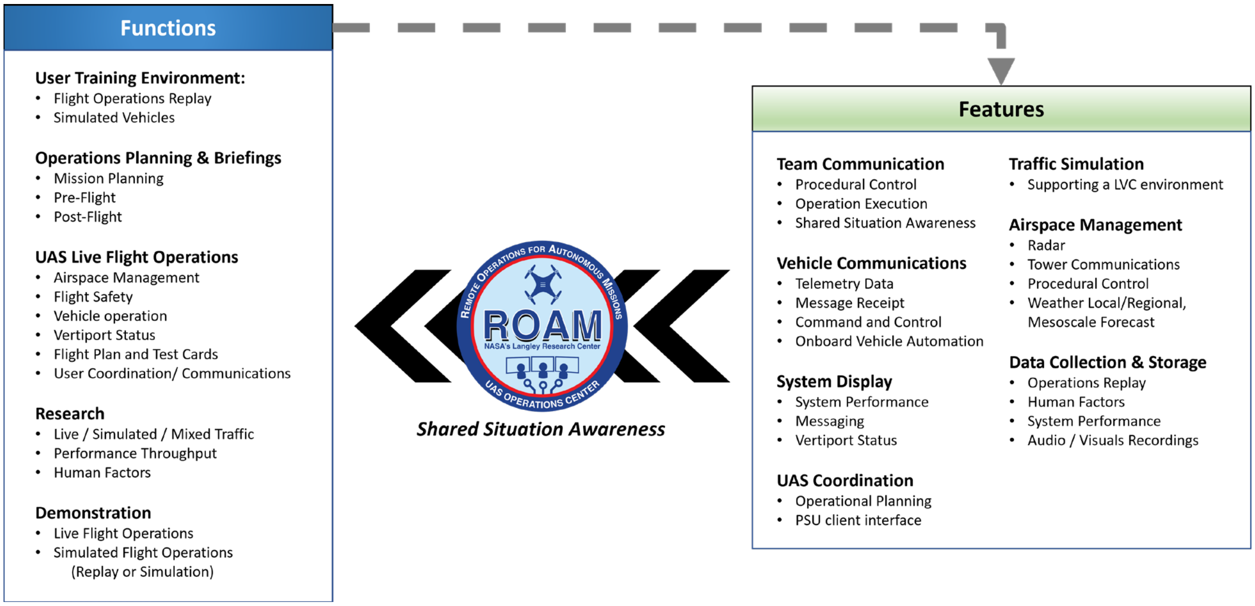

Figure 3: High-Level Functions and Features of the ROAM UAS Operations Center

Several functions were initially envisioned for the operations center like creating a user training environment, providing support for live flight operations, as well as enabling research studies. It was also important that ROAM be able to continually demonstrate established capabilities and successes from data collection activities. From these functions, features could be defined to meet and support the previously defined Goals, Objectives, and Research Capabilities. Such features as communications between team members and the vehicles, displays from various information sources, and data collection to support research activities enable the functions that ROAM delivers on. The features listed in Figure 3 were a starting point for the concept development and to create a shared situation awareness between all users within the facility and the other connected locations. It is noted that one function may require multiple features and different functions may have overlapping need in required features within ROAM. Later, the methodology described in Section 4 refined the conceptual vision and validated many of the initial features.

3.4 Technology Maturation and Transition Approach

The ROAM UAS Operations Center is in a unique position to foster the development, maturation, and use of new concepts and technology along the Technology Readiness Level (TRL) scale at LaRC. As the operations center matures in its initial development, ROAM sits in the middle of labs like the Crew System and Aviation Operations' Agile Lab[10] and the LaRC MOSAIC facility as a premier location to develop, test, and further refine concepts and technologies (see Figure 4). A facility like the Agile Lab can be the location of prototype concepts and the birth of research ideas. As a research concept becomes established, it can be brought into ROAM to further its development and prove the technology, concept, or procedure in representative operations, thereby increasing the TRL over time. As the research matures out of capabilities of ROAM, it can be advanced forward into facilities at LaRC like MOSAIC, or other industry partners, where it can be put into a more 'production like' environment for routine operational use. A facility like MOSAIC requires refined concepts that have matured out of the development stage to support routine use by its operators.

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[10] The Agile Lab is the NASA LaRC Crew Systems and Aviation Operations Branch (D318) Human Factors Research and Development Laboratory led by Dr. Eric Chancey and Mike Politowicz.

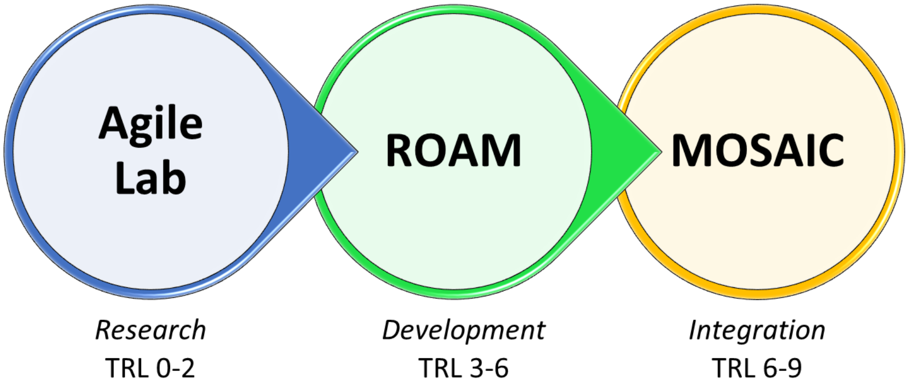

Figure 4: Technology Maturation and Transition Approach for the ROAM UAS Operations Center

This technology maturation and transition approach lowers the transfer risk of ideas and new technologies as outlined in Figure 4. This approach also leverages the established flow of research and development from the LaRC Research Directorate to the LaRC Research Services Directorate using the established 'Sim to Flight' concept.

3.5 Phased Development Approach

From the onset of the concept, the ROAM UAS Operations Center was envisioned to have a phased development approach that builds on successive phases, meeting the needs of research areas like the HDV subproject. The following table presents the phase, description, and a targeted date for completion.

Table 1: ROAM UAS Operations Center Development Phases

Phase	Description	Instantiation Date
1	• Support first simulation and data collection. • Begin the monitoring of Field operations with backup operators within the ROAM UAS Operations Center.	September 2021
2	• Monitor Field operations with backup operators within the ROAM UAS Operations Center. • Field Operator provides commands to vehicle on the flight range.	January 2022
3	• BVLOS Field operations with primary operators within the ROAM UAS Operations Center.	June 2023

3.6 General Facility Description

The ROAM UAS Operations Center is located within the Air Traffic Operations Laboratory (ATOL) within Building Complex 1268 at LaRC in Hampton, Virginia, USA (see Figure 5). The first of two rooms (ROAM-I) measures approximately 26 feet by 15.5 feet, with the second (ROAM-II) measuring approximately 19 feet by 24 feet, both with one accessible exit point each. An attached control/observation room is also available for observers during simulation and live flight operations. Suitable power and networking infrastructure are already in place within the planned location. Temperature, humidity, and ventilation needs are managed within the ATOL space. Communication infrastructure is available to support the intended flight operation of sUAS vehicles from the remote vehicle operations center.

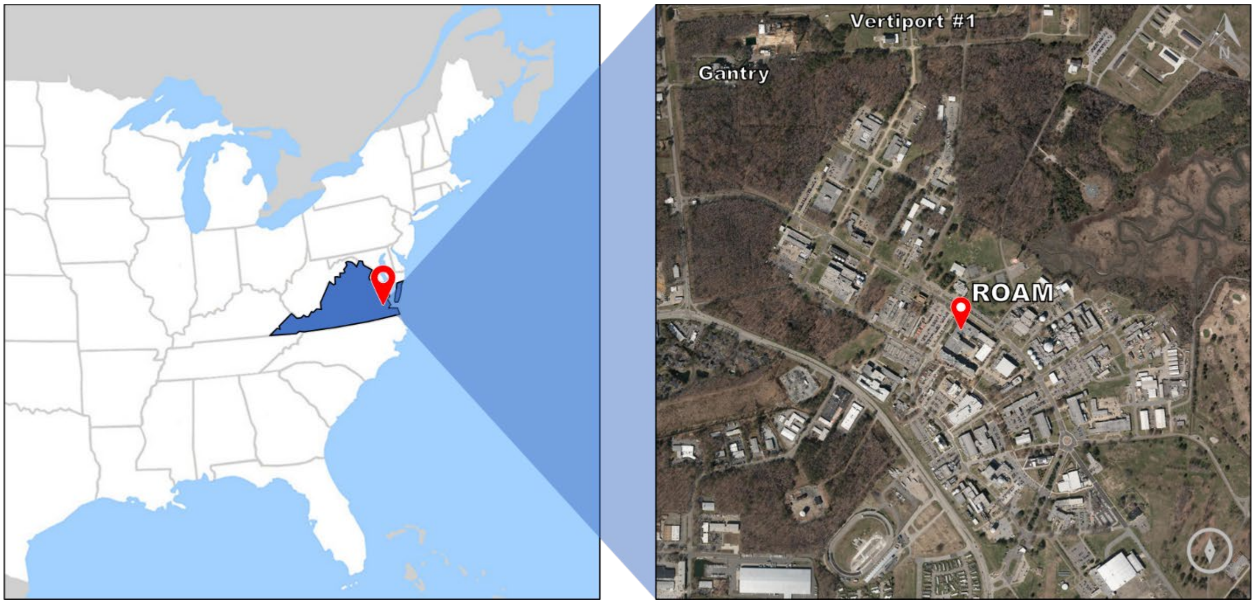

Figure 5: Location of the ROAM UAS Operations Center at LaRC in Hampton, Virginia, USA

3.6.1 Intended Occupancy

The ROAM UAS Operations Center has a maximum intended occupancy of 15 individuals consisting of flight crew, safety officials, and visitors. When required, this occupancy can be reduced based on LaRC's COVID-19 response protocols to maintain social distancing for prolonged periods of research/work within an enclosed room at a NASA facility. This restriction was exercised during initial integration in 2020 and data collection activities with ROAM in 2021.

3.6.2 Proposed Facility Modifications

No significant physical modifications were intended nor required for the design and development of the ROAM UAS Operations Center to be located within the ATOL of the Building Complex 1268 at LaRC. Additional networking and visual display cabling were identified and addressed as part of the initial phased development of the operations center. The phased development approach of the ROAM UAS Operations Center included the re-arrangement of workstations and their desks, expansion into other rooms within ATOL, and extending capability into additional connected systems to be made available across the LaRCnet. Redundant power supply systems and battery backup of core systems and support services were also considered.

4. Role-Based Ontology Design Methodology

One of the first steps in designing a new concept, whether it is a remote vehicle operations center or the latest widget for a mobile computer display, is the development of a system architecture. There are many possible approaches that can be used in a system architecture design from the rigorous to the informal. Borrowing from systems engineering [8], the role-based ontology design approach is a human-centered, logical, and structured methodology used to define a system architecture based on the roles and responsibilities of system users. An ontology is a descriptive process of linking a collection of human actors to various functions, technologies, standards, and regulations within a domain through a series of pathways and connections. The ontology framework allows for inferences and comparisons between different "models" (e.g., the relationship between Actor 'A' and Actor 'B'—they need the same set of capabilities even though their roles and responsibilities are different). This ontology approach was identified as an excellent candidate for the design and development process of the ROAM UAS Operations Center to support sUAS vehicles.

Figure 6 presents the role-based ontology approach used in the design of ROAM. Each square-cornered block within the figure relates to a parent or child area(s) of the ontology, successively building upon the previous and adding further detail. In practice, each of these blocks is implemented as an individual diagram or spreadsheet, which fits within the larger model. For each of the areas that represent a relationship-type paradigm (i.e., Actor Inventory, Organization Model, Service Inventory, Display Model), a 'fill-in-the-blank' style sentence can be developed, which then guides the spreadsheet structure and content for that block. Simultaneously defining the core inventories and models of the logical architecture allows for synchronization of system design (i.e., Network Architecture Design) and the physical design (i.e., Workstation Design), represented by the rounded-cornered blocks in the figure.

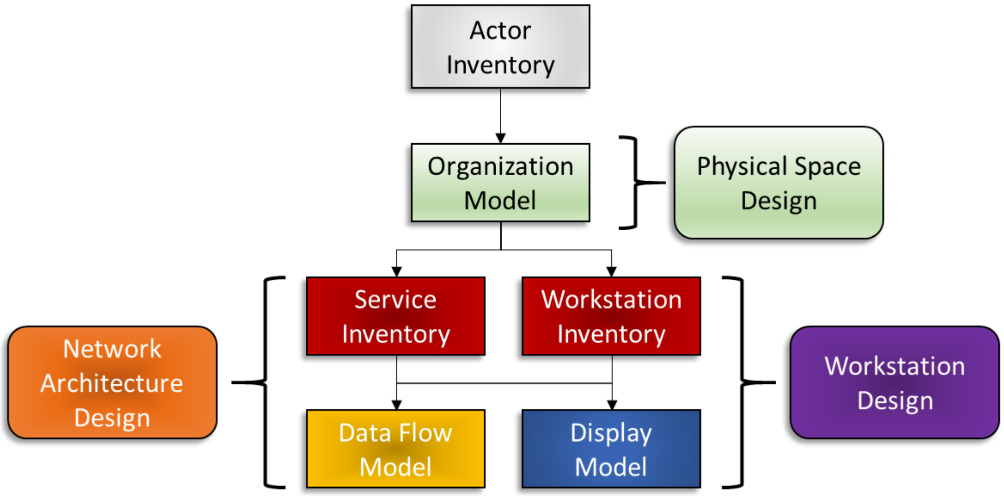

Figure 6: Role-Based Ontology Design Approach for the ROAM UAS Operations Center

Table 2 provides a short summary of each model element presented in Figure 6. Further details on each of the boxes presented in Figure 6 are described in the following subsections and within Section 5.

Table 2: Role-Based Ontology Design Model Element Summary

RBO Design Model Element	Description
Actor Inventory	The users of the system, called Actors. This inventory also includes individuals that Actors may need to interact with to accomplish a task goal.
Organization Model	Description of the core functions of an Actor, which cover the roles and responsibilities of that Actor and any guiding regulations.
Service Inventory	Capability or information resource that supports the role of an Actor and their core function to accomplish a task goal.
Workstation Inventory	Physical hardware interfaces for the Actor to directly support their core function.
Display Model	Arrangement of interfaces of Services provided to an Actor on the Workstation that directly supports their core function and fit within the Physical Space Design and Workstation Design.
Data Flow Model	Digital data and voice communication information received and transmitted by the Actor within the Network Architecture Design to accomplish a task goal.

4.1 Actor Inventory

The first step in the design process is the definition of the Actor Inventory that is a part of a small UAS vehicle's flight operation. This important identification process focused on roles filled by the users of the remote vehicle operations center and other users within the airspace system they interact with during a flight operation. The Actor Inventory defines the **{ACTOR}** with **{PRIORITY}** at **{LOCATION}** and it is a parent of the "Organization Model," "Service Inventory," "Display Model," "Data Flow Model," and "Workstation Inventory." Table 3 presents the Actor Inventory that has been developed within the AAM-HDV subproject to support flight operations at LaRC. The Actor's title and abbreviation is defined, indicating their role. Next, a Priority for the Actor is identified, which is used with redundant positions and indicates if during any phasing of the command and control of a vehicle if the Actor is in a Primary (or leading) responsible position to a Secondary counterpart. Lastly, the physical Location of the Actor is defined, indicating if the Actor is on the flight test range (Field), at the remote vehicle operations center (Remote), or outside of the local area of LaRC (External). Each Actor is described further in Section 8.

Table 3: Actor Inventory – Identification of Roles supporting AAM-HDV (up to 3 vehicles)

Abbreviation	Actor	Priority	Location
RSO	Range Safety Officer	Primary	Field
		Secondary	Remote
PIC	Safety Pilot #1 (Pilot-In-Charge)	Primary	Field
SP	Safety Pilot #2	Primary	Field
	Safety Pilot #3	Primary	Field
GCSO	Ground Control Station Operator #1	Primary	Field
		Secondary	Remote
	Ground Control Station Operator #2	Primary	Field
		Secondary	Remote
	Ground Control Station Operator #3	Primary	Field
		Secondary	Remote
xTMO	xTM[11] Operator	Primary	Remote
FTM	Flight Test Manager	Primary	Field
		Secondary	Remote
SD	Simulation Director	Primary	Remote
VM	Vertiport Manager	Primary	Remote
RO	Radar Operator	Primary	Remote/External[12]
ASM	Airspace Surveillance Manager	Primary	Remote
FM	Fleet Manager (ARC-AOL)	Primary	External
TC	Test Coordinator	Primary	External
VSC	Vehicle Service Crew	Primary	Field
VO	Visual Observer #1	Primary	Field
	Visual Observer #2	Primary	Field
	Visual Observer #3	Primary	Field
ROE	ROAM Operations Engineer	Primary	Remote
-	Researchers	Primary	Field
			Remote
-	ATOL Operations (LaRC-ATOL)	Primary	Remote
-	Airspace Control, KLFI Tower	Primary	External
VNP	Visitors / Non-Participants	Tertiary	Field
			Remote

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[11] eXtensible Traffic Management (xTM) refers to a web-based interface that connects to the PSU.

[12] The location of the Radar Operator is not collocated with other Actors in the Field. The Operator could be located within ROAM or at another designated location on LaRC.

For initial planning of the small UAS vehicle operations, redundant positions were created between the Field and Remote so that these positions could refine their actions and responsibilities with the eventual transition to being fully remote. It will also be noted that Table 3 does not include expected field/vertiport setup personnel or maintenance personnel. The actors identified in multiple locations support the functional transition of responsibility in early phases of development between Field and Remote locations.

4.2 Organization Model

Following the Actor Inventory, the next component defined is the Organization Model focused on the users of the remote vehicle operations center. This defines the Actor's role and individual responsibilities for a flight operation and what they would need to accomplish a vehicle's safe and efficient control from a remote location while supporting BVLOS flight. The Organization Model defines the **{MAX NUMBER}** of **{PRIORITY}** **{ACTOR}** at **{LOCATION}** on **{WORKSTATION}** that perform **{FUNCTIONS}** per the **{GUIDING REGULATIONS}**, and it is a parent of the "Service Inventory," "Display Model," "Data Flow Model," and "Workstation Inventory." The core functions of the user are defined with supporting individual tasks of the user. Much of this information is basis for a hierarchical task analysis of the Actors within the system. Presented in Table 4 is a single Actor for the Organization Model for the ROAM UAS Operations Center highlighting the Actor, their workstation, core functions, and guiding regulations if any.[13] The comprehensive Organization Model for ROAM (remote location only as identified in Table 3) is presented in Appendix A. The Functional Tasks that feed into the Core Functions are also presented in the appendix tables.

Table 4: Partial Organization Model depicted, highlighting the Range Safety Officer

Actor	Priority	Location	Workstation	Core Functions	Guiding Regulations
Range Safety Officer	Primary	Field	Range Safety Station	• Provides safety oversight for flight operations by monitoring Range airspace for potential risks with vehicle operations • Opens/ closes the airspace to flight operations. Contacts Tower Control • Monitors a vehicle(s) [state, trajectory, and intention] in real-time • Monitors Field airspace for other aircraft • Monitors Field current and forecasted weather • Visually monitors local airspace and operations by remote means • Communicates with SP(s), GCSO(s), VO(s), FTM, and Tower Control	• NPR 8715.5B • NPR 79003.D, Sec. 5.1.4.7 • LPR 1710.16J, Sec. 5.1.5.7, 5.8.2.3 and 5.8.2.4 • NASA-STD-8719.25, Sec. 7.2
	Secondary	Remote			
···	···	···	···	···	···

4.3 Service Inventory

Another part of the design process is the definition of the Service Inventory that supports the role of the Actor within the system. Services can be anything from the software to command and control the vehicle, to video feeds streaming from multiple locations, weather information (both current and forecasted), and even the voice communication services. The Service Inventory defines the **{FUNCTION}** that requires **{SERVICE}** from **{SOURCE}** and while it is a child of the "Organization Model," it is the parent of the "Display Model" and "Data Flow Model." As the Service Inventory developed, it was important to use common labels for functions where applicable within the Organization Model so that the required services

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[13] The ellipses (···) presented on the last row of this table and other tables in this section indicate more information is present for the system.

could be easily identified and cross-populated with multiple Actors. The Functions described in this section are defined from a user role perspective (as identified in the Organization Model) and they trace to the Functions defined by the stakeholders in Section 3.3. Additionally, the services described in this part of the role-based ontology enable the Features desired by the stakeholders as described in Section 3.3.

Table 5: Service Inventory

Core Function	Service	Source	Information Location
• Execution of simulation studies and live vehicle flights • Checklists for vehicle readiness	Procedures	• Flight Test Manger / Simulation Director	• ROAM
• Monitors Field airspace for other aircraft • Manages and coordinates flight crews and vehicle flight to conduct the test scenario(s) properly	Surveillance	• ADS-B[14] Receiver (multiple) • Flight Alarm (FLARM) Receiver • RADAR (multiple)	• CERTAIN • Field
• Monitors flight trajectory approvals from the PSU • Submits and acquires flight trajectory approvals from the PSU • Manages virtual aircraft in the simulation and flight operations	PSU	• Telemetry Service • Vertiport Automation System Service • HDV Client	• AOL/AVAL
• Monitors a vehicle(s) [state, trajectory, and intention] in real-time • Support vehicle setup, checkout, and shutdown	Telemetry	• Vehicle Telemetry Link[15], including Onboard Autonomous Vehicle Information	• Field • SIVL
		• MPATH[16] Ground Control Software	• Field • ROAM
• Manages arrival and departure operations in the terminal areas of the vertiport • Supports functionality of vertiport scheduling and closures	VAS	• Telemetry Service	• SIVL
• Visually Monitors Local Airspace and Operations by Remote Means	Video	• Flight Line • Local Airspace (multiple sources) • Point of View of sUAS Vehicle (multiple sources) • Remote vehicle operations center • Vertiport (multiple sources)	• CERTAIN • Field • ROAM • Vehicle
• Communicates with Actors in Remote Location (AOL/AVAL, ROAM, SIVL) • Communicate with Actors in the Field	Voice Comms	• User to User Communications via Clear-Com Equipment • User to User Communications via Microsoft (MS) Teams • User to User Communications via Voice over Internet Protocol (VoIP) Equipment	• AOL/AVAL • Field • ROAM • SIVL
• Opens/closes the airspace to flight operations. Contacts Tower Control.		• Actor to External (Tower Control) Communications via Over-the-Air (OTA) Aeronautical Radio	• Tower Control
• Monitors Field current and forecasted weather	Weather	• Local Weather Sensor (multiple)	• CERTAIN
		• Regional Weather Sensor (multiple)	• Internet
		• Mesoscale Weather Forecasts	• Internet

4.4 Workstation Inventory

The Workstation Inventory portion of the design process helps to identify the physical hardware interfaces and specifications needed for individual Actors that are part of the Organization Model and where common equipment can be used if a workstation is reconfigured for another Actor. The Workstation Inventory

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[14] Automatic Dependent Surveillance – Broadcast [13-16].

[15] Vehicle Telemetry Link may use any one of the desired and proven paths into the ROAM UAS Operations Center like Botlink Relay or uAvionix microLink using MAVLink as the coded message format.

[16] NASA modification of QGroundControl open-source software platform.

defines specifications of the physical hardware interfaces at **{WORKSTATION}** and while it is a child of the "Organization Model," it is the parent of the "Display Model." This inventory can be used for a build sheet of human machine interfaces and support the cost estimation process of the development of a remote vehicle operations center. After identification of the requirements of the hardware to support the services needed by individual Actors, this inventory is used to estimate the number of spares required to support uninterrupted operations. The Workstation Inventory for the ROAM UAS Operations Center is presented in Table 6, and the current specifications for the workstation designated as ROAM Workstation Type 1 and the forward Video Wall description is presented in Table 7.

Table 6: Workstation Inventory

Workstation	Computer Equipment	Human Factors Equipment	Voice Communications	Additional Voice Hardware
Range Safety Station	ROAM Workstation Type 1		VoIP Telephone, Clear-Com Desk Panel	Aeronautical Radio
Ground Control Station	ROAM Workstation Type 1	Tobii Pro Nano[17] iPad Pro Tablet or Digital Questionnaire	VoIP Telephone, Clear-Com Desktop Software	
xTM Station	ROAM Workstation Type 1		VoIP Telephone, Clear-Com Desk Panel	
Flight Test Manager Station	ROAM Workstation Type 1		VoIP Telephone, Clear-Com Desk Panel	
Simulation Director Station	ROAM Workstation Type 1		VoIP Telephone, Clear-Com Desk Panel	
Airspace Surveillance Station	ROAM Workstation Type 1		VoIP Telephone, Clear-Com Desk Panel	
Radar Station	ROAM Workstation Type 1		VoIP Telephone, Clear-Com Desk Panel	
Vertiport Station	ROAM Workstation Type 1	iPad Pro Tablet or Digital Questionnaire	VoIP Telephone, Clear-Com Desk Panel	
...	...	...	...	...

Table 7: ROAM Workstation Type 1 and Video Wall – Current Specifications

Workstation Type 1	
Computer	• Dell Precision 7820 Tower • NVidia GeForce RTX 2080 Super, 8GB • Windows 10 Pro for Workstations • Integrated NIC • Secondary NIC for telemetry connection to vehicle (live or simulated) • 8x DVD +/- RW Optical Drive • 8x Half-Height BD-RE Drive • M.2 512Gb Solid Sate Drive • 2.5" 500Gb 7200rpm SATA Hard Drive • 3.5" 1Tb 7200rpm SATA Hard Drive • 64Gb DDR4 Memory • Intel Xeon Silver 4210 2.2GHz, Dual Core
Operating System[18]	• Windows 10 Pro
Monitors[19] & Stand	• Dell P2721Q 26.96" 16:9 4K USB Type-C IPS Monitor • Dell P2418HT 24" 16:9 10-Point Touchscreen IPS Monitor • Dell MDS19 Dual Monitor Stand
Peripherals	• Keyboard (Dell KB813) - wired with embedded PIV card reader • Mouse (Dell MS116) – wired

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[17] Screen based eye tracker which captures gaze data at 60Hz and is designed for fixation-based studies. https://www.tobiipro.com/product-listing/nano/

[18] Workstations begin as a bare system with only the Windows 10 Pro operating system installed. Basic software required of all LaRCnet computers is installed and configured by ATOL System Administrators. Additional software is added as necessary.

[19] Each workstation has at least three monitors attached to the computer. Monitors are capable of portrait or landscape presentation, allowing for a variety of configurations. A touchscreen monitor is available for the Ground Control Station Operators allowing for a tilted screen of forty-five degrees.

Video Wall[20]	
Wall No. 1 (ROAM-I)	• Type: Live Wall Media Display Video Wall • Composition: Nine (9) 55" Ultra-Thin Bezel (UTB) Light Emitting Diode (LED) Display Panels • Arrangement: 3 panels wide x 3 panels tall • Physical Dimensions of Wall: 144" wide, 81" high • Combined Screen Resolution: 5760 pixels wide, 3240 pixels tall
Wall No. 2 (ROAM-II)	• Type: Live Wall Media Display Video Wall • Composition: Six (6) 55" UTB LED Display Panels • Arrangement: 3 panels wide x 2 panels tall • Physical Dimensions of Wall: 144" wide, 24" high • Combined Screen Resolution: 5760 pixels wide, 2160 pixels tall
Display Panel	• 55" LED UTB Display Panel • Ultra-Thin 1.7mm Bezel (3.5 mm total bezel between adjacent panels) • Inputs - HDMI, DVI, VGA • HD Native Resolution 1920 x 1080 LED back lit • Brightness: 500 nits • Mean Time Between Failures: 60,000 hours • All Metal Construction • RS-232 display control • Pull-Out Wall Mount
Video Processor	• Live Wall Media Video Processor 40i • (9) HD Display Output, max resolution 3840 x 2160 at 60Hz (max 594 MP/s) per channel • (34) HD Video Inputs, HDMI 3840x2160 at 60 fps • 19” 4U Industrial PC chassis, 11 slot / 19" 4U Expansion Chassis, 11 slot • Intel i7 processor • 16 GB system memory • Dual Hard Drives, RAID 1 • Two Gigabit Ethernet ports • Dual redundant power supplies
Video Processor Expansion (x2)	• (12) HD Display Outputs in HDMI, Max output resolution per display - 1920 x 1080 • (16) HD Video Inputs, HDMI, Max input resolution - 2048 x 1536
Operating System	• Windows 10 LTSC 64-bit operating system • Wall Control Pro
Peripherals	• Keyboard - wired with embedded PIV card reader • Mouse – wired

Another essential part of the Workstation Inventory is the software applications that are needed at a particular workstation for each Actor. Not every Actor in the Organization Model needs access to all the same software applications to perform their respective roles. However, it was taken into consideration that every workstation should be capable of running any software application or access any service as identified in Sections 6 and 7 to ensure flexibility of the workstations of ROAM in future configurations.

For details on the current hardware specifications of the workstations and the software applications that are in use within the ROAM, please refer to the current version of the ROAM UAS Operations Center Hardware and Software Manifest (Reference [9]).

4.5 Data Flow Model

The Data Flow Model joins together information from the Workstation Inventory and the Service Inventory to define the consumption and production of information necessary for the conduct of operations within the ROAM UAS Operations Center. The Data Flow Model defines the **{WORKSTATION}** that requires **{SERVICE}**, and it is a child of the “Organization Model,” “Workstation Inventory,” and the “Service Inventory.” This model describes the receipt and transmission of data from possible services required by the Actor to support their role in the remote vehicle’s operation in a BVLOS situation. With these data

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[20] Video Wall Hardware specific acronyms: DVI = digital visual interface, HD = high definition, HDMI = high-definition multimedia interface, LTSC = long-term servicing channel, PIV = personal identity verification, RAID = redundant array of independent disks, RS = recommended standard, U = rack unit (standard height measurement within a network rack enclosure, VGA = video graphics array

flows identified for the organization model, data and voice services can be 'connected' for the Actors within the remote vehicle operations center. Table 8 presents a listing of the Data Flow Model. A checkmark (✓) represents a need for the model and empty gray boxes (☐) indicates that no primary need is currently present.

Table 8: Data Flow Model

Workstation	Data Comm - Receive	Data Comm - Transmit	Voice Comm - Receive	Voice Comm - Transmit
Range Safety Station	✓	☐	✓	✓
Ground Control Station	✓	✓	✓	✓
xTM Station	✓	✓	✓	✓
Flight Test Manager Station	✓	☐	✓	✓
Simulation Director Station	✓	☐	✓	✓
Airspace Surveillance Station	✓	☐	✓	✓
Radar Station	✓	☐	✓	✓
Vertiport Station	✓	✓	✓	✓
…	…	…	…	…

4.6 Display Model

The part of the design process that is most important to the Actor is the Display Model. The Display Model defines the **{ACTOR}** at **{WORKSTATION}** that requires **{SERVICE}** and it is a child of the "Organization Model," "Workstation Inventory," and the "Service Inventory." This model describes all the different services required by the Actor to support their role in the remote vehicle's operation in a BVLOS situation. With the services identified in the display model, initial display concepts can be developed for the Actors within the remote vehicle operations center. Table 9 presents a partial listing of the Display Model highlighting the Service for Data Communications. Presented in Table 10 is a partial listing of the Display Model highlighting the Service for Voice Communications. For both tables, a checkmark (✓) represents a need for the model and empty gray boxes (☐) indicates that no primary need exists.

Presented in Figure 7 is a potential display concept for the Ground Control Station Operator (GCSO). Primary screen real estate is given for the Ground Control Station (GCS) software with the many supporting information sources located on separate screens. Once the hardware is physically set up with sources displayed, additional human factors design considerations can be evaluated with the Actors to improve the location of information for display and to qualify its ease of consumption for the safe and efficient operation of a remote vehicle. Specifically, display design considerations relating to proximity compatibility issues [10], selective attention (see salience effort expectancy value model outlined in Reference [11]), and ergonomic accommodations (e.g., 45° angle of desktop touch screen [12]) were important at this step. Additional conceptual individual workstation designs based on the needs of the role performed by the Actor in ROAM are presented with several of the Internal Operators located in Section 8.1.

Table 9: Partial Display Model Depicted, Highlighting Service – Data Communications

Actor	Workstation	Video	Weather	Surveillance	Vehicle[21]	Messaging[22]	Operation Info[23]	PSU
RSO	Range Safety Station	✓	✓	✓	✓	✓	✓	
GCSO	Ground Control Station	✓	✓		✓	✓	✓	✓
xTMO	xTM Station				✓	✓	✓	✓
FTM	Flight Test Manager Station	✓	✓	✓		✓	✓	
SD	Simulation Director Station	✓				✓	✓	
ASM	Airspace Surveillance Station	✓				✓	✓	
RO	Radar Station			✓	✓	✓		
VM	Vertiport Station	✓	✓		✓	✓	✓	✓
-	Video Wall	✓	✓	✓	✓	✓	✓	✓

Table 10: Partial Display Model Depicted, Highlighting Service – Voice Communications

Actor	Workstation	Remote	Field	External – Tower	External – ARC AOL/AVAL
RSO	Range Safety Station	✓	✓	✓	
GCSO	Ground Control Station	✓	✓		
xTMO	xTM Station	✓	✓		✓
FTM	Flight Test Manager Station	✓	✓		✓
SD	Simulation Director Station	✓			✓
ASM	Airspace Surveillance Station	✓	✓		
RO	Radar Station	✓			
VM	Vertiport Station	✓	✓		✓
-	Video Wall	N/A	N/A	N/A	N/A

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[21] Vehicle Control & Onboard Autonomous Vehicle Information

[22] System Messaging / User Messaging

[23] Procedures, Checklists, and Test Card for planned operations

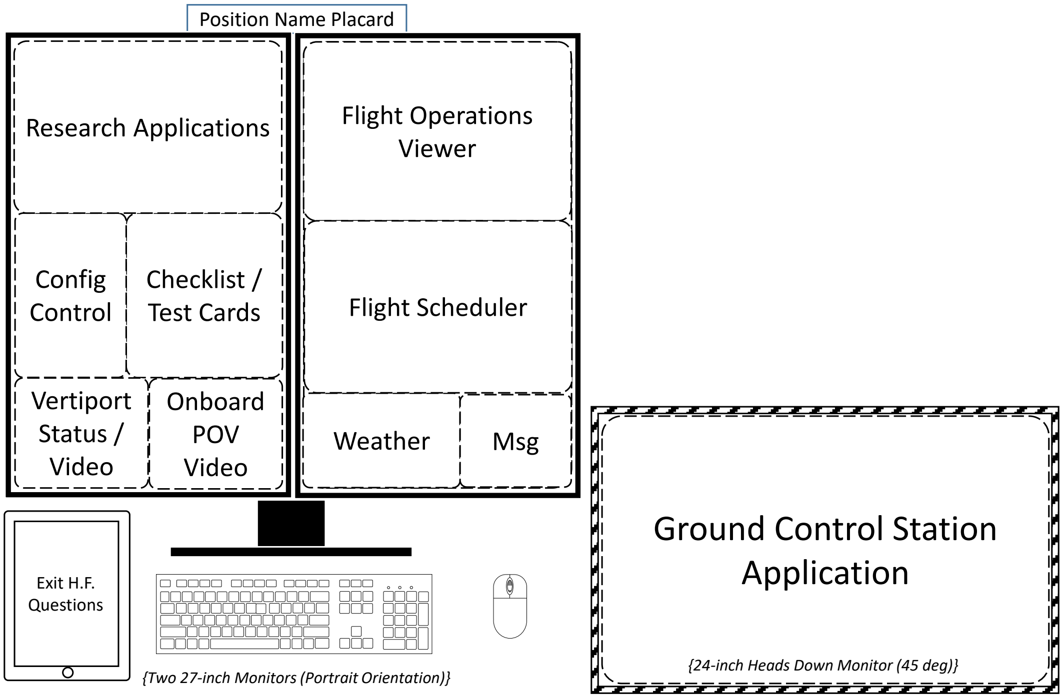


Figure 7: Conceptual Display Arrangement for a Ground Control Station Operator

An important aspect of the design process is the promotion of a shared situation awareness among all Actors within the remote vehicle operations center. This starts with common services that support the display of information to a user across multiple roles. The next step is to create a common source of information that can be shared by the Actors from their individual workstations. This can be accomplished with the use of individual large format monitors, or a video wall composed of multiple monitor displays, either located in a position viewable from all individuals present in the room. Figure 8 presents the option selected at LaRC for ROAM-I to provide this common knowledge interface. The video wall can support multiple layouts and configurations of information data sources. The video wall can be used during pre- and post-flight briefings for an operation, it serves as the common source of information during a flight for users and visitors to the remote vehicle operations center, and it can be used as a central messaging location for Actors like the Flight Test Manager or Range Safety Officer to communicate planned or unplanned changes or to handle unexpected events. In our initial design of the video wall, the data sources displayed matched those required by the Range Safety Officer.

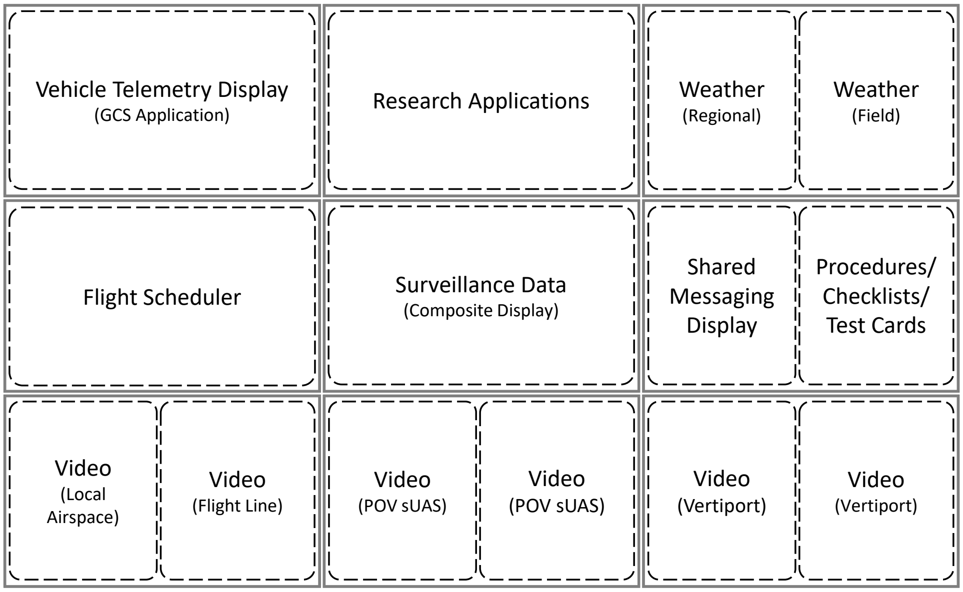


Figure 8: Conceptual Shared Situation Awareness Display for the ROAM UAS Operations Center

A Video Wall, like the one that is present in the ROAM UAS Operations Center, offers considerable flexibility for the planning, conducting, and wrap-up of both simulated and live vehicle flight operations. The Video Wall is located at the forward end of the room, making it visible to all Actors in ROAM and it provides a common and shared situation awareness for the personnel. In ROAM-I it is composed of a three-by-three grid of 55-inch monitors, and in ROAM-II it is composed of a three-by-two grid of 55-inch monitors. Both are connected to a video controller capable of a final output native resolution of 1920x1080 at each monitor. Inputs to the video controller come from each of the individual workstation screens and are connected via HDMI extenders. The video wall supports multiple, quick-switching video layout configurations that meet the need of the operations within ROAM. Layouts can also span across monitors uninterrupted, as well as including multiple full monitor sources inset within a single display monitor on the video wall. Actors that nominally sit at the rear of the room like the Range Safety Officer (RSO) have most Video Wall displayed content available for presentation on their individual workstation monitors.

5. System Design

The System Design of the ROAM UAS Operations Center is an outcome following the Role-Based Ontology design methodology presented in Section 4. While simultaneously defining the core inventories and models of the logical architecture, the RBO allows for synchronization of the physical design (i.e., Workstation Design) and the system design (i.e., Network Architecture Design), which are represented by the rounded-cornered blocks in Figure 6. Table 11 provides a summary of the RBO Design Model Outcome with details provided in the following subsections.

Table 11: Role-Based Ontology Design Model Outcome Summary

RBO Design Model Outcome	Description
Physical Space Design	Physical layout of Actors and the Workstations with accompanying Services that they engage with to accomplish a task goal.
Workstation Design	Equipment or resource with a Service that the Actor uses with a matching Display design to accomplish a task goal.
Network Architecture Design	Structured arrangement of Workstations and Services for the Actors across a network realizing the desired Data Flow.

5.1 Physical Space Design

With the creation of an Organization Model for the Actors of the remote vehicle operations center, the design of the physical space can begin. Knowing the number of Actors and their role helps to identify their placement within a room or facility. Figure 9 presents a conceptual workstation layout for up to six Actors, their workstations, and a forward video wall for shared situation awareness. During the physical layout portion of the design, consideration was given regarding the spacing of individuals for both comfort and for social distancing related to the COVID-19 pandemic. An operations center design should also consider if some personnel may be located within another room nearby or other location on center, based on their functional role.

The initial design and layout of the ROAM UAS Operations Center for the first scheduled work package for the AAM-HDV subproject assumes four individual workstations, as denoted by solid lines/colored boxes in Figure 9. Additional future positions within ROAM for supporting multiple vehicles are denoted by dashed lines surrounding a physical location. This initial design focused on the placement of workstation positions with associated computer hardware and consideration was given for line-of-sight for Actors at a workstation to see the forward video wall. Approximate dimensioning is shown with conceptual locations of workstation monitors (represented by the black colored rectangles, thin arcs, and thin rectangles.

This early design of the facility took place the COVID-19 pandemic where spacing was created to remain compliant (six feet between personnel) for up to six positions within the ROAM UAS Operations Center; a limitation imposed from 2020 to 2021 for the number of personnel in an enclosed room. Personnel required for additional vehicles in future operations within ROAM were identified to be in another room nearby to remain compliant.

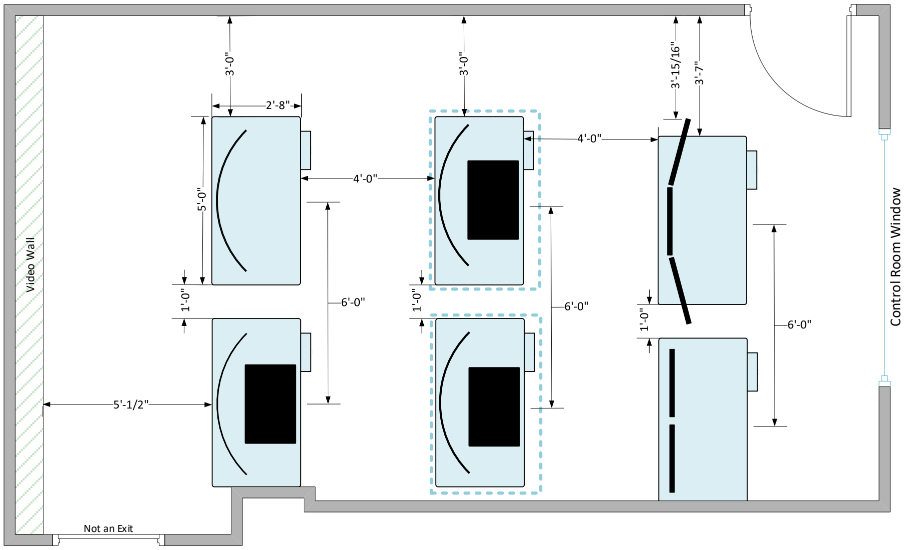


Figure 9: Prototype ROAM Initial Physical Space Design and Layout

A generalized layout for the ROAM UAS Operations Center is presented in Figure 10. The initial design of the operations center and its layout is intended to support workstation areas for the Ground Control Station Operator, Range Safety Officer, Flight Test Manager (FTM) or Simulation Director (SD), and the xTM Operator (xTMO). At full build-out, the ROAM UAS Operations Center is able to support six workstations, three of which are for the Ground Control Station Operator monitoring and (in the future) controlling remotely operated vehicles. As the role of the xTM Operator is eventually transferred over to that of the Ground Control Station Operator to work with the Fleet Manager (FM) (located remotely at

ARC), the xTM Operator workstation can be transitioned to another workstation for a Ground Control Station Operator.

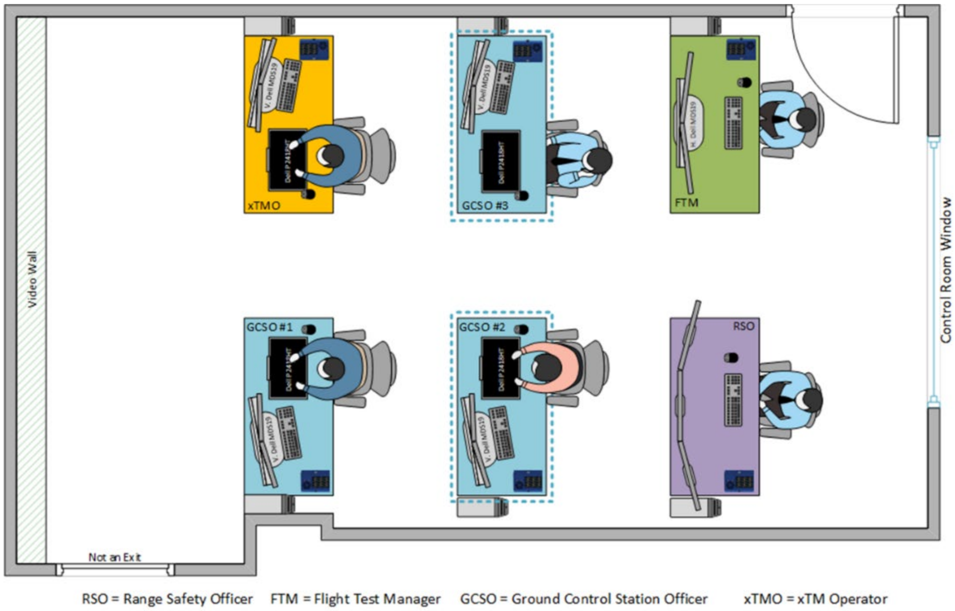


Figure 10: Prototype ROAM UAS Operations Center Generalized Layout

An exploration of the phased implementation of ROAM and its varied layouts is presented in Section 8.

5.2 Workstation Design

An outcome of the development of several individual elements of the Role-Based Ontology design methodology is the Workstation Design. The workstation is a part of the physical space that each Actor uses to complete their assigned roles and support the mission of the operations center. Several guidelines were considered in the Workstation Design, including keeping the displays of information simple and in a consistent presentation format while facilitating the user's movement among the output sources. It was important that the workstation be easily reconfigurable and interchangeable, dependent on the needs of planned activities for a day/week. So, flexibility is key and services running within the remote vehicle operations center be capable of display on each workstation, dependent on the Actor. The Workstation Design comes after, but may also return requirements to and inform, the Physical Space Design.

Six workstations were initially planned for the ROAM UAS Operations Center to support simulated and live vehicle operations during initial HDV data collection activities in 2021 and 2022. These first workstations supported the following positions within ROAM:

- Flight Test Manager / Simulation Director
- Range Safety Officer
- Ground Control Station Operator (up to 3)
- xTM Operator (removed prior to first simulated data collection activity)

The subsequent expansion of ROAM added an additional six workstations in an adjoining room, to increase the number of vehicles supported in live flight operations and additional Actor roles. This new arrangement of workstations supported the following positions within ROAM:

- Flight Test Manager / Simulation Director
- Range Safety Officer

- Ground Control Station Operator (up to 6)
- Vertiport Manager (VM)
- Airspace Surveillance Manager (ASM)
- Radar Operator (RO)

A workstation's design for the ROAM UAS Operations Center includes a desktop computer component capable of supporting the software applications and storage needs of the Actors within the Organization Model, multiple monitors capable of portrait and landscape orientation, and standard wired peripherals. For human factors assessment questionnaires for the Ground Control Station Operators, an iPad with stand can also be included at the workstation (paper versions are available as a backup option). Details on the workstation specifications can be found in the Workstation Inventory within Section 4.4. Additional hardware interfaces are added and arranged to support voice communications internal and external to the operations center, including an aeronautical radio for the Range Safety Office. The voice communication service and hardware are described in Section 6.7.

The roles and responsibilities of the personnel within ROAM during simulated and live flight operations are varied, and each role has a workstation with a layout and various data sources that personalize the workstation to suit their needs. The specific design layout of each workstation and of the video wall undergoes an iterative process based on feedback from users during the operational use of the space to ensure that user's needs are met. Figures 11-14 presents the various workstation layouts within the ROAM UAS Operations Center during a flight activity in April 2022.

Figure 11: Flight Test Manager Workstation with Forward Video Wall

Figure 12: Range Safety Officer Workstation

Figure 13: Ground Control Station Operator Workstation

Figure 14: Six Interconnected LaRCnet Workstations / Interchangeable Based on User's Role

Figure 15: Forward Video Wall, Connected to Any ROAM Workstation Monitor

Individual workstation designs based on the needs of the role performed by the Actor in ROAM are presented with several of the Internal Operators located in Section 8.1.

5.3 Network Architecture Design

The ROAM UAS Operations Center is a single piece of a larger, complex system that supports both simulated and live flight operations of sUAS at LaRC. An outcome in the process to develop the Organization Model and other elements for ROAM is a Network Architecture Design that is directly based on the identification of the Service and Workstation Inventories with the Data Flow Model. The role of an Actor dictates the services required and their need to communicate or receive data from a 'source' has helped to identify the prototype design of a network architecture for ROAM.

Presented in Figure 16 is the conceptual network architecture design for the remote vehicle operations center. ROAM is dependent upon the data information flows coming into it to be an effective facility in the remote command and control of vehicles. Operators within the facility need various services as sub-systems to complete and monitor information, typically in a publish/subscribe format where the data is generally always available and the users query for the information on a periodic or manual basis. As a conceptual design, the input components are not fixed but remain flexible so that as new information sources or capabilities are identified, then they too may be incorporated into the operations center. Sub-systems are broken down into simulation and live vehicle operations, scheduler, surveillance information systems, communications, vertiport information, etc.

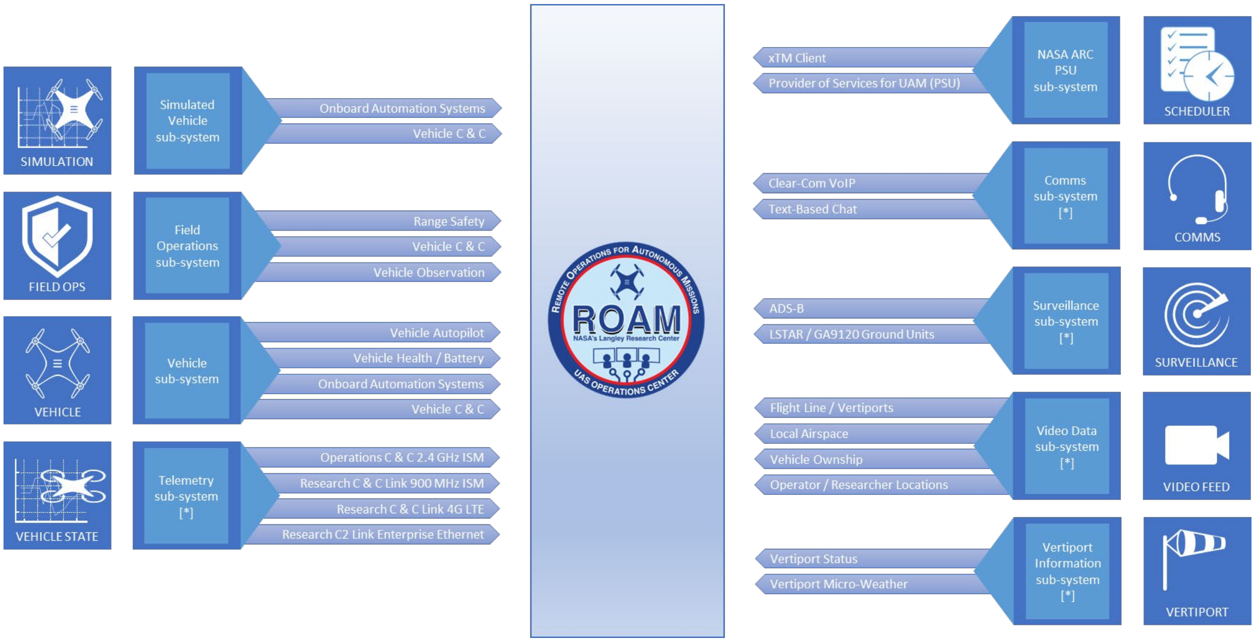


Figure 16: ROAM UAS Operations Center Conceptual Network Architecture

A formalized network architecture can be broken down into multiple parts, focused on specific aspects and relationships of components and functions while always illustrating the data flow to, from, and between resources. Often a physical network architecture is focused on the hardware devices that move the data within the boundary of a facility, and at times interfacing with external resources like the internet. A physical network architecture is beyond the scope of this report. Some network architectures define the security standards of the system, including access control and data movement. For the ROAM UAS Operations Center, the security of the system is managed and implemented by system administrators that follow a NASA Software Security Plan (SSP) agreed to by all responsible officials. In addition to a NASA SSP, one or more Interagency Security Agreements (ISA) may be required for the communication of information between data systems at different locations within NASA. An ISA was required to establish connectivity between ROAM and resources at ARC that supported the fleet scheduler.

Another distinct network architecture is one that is bound by standards on performance, reliability, and efficiency. As a research facility at LaRC, ROAM does not require the 24/7/365 uptime guarantee or low measurable latencies dictated by commercial systems servicing users around the world. Research within an evolving area like AAM can take many different directions and although ROAM is designed to make the most use out of its resources and be cost effective, it is meant to support the objectives and needs of the research community and not that of the business world. The network architecture design that is presented within this report is more akin to a logical network. An outcome of the Role-Based Ontology defined resources and their interconnectivity can be shown clearly focused on the needs of the Actor.

Presented in Figure 17 is Network Architecture Design for ROAM as it was established through the data collection activities of 2023. The main columns of the figure present the Source of information (vehicles, sensors, cameras, etc.), the Service sub-system (surveillance, telemetry, voice comms, etc.) that may be the amalgamation of multiple sources at different locations, and the software on ROAM workstations (camera displays, weather displays, etc.). On the right-hand side of the figure, the role of the Actors within ROAM are listed as rows separated by a dashed line. Interconnectivity of the resources are shown by the lines with arrows directing the flow of information. It will be noted that many acronyms and abbreviations are used within the figure for brevity and these individual components are discussed throughout Section 6 and 7.

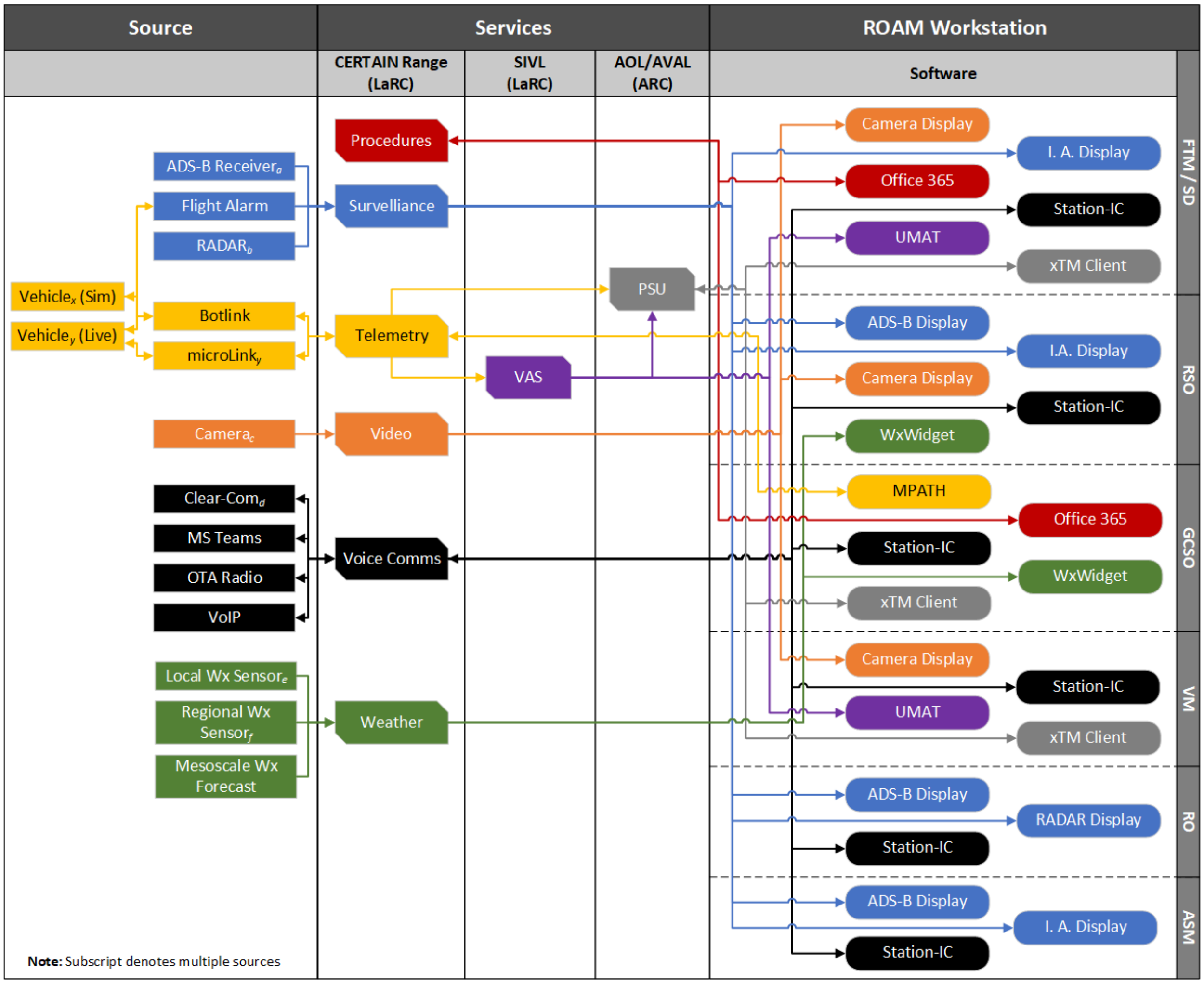


Figure 17: ROAM Network Architecture Design

6. Digital Services

Identified within the Role-Based Ontology design methodology is the Service Inventory (Section 4.3) followed by the Network Architecture Design (Section 5.3) that supports multi-vehicle operations from the ROAM UAS Operations Center. The outcome is a collection of Digital Services for the implementation of a service-oriented architecture following a pseudo publish-subscribe model, where the services and information within are available for the Actor's consumption on an as-needed basis and they provide feedback into the system asynchronously based on their role. It will be noted that multiple services inform multiple actors in the system design of a remote vehicle operations center. Overall, this collection of Digital Services fosters a loosely coupled, scalable, and responsive system by allowing services and Actors to communicate efficiently through an asynchronous timeline in a publish-subscribe paradigm.

The following subsections describe the various forms and methods used to support digital communication links between the ROAM UAS Operations Center, the Field, and external operators during simulation and flight test operations. Each service is described followed by a brief description of the sources that provide the data to the service. The underlying telemetry format is discussed as well as future platforms that can support a larger system of components for vehicle control. Additionally, the simulated versus live vehicle operation is discussed with connection of digital communication to the HDV Client and the Voice Communication Service that has been developed is presented.

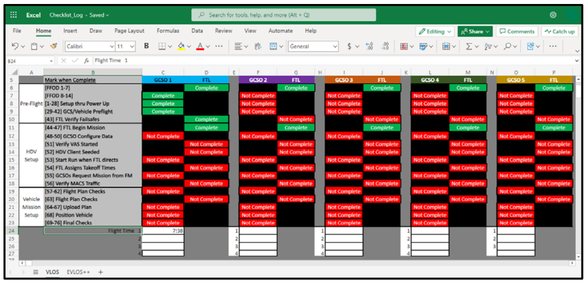
6.1 Procedures

An early identification in the role-based ontology for the remote vehicle operations center key to mission success is the sharing of information among Actors within ROAM and with Actors located in the Field. The Procedures Service is a collection of these information sources used in simulated and live vehicle flight operations. These sources include the checklists for vehicle flight and their safe action, procedures for response to off-nominal conditions of the vehicle or the surrounding airspace, and the Test Card—a summary of key information of the expected flight for one or more vehicles. The sharing of information through the Procedures Service connects all Actors, allowing them to function as a unit during an operation and not in isolation during flight operations.

Initial instantiations of the ROAM UAS Operations Center enabled the Procedures Service using analog items like paper checklists, requiring frequent updates and coordination of status validity; communications through the Voice Comms Service often over LaRC telephones and personal cellular phones; and disparate coordination of multiple Actors in multiple locations. As the number of simultaneous vehicle flight operations increased, the initial solution was no longer tenable. The Procedures Service would need to grow with the increasing complexity of the operations that were desired to be conducted to ensure the safety of people and property participating.

Although an in-house solution would have allowed full customization of the needs of the multiple Actors, initial schedules of projects using sUAS vehicles on the CERTAIN range and commanding them from ROAM was aggressive, not allowing significant research and development time. A tractable solution that all users at NASA were familiar and comfortable using is the suite of Microsoft Office365 products including Excel, Word, and PowerPoint. The software product is already established within the LaRCnet allowing for the sharing of digital information between identified users and initially fits the needs of shared checklists, procedures, and test summaries. Individual Actors access the shared resource files at a ROAM workstation or remote computer located in the Field, allowing real-time connectivity and status with each other, and thereby reducing the volume of necessary voice communication. Additionally, the Voice Comms Service continued to evolve, adding new improvements and capabilities, supplementing the Procedures Service, and enhancing Actor experiences. The Voice Comms Service is explained further in Section 6.7.

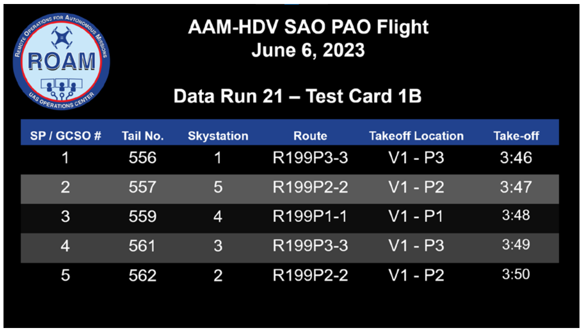
The content of the operational checklists and procedures is customized by the subproject holding the data collection activity and is often directed by the role of the Flight Test Manager or Simulation Director. With digital versions of these shared sources, updates can be made ensuring that all Actors are using the most up-to-date version at the start of a day (most often confirmed at the Safety Briefing before First Flight of the Day). Given the length of time for vehicle readiness prior to flight, individual remote pilot and vehicle status is conveyed across a shared Excel spreadsheet, using fill colors of cells to quickly convey immediately where a particular Actor is within a given checkout. An example of a checklist status used for flight operation is presented in Figure 18. Similarly, a Test Card is used to inform and remind remote pilots of information on the scenario to be flown, take-off information including vertiport, vertipad, and launch time, and the sequence of flights if multiple vehicles are included. An example of a Test Card is presented in Figure 19.



Flight Time 1

	Mark when Complete	GCSO 1	FTL	GCSO 2	FTL	GCSO 3	FTL	GCSO 4	FTL	GCSO 5	FTL
Pre-Flight	[FFOD 1-7]		Complete		Complete		Complete		Complete		Complete
	[FFOD 8-14]	Complete		Not Complete		Not Complete		Not Complete		Not Complete	
	[1-28] Setup thru Power Up	Complete		Not Complete		Not Complete		Not Complete		Not Complete	
	[29-42] GCS/Vehicle Preflight	Complete		Not Complete		Not Complete		Not Complete		Not Complete	
	[43] FTL Verify Failsafes		Complete		Not Complete		Not Complete		Not Complete		Not Complete
HDV Setup	[44-47] FTL Begin Mission		Complete		Complete		Complete		Complete		Complete
	[48-50] GCSO Configure Data	Not Complete		Not Complete		Not Complete		Not Complete		Not Complete	
	[51] Verify VAS Started		Not Complete		Not Complete		Not Complete		Not Complete		Not Complete
	[52] HDV Client Seeded		Not Complete		Not Complete		Not Complete		Not Complete		Not Complete
	[53] Start Run when FTL directs	Not Complete		Not Complete		Not Complete		Not Complete		Not Complete	
	[54] FTL Assigns Takeoff Times		Not Complete		Not Complete		Not Complete		Not Complete		Not Complete
	[55] GCSOs Request Mission from FM	Not Complete		Not Complete		Not Complete		Not Complete		Not Complete	
	[56] Verify MACS Traffic		Not Complete		Not Complete		Not Complete		Not Complete		Not Complete
Vehicle Mission Setup	[57-62] Flight Plan Checks	Not Complete		Not Complete		Not Complete		Not Complete		Not Complete	
	[63] Flight Plan Checks		Not Complete		Not Complete		Not Complete		Not Complete		Not Complete
	[64-67] Upload Plan	Not Complete		Not Complete		Not Complete		Not Complete		Not Complete	
	[68] Position Vehicle	Not Complete		Not Complete		Not Complete		Not Complete		Not Complete	
	[69-76] Final Checks	Not Complete		Not Complete		Not Complete		Not Complete		Not Complete	
	Flight Time 1	7:38		1		1		1		1	
	2			2		2		2		2	
	3			3		3		3		3	
	4			4		4		4			

Figure 18: Flight Operation Checklist Display



AAM-HDV SAO PAO Flight
June 6, 2023

Data Run 21 – Test Card 1B

SP / GCSO #	Tail No.	Skystation	Route	Takeoff Location	Take-off
1	556	1	R199P3-3	V1 - P3	3:46
2	557	5	R199P2-2	V1 - P2	3:47
3	559	4	R199P1-1	V1 - P1	3:48
4	561	3	R199P3-3	V1 - P3	3:49
5	562	2	R199P2-2	V1 - P2	3:50

Figure 19: Flight Operation Test Card Display

When suitable, information within the Procedures Service is shared on the forward video wall(s) of the ROAM UAS Operations Center. This presents key information to Actors for status and intention of the flight operation. This displayed information is often shared across the digital camera to the researchers within ROAM and remote locations and observers if present. Various layouts of the forward video wall with the shared information are presented in several figures within Section 9.

6.2 Surveillance

One of several resources within the CERTAIN Range at LaRC is the ground-based surveillance infrastructure that has been established to support sUAS flights in BVLOS conditions. Multiple source devices provide information with real-time data as both processed “raw” information for display and as an input into an integrated fusion display of vehicle traffic above the LaRC campus, forming the backbone of the Surveillance Service used by the remote vehicle operations center. The surveillance infrastructure is used to detect and track air traffic in the Class D airspace around the CERTAIN Range during research flight operations with the primary purpose of detecting non-participating aircraft so that the “see and avoid” requirements of BVLOS flight operations can be met. This allows the determination of potential threats to BVLOS sUAS operations while providing Actors enough time to apply corrective actions if necessary. The additional information provided by the Surveillance Service provides Actors in the Field and Remote locations to manage and coordinate the conduct of the test scenario(s) for mission safety according to guidelines set by the NASA ER-ARB.

Input sources into the Surveillance Service include multiple radars on CERTAIN with each type providing a complementary capability and coverage area to the other type, multiple receivers of ADS-B transmission of equipped aircraft in the local airspace, and a FLARM receiver. A brief description of each surveillance source is presented below. The software application descriptions that use or display the surveillance source is presented in Section 7.

6.2.1 Automatic Dependent Surveillance-Broadcast (ADS-B)

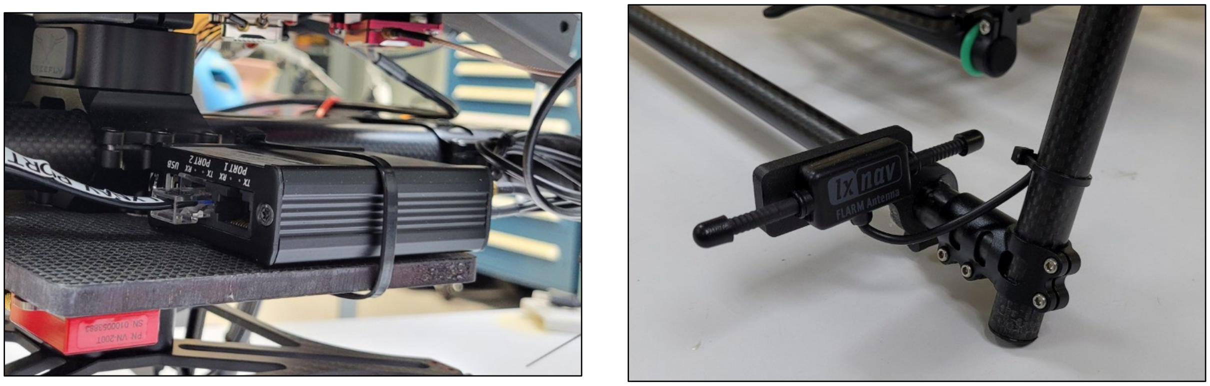
Knowing the real-time position of general aviation and commercial aircraft near the CERTAIN range at LaRC is accomplished using ground-based Automatic Dependent Surveillance-Broadcast (ADS-B) receivers. ADS-B [13-16] is the regular broadcast of a vehicles position, typically known from the vehicle or satellite navigation system, using a transponder operating at either 1090 or 978 megahertz. As a source for the Surveillance Service, telemetry data from ADS-B supports onboard vehicle detect and avoid algorithms and is used as an input into an integrated fusion display of vehicle traffic.

The CERTAIN range is currently equipped with several ADS-B ground-based receivers at one or more locations, with the primary being located near the top of the Gantry Structure next to Building 1297 at LaRC (see Figure 20). Data from the selected hardware device, uAvionix pingStation 3, is routed through the LaRCnet to Actors within ROAM and for display within the Integrated Airspace Display. Although the reception of aircraft ADS-B transmissions vary depending on the transmitting aircraft altitude and transmitter power, the range of reception far exceeds the minimums required for monitoring the local airspace during sUAS flight operations. Further details on the use of ground-based ADS-B receivers at LaRC can be found in Reference [7].

Figure 20: ADS-B Receiver at NASA's Langley Research Center

6.2.2 Flight Alarm (FLARM)

A source implemented by the AAM-HDV subproject to the Surveillance Service is Flight Alarm (FLARM), providing position information directly to other vehicles and to ground fusion systems with an integrated fusion display. FLARM, also known as PowerFLARM, as a product [17] was originally developed to support crewed sailplanes, providing situation awareness and specialized rules to make the monitoring user aware of the location of other sailplanes. For remote controlled sUAS at LaRC on CERTAIN, FLARM provides a data telemetry link for sUAS-to-sUAS vehicle communications. This telemetry supports onboard vehicle detect-and-avoid algorithms and a fully independent vehicle position source while airborne. FLARM information is also captured by a ground-side computer located in the field during flight operations, routing that data to destinations across the LaRCnet. For simulation data collection activities, a similar unit is used within hardware-in-the-loop testing and connected to benchtop vehicle hardware, emulating a complete system. The FLARM unit selected and installed for the current sUAS vehicles is the PowerMouse by LXNAV [18] and is presented in Figure 21(a) and the vehicle antenna mount is presented in Figure 21(b). The PowerMouse FLARM unit transmits position information once per second on a range of 902 to 928 megahertz using a frequency hopping spread spectrum schema.



(a) FLARM Vehicle Transceiver (b) FLARM Antenna

Figure 21: FLARM Hardware Installation on sUAS Vehicle

6.2.3 Radar

Multiple radar hardware devices provide data as a source to the Surveillance Service. The first is the Lightweight Surveillance and Target Acquisition Radar (LSTAR), a single hardware device within a protective enclosure that is mounted on the top of Building 1244 at LaRC. The LSTAR, pictured in Figure 22, is located approximately 100 feet above ground level, creating an excellent field of view for the radar to monitor operations around the CERTAIN Range.

The LSTAR operates an adjustable L Band[24] frequency between 1215 and 1300 megahertz with a transmission power of 720 watts. With a 360-degree coverage of the airspace surrounding CERTAIN, the LSTAR is set up to detect general aviation aircraft out to at least five miles up to altitudes of 2,500 feet. Further details on the LSTAR and its application at LaRC can be found in Reference [7].

Figure 22: LSTAR Radar at NASA's Langley Research Center

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[24] L Band is an Institute of Electrical and Electronics Engineers (IEEE) designation of the frequencies from 1 to 2 gigahertz (GHz).

The second radar type installed on the CERTAIN range is a pair of Ground Aware 9120 (GA9120) Radar hardware units, located near the top of the Gantry Structure next to Building 1297 at LaRC. The GA9120s, shown in Figure 23, are located approximately 200 feet above ground level, creating an excellent field of view for the radar to monitor operations around the CERTAIN Range and providing partial coverage above the LSTAR for its cone of silence that exists approximately 30 degrees above the horizon. The addition of the GA9120 Radar complements the LSTAR installation and adds enhanced capabilities to detect and track sUAS vehicles due to its higher operational frequency.

The GA9120 operates an adjustable S Band[25] frequency between 3150 and 3250 megahertz. As a stationary unit, the GA9120 pair are installed to provide overlapping coverage and directed toward to majority of the CERTAIN Range. The GA9120 is capable of detection of aircraft up to nine miles out and sUAS vehicle types up to three miles out. Further details on the GA9120 Radar and its application at LaRC can be found in Reference [7].

Figure 23: GA9120 Radars at NASA's Langley Research Center

6.3 Provider of Services to UAM (PSU)

A unique service envisioned by stakeholders in the support of urban air mobility vehicle operations is the concept of a PSU. Reference [19] defines a PSU as "an entity that assists UAM operators with meeting UAM operational requirements to enable safe and efficient use of UAM corridors and vertiports [while the] service provider shares operational data with stakeholders and confirms flight intent." At NASA and within subprojects like AAM-HDV, the PSU is a service that provides a strategic deconfliction capability of small-UAS operations (simulated, live, and a hybrid mix) prior to takeoff and can provide continued up-to-date information on operational intent of other vehicles. With new information from a vehicle operator, the PSU reviews the planned operation for potential conflicts prior to take-off and continue to monitor the vehicle position to that original plan and alert the operator if a vehicle is out of that planned volume or off schedule. [20] The PSU provides this shared intent among connected users, and possibly other PSUs, enhancing "the capabilities of individuals operators in all phases of operations through exchange, analysis, and mediation among all relevant actors" [19].

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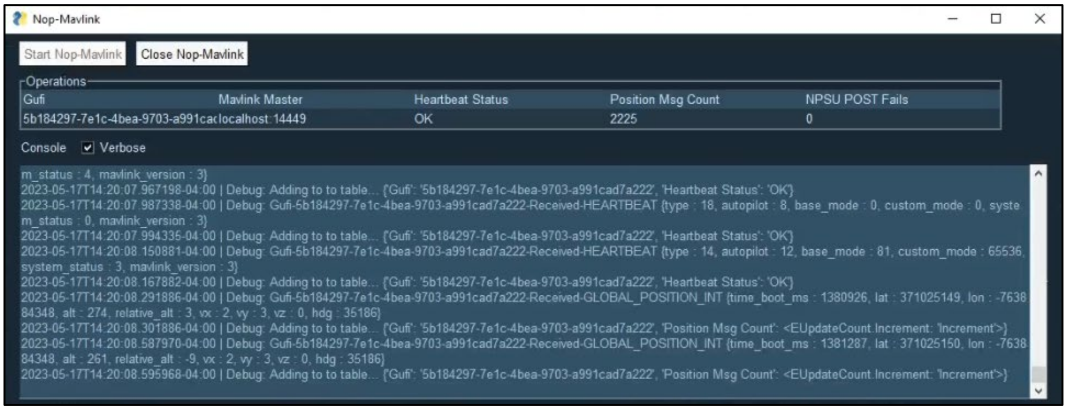
[25] S Band is an IEEE designation of the frequencies from 2 to 4 GHz.

The PSU is connected to multiple information sources including vehicles and the Vertiport Automation System—providing resource status at target sites like vertiports, vertipads, and vertistops. In the case of flight plan negotiations, the PSU can modify the original operation so that the vehicle can remain contingent with the expected flight trajectory and confirms a new landing time slot with the Vertiport Automation System. When an operation is submitted to the PSU by an operator, it reserves the airspace for that operation and the intent of the vehicle to occupy the volume at the scheduled time. Further information on the cloud-based PSU that has initially been used in connection to the ROAM UAS Operations Center and details on the concept of vehicle conformance with airspace volumes is presented in References [20] and [21].

Directly connected to the PSU is the HDV Client, a user software interface (see Section 7.3 for additional information) and the airspace management tool for Actors in ROAM during data collection activities for the AAM-HDV subproject. During operations (simulated and live flight), vehicle telemetry data is sent from the GCS software application to the HDV Client via a telemetry forwarding module developed by the researchers at ARC called the NASA Operations Planner, or NOP (see Figure 24). With this information, the HDV Client interface can present to a Ground Control Station Operator in ROAM the location of the ownship vehicle, other vehicles (live or simulated) in the local airspace, and airspace volumes for those vehicles. Access to the HDV Client is provided by secure Internet connection and login credentials to a secure site that is within the Interagency Security Agreement. This is viewed at the workstation of the Ground Control Station Operator alongside of the MPATH GCS and other software application for command and control of a vehicle.



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84348, alt : 274, relative_alt : 3, vx : 2, vy : 3, vz : 0, hdg : 35186}
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Figure 24: NASA Operations Planner with Connection to a Vehicle

6.4 Telemetry

The Telemetry Service is a key component in the remote command and control of a vehicle from a remote vehicle operations center. Telemetry data provides not only vehicle health and state data to the remote pilot but also allows for mission plan changes as needed to be uploaded to the vehicle. For visual line of sight operations, vehicle telemetry is communicated to a handheld radio controller unit that allows for manual control of the vehicle and other information needed is obtained by eye from the pilot. With Extended Visual Line of Sight (EVLOS) and beyond, telemetry data of the vehicle plays a more critical role in the success of the mission's objectives. At NASA, researchers have implemented and tested several communication data links within a fleet of vehicles at LaRC while connecting to new NASA technologies being tested onboard the vehicle. The information and rate at which the telemetry data is updated is important to not only the remote Ground Control Station Operator, but to the Range Safety Officer overseeing the local airspace, and the Flight Test Manager managing the data collection activities.

For the buildup to multi-vehicle flight and BVLOS operations, redundant and separate telemetry links are utilized to minimize link, connectivity, and antenna failure. As documented in Reference [7], the telemetry links to the vehicle use separate frequency bandwidths to minimize the chances of electromagnetic inference in one band affecting the connectivity in the other band. Current implementation uses the 4G LTE band (cellular communications) and the industrial, scientific, and medical (ISM) frequencies at 900 megahertz (MHz). The ISM 900 MHz is unlicensed frequency band and is primarily used in visual line of sight of the receiver unit and often in low altitude flight. These datalinks provide the remote pilot information to monitor and manage the vehicle in real-time through all phases of flight.

The Telemetry Service includes the transmitter and receivers located on the vehicle and on the CERTAIN range that move the messaging data back and forth. Currently, two sources for the telemetry datalinks are Botlink XRD 4G LTE Cellular and uAvionix microLink, described in Section 6.4.2 and 6.4.3 respectively. Another component feeding into the Telemetry Service is the command and control of the vehicle from the remote GCS software. For the current operations within the ROAM UAS Operations Center, that software is MPATH (see Section 7.6 for further details) providing ongoing pilot input into the vehicle system. The following subsections describe details on the vehicles, communication protocol, and the datalink sources.

6.4.1 Vehicles

Vehicles in use today on the CERTAIN range are separated into the three categories noted within Appendix A of Reference [22].

- Category I – Takeoff gross weight less than 55 pounds, and level flight airspeed less than 87 knots indicated airspeed (KIAS).
- Category II – Takeoff gross weight greater than or equal to 55 pounds, but less than 330 pounds, and level flight airspeed less than 200 KIAS.
- Category III – Takeoff gross weight greater than 330 pounds, and maximum airspeed in level flight may be greater than 200 KIAS.

The small-UAS vehicles used by projects like the AAM-HDV subproject fit into the Category I definition and include advanced technologies for onboard automation developed by NASA. Two of these technologies are the Independent Configurable Architecture for Reliable Operations of Uncrewed Systems (ICAROUS) and Safe2Ditch (S2D), although not always enabled for flight operations both are designed to serve as backup safety features for remote operations of small-UAS in BVLOS conditions. ICAROUS provides safe separation of the ownship vehicle with nearby neighboring vehicles and is permitted when enabled to maneuver the small-UAS to avoid other traffic and maintain the minimum preset separation distance. More information on ICAROUS can be found in References [23] and [24]. The S2D technology provides alternate re-route guidance to the operator should the designated landing site become unavailable for safety reasons. More information on S2D can be found in References [25-27]. Both autonomous systems are designed as secondary safety devices for deconfliction actions, should human intervention fail.

One type of the Category I vehicles that are operated on the CERTAIN range and managed from ROAM is the Alta 8 Pro Multi-Rotor, shown in Figure 25. With a diagonal length of 52 inches (not including the props) and a typical weight of approximately 30 pounds (not exceeding the vehicle maximum of 40 pounds), the Alta 8 Pro has a maximum speed of 30 KIAS with a typical flight time of 15-20 minutes. The vehicle supports multiple digital communication links including a 2.4 GHz radio-controlled link, 4G LTE cellular link, and a 900 MHz radio link. The vehicles used in flight testing are configured with a mission computer housing several of the previously mentioned autonomous system technologies providing autonomous detect and avoid and emergency landing with contingency management. By design, the resulting vehicle capabilities are technologically comparable to envisioned UAM aircraft of future systems of test.

Figure 25: Small-UAS Alta 8 Pro Multi-Rotor Vehicle

6.4.1.1 Vehicle Simulation vs Live Flight

Throughout this document, it has been described that the ROAM UAS Operations Center can connect to vehicles that are part of live flight operations, simulated flight operations, or a hybrid of the two. The main discriminator between the two main forms of operations is that 'live' vehicle operations includes the Field and its Actors as described in Section 8. A small-UAS vehicle of up to 50 pounds is controlled and monitored from ROAM by the Ground Control Station Operator over one of the vehicle control telemetry links.

Enhancing the realism of the simulation data activities conducted, two options can be used. The first is a very close match to the live vehicle operations by connecting to a hardware-in-the-loop vehicle simulation that is in SIVL. A simulated vehicle operation from SIVL includes a hardware-in-the-loop representation of the research payload (NVIDIA Jetson Xavier computer) and command and control (Pixhawk Cube Blue) for a single vehicle. Communication to the simulated vehicle may be either using the Botlink Relay with the Botlink XRD or across the LaRCnet is transmitted to a ROAM workstation running the MPATH QGroundControl Software, which forwards vehicle data to an airspace management tool, HDV Client. The simulated vehicle dynamics model is a modified version of the xProHelixPX software and global positioning system (GPS) data are connected directly to the Pixhawk Cube Blue. Additional data sources like traffic data are generated and received by the Xavier computer. This allows the simulated vehicles to be aware of other traffic in the simulation, both hardware-in-the-loop vehicles and simulated vehicles) with the sharing of traffic position information within a common simulation hub connected to each offboard computer. NASA technologies being tested or demonstrated are run within the NVIDIA Jetson Xavier computer.

The other option available for simulated vehicles is the connection to open-sources models available like those in MissionPlanner 1.3.74 [28] or other NASA developed UAS vehicle models like the UAM Flyer [29]. Connections to these vehicle models can be done locally at a workstation computer or across networked systems. These resources offer an extended group of options that can be applied to research questions in the development of an operations center or an UAS ecosystem.

6.4.1.2 Micro Air Vehicle Link (MAVLink) Vehicle Telemetry

The Micro Air Vehicle Link (MAVLink) is the selected communication protocol [30] used for vehicle control using digital communication links on the CERTAIN range. The telemetry protocol allows for vehicle state and health data to be received by a GCS and the command and control of the vehicle for simulated and live operations. MAVLink also supports messaging for NASA technologies that may be tested with the vehicles. Detailed information can be found online at ardupilot.org and within Reference [31].

Also, a mesh radio system was initially installed at multiple locations within the CERTAIN range at LaRC. It was tested and eventually abandoned before the start of the first simulation activities because of reliability issues. It is superseded by the vehicle telemetry system described in Section 6.4.3.

6.4.1.3 Message Queuing Telemetry Transport (MQTT) and Internet of Things (IoT)

Another method under consideration for vehicle control from the ROAM UAS Operations Center is the use of the NASA Internet of Things (IoT). The IoT can describe many different types of devices, applications, and sensors that can be networked together to provide a sense of shared services and information using the Internet as its backbone architecture. The NASA IoT is a specified collection of network services for use by engineers and researchers at NASA to build and deploy for use IoT applications and data gathering/collection. Core services include a publish/subscribe message broker known as Message Queuing Telemetry Transport (MQTT), message routing, data collection and storage, web-based dashboards and analytics, automation, and integration with other extended services. Although best suited for numeric time-series data in a JavaScript Object Notation (JSON) format, it is capable of transmitting data like MAVLink vehicle telemetry data between authorized devices and users. This allows the development of the publish/subscribe model first envisioned for the Data Flow Model that the ROAM UAS Operations Center and other devices and facilities would connect to, instead of multiple and redundant peer to peer connections within the NASA Enterprise Network.

6.4.2 Botlink eXtended Range Datalink (XRD) 4G LTE Cellular

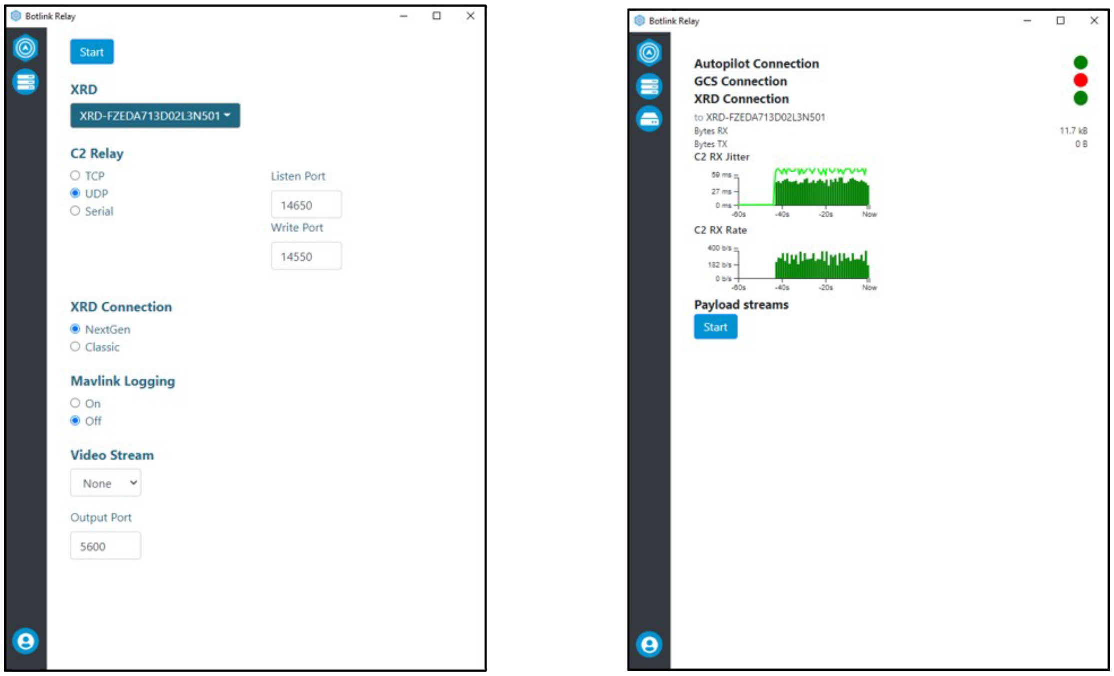
The Botlink eXtended Range Datalink (XRD) is a 4G telemetry link used to connect a GCS with a vehicle's autopilot module. NASA has included this equipment (see Figure 26) on small-UAS to provide a redundant communication link between the ROAM UAS Operations Center and the vehicle for all phases of flight, including surface operations. The Botlink uses licensed frequency spectrum for 4G telecommunications. A software application, Botlink Relay, is installed on the GCS workstation and used by a software application like MPATH. This digital communication link offers all the GCS controls that are provided by nominal 900 MHz telemetry links to handheld control units. The Botlink system requires the GCS to be connected to the Internet and the small-UAS to be connected through 4G LTE[26] to the internet. Pairing the Botlink and uAvionix microLink (see Section 6.4.3) digital communication links, they provide dual, fully independent communication links to the small-UAS with similar response times (< 0.5 seconds). Further information on the Botlink XRD can be found in References [32] and [33].

---

[26] Fourth Generation Long-Term Evolution, standard for wireless broadband communications for mobile devices.

Figure 26: Botlink XRD 4G LTE Device for small-UAS Vehicles

Figure 27 presents the user interface for the Botlink Relay software that is used from the ROAM UAS Operations Center.



XRD
XRD-FZEDA713D02L3N501

C2 Relay
○ TCP
● UDP
○ Serial
Listen Port: 14650
Write Port: 14550

XRD Connection
● NextGen
○ Classic

Mavlink Logging
○ On
● Off

Video Stream
None
Output Port: 5600

(a)

Autopilot Connection 🟢
GCS Connection 🔴
XRD Connection 🟢
to XRD-FZEDA713D02L3N501
Bytes RX 11.7 kB
Bytes TX 0 B

(b)

Figure 27: Botlink Relay Graphical User Interface (Two Screens)

6.4.3 uAvionix microLink

The uAvionix microLink [34] may also be used to connect a GCS to the vehicle's autopilot. The 900 MHz mesh radio from uAvionix has been installed in the small-UAS to provide a redundant communication link between the ROAM UAS Operations Center and the vehicle for all phases of flight, including surface operations. Although direct line-of-sight communication to the vehicle is not possible from ROAM, the uAvionix microLink provides the ability to communicate to the vehicle through the Internet using a software platform provided by the manufacturer. Flight operations on CERTAIN can use an installation of an uAvionix microLink unit called skyStation at the vehicle takeoff and landing location directly connected to the LaRCnet. Pairing the Botlink and uAvionix microLink digital communication links, they provide dual, fully independent communication links to the small-UAS with similar response times (< 0.5 seconds). Figures 28 and 29 present a picture of the microLink Radio installed on a small-UAS vehicle and the flight line microLink receiver (skyStation) connected to LaRCnet. Figure 30 presents the user interface for the microLink, called skyLink, that is used within the ROAM UAS Operations Center.

Figure 28: uAvionix microLink Radio Installed on Vehicle

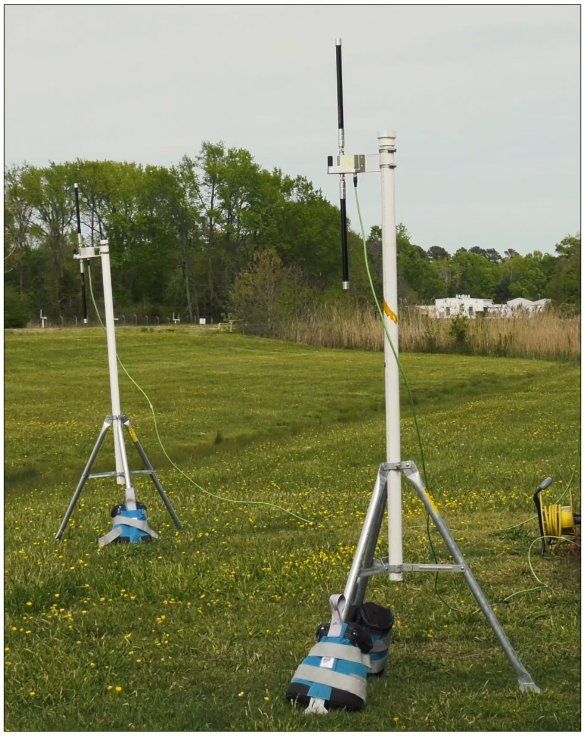
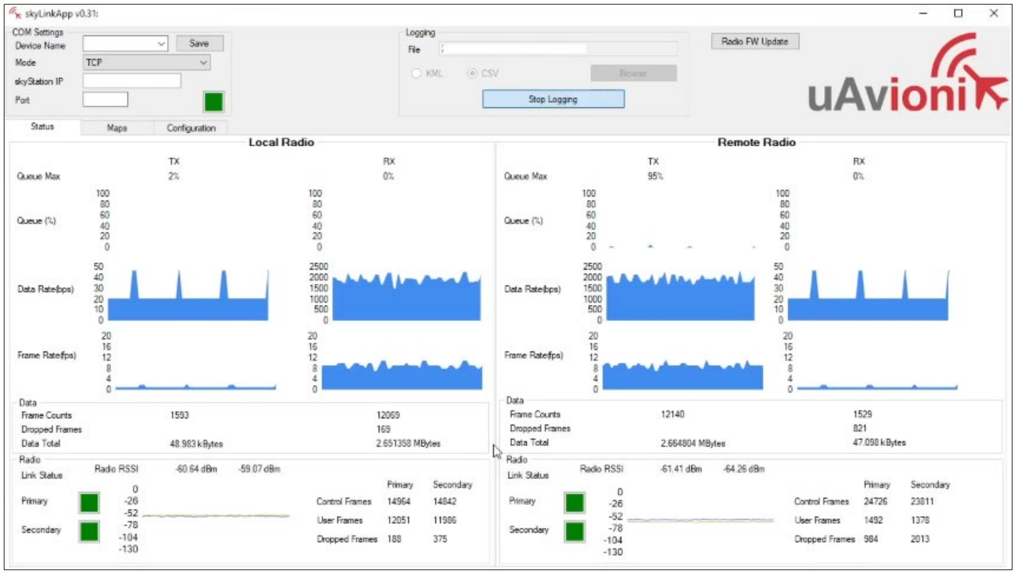


Figure 29: uAvionix microLink Receiver on CERTAIN (Temporary Installation)



Mode: TCP

Local Radio

	TX	RX
Queue Max	2%	0%

Data		
Frame Counts	1593	12069
Dropped Frames		169
Data Total	48.983 kBytes	2.651358 MBytes

Radio

Link Status	Radio RSSI	-60.64 dBm	-59.07 dBm
Primary 🟩			
Secondary 🟩			

	Primary	Secondary
Control Frames	14964	14842
User Frames	12051	11986
Dropped Frames	188	375

Remote Radio

	TX	RX
Queue Max	95%	0%

Data		
Frame Counts	12140	1529
Dropped Frames		821
Data Total	2.664804 MBytes	47.098 kBytes

Radio

Link Status	Radio RSSI	-61.41 dBm	-64.26 dBm
Primary 🟩			
Secondary 🟩			

	Primary	Secondary
Control Frames	24726	23811
User Frames	1492	1378
Dropped Frames	984	2013

Figure 30: skyLink, the uAvionix microLink Graphical User Interface

6.5 Vertiport Automation System (VAS)

The Vertiport Automation System (VAS) developed by the AAM-HDV subproject is a reference design to support the management of arrival and departure operations in the terminal area of a vertiport in a vertiplex environment [35]. Critical to the success of the second phase of the HDV subproject, the development and testing of the VAS was one of the three primary objectives for the Scaled Autonomous Operations (SAO) spiral wrap. The initial development and aspects of integration of the VAS for HDV are described in Reference [35] with the basis of the architecture and requirements presented in Reference [36].

The VAS for HDV was developed and is managed at LaRC by the Simulation Development and Analysis Branch (SDAB) and is an asset run on a local server in the SIVL facility. The VAS is connected to the LaRCnet, and it connects with the HDV Client located at ARC, supporting the functionality of vertiport scheduling and closures. The VAS also directly supports the display of information for the Vertiport Manager role in ROAM.

For internal message communications and to established Connectors, the VAS uses a MQTT Broker. Connectors establish communication pathways between the VAS and external clients or servers to provide required information over topics. It will be noted that the Connectors may provide translation of information into the required format for either side of the Connector. Table 12 provides a short summary of the VAS connectors [37] and data it forwards.

Table 12: VAS Connector Instances

Connector	Description	Data
PSU	Communicates to the PSU hosted by ARC using methods for routine and periodic data updates.	Active operation state, operation request and status, landing request, schedule summary, etc.
Integrated Airspace	Target information from fused sensor sources for display	Target positions (e.g., ADS-B, FLARM, Radar(s))
Weather	Provides information from local weather sensors on the CERTAIN range.	Local Weather Sensors (e.g., wind speed and direction)
WAHLDO[27]	Subscribes to messages from WAHLDO Service regarding detected objects within the take-off and landing area of a monitored vertiport.	Count of detected objects (e.g., people or sUAS vehicles)
UMAT	Transmits vehicle position data for display to the Vertiport Manager using the UMAT software application.	Simulated Vehicle Position

6.6 Video

One of the goals of developing a remote vehicle operations center is to facilitate the functional transition of key user roles from the Field to the Remote location (ROAM). In the process of doing that, the Actors that would normally be in the Field with accessible views of the vertiport environment and visual cues of vehicle motion in and out of the terminal area need a replacement for this loss to effectively manage the remote operations of a vehicle. This is currently accomplished using remote cameras mounted both in the Field and Remote locations. This Video Service is provided by cameras that are connected to the LaRCnet and located at key positions at the vertiports on the CERTAIN range and within the ROAM UAS Operations Center. To suit the functional needs of many Actors, the cameras' position and zoom level is fixed; but a digital zoom capability in the online software application does allow an Actor to virtually zoom into a portion of the camera's view without disturbing others using the source.

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[27] WAHLDO, Wide-Area Hazard Locator for Drone Overflight, is envisioned to identify potential hazards during UAS flights in the takeoff and landing zone of vertiports. The WAHLDO Connector was planned for during the VAS development, but not established as a functional source of information for AAM-HDV flight operations on CERTAIN.

The camera devices that support the Video Service are typically networked resources that have pan, tilt, and zoom capabilities managed by an administrator. The common manufacturer of the cameras is Axis Communications and the typical vertiport camera (model Axis P1445) and ROAM camera (Axis P5655-E) is presented in Figure 31. The cameras, located in the Field and within ROAM, provide Actors visual information (see the Organization Model presented initially in Section 4.2 and in detail in Appendix A) on the vehicles in use while monitoring the local airspace and the cameras also support the researchers at LaRC and ARC during data collection activities.


(a) Vertiport Camera, Typical (b) ROAM Camera, Typical

Figure 31: Camera Installation for Remote Viewing

Cameras on CERTAIN are currently located at Vertiport 1, 2 and 6 and a view from each of these cameras is presented in Figures 32 through 34. Because Vertiport 1 was the primary site of operations for the HDV subproject flight testing operations, two cameras were installed at this location to provide almost a 180-degree field of view. Future camera locations are expected to be added on CERTAIN for Vertiport 3 located near Vertiport 2, Vertiport 4 on the Measurement Systems Laboratory (B2104), and Vertiport 5 next to the Main Hangar at LaRC (Building 1244). The ROAM UAS Operations Center currently has two cameras installed at the back of each room allowing researchers and spectators to observe simulated or flight operations and the Actors without interference. A view of ROAM I and II from the camera is presented in Figures 35 and 36. Additional camera resources within ROAM and the Field would provide Actors and observers more visual information, but the number of video sources needs to be balanced with the amount of information the Actors using the Video Service can consume reasonably with expected workloads.


(a) Vertiport 1 - Left (b) Vertiport 1 - Right

Figure 32: Camera View – Vertiport 1

Figure 33: Camera View – Vertiport 2

Figure 34: Camera View – Vertiport 6

Figure 35: Camera View – ROAM I

Figure 36: Camera View – ROAM II

Access to this online application for display of the video feeds with secure user credentials is accomplished with a web browser installed locally to a ROAM workstation. The web browser may be Google Chrome, Microsoft Edge, or Mozilla Firefox, any of which run on a Microsoft Windows operating system.

6.7 Voice Comms

With multiple Actors in different locations carrying out various functional tasks as identified in the Actor Inventory and Organization Model of the Role-Based Ontology design methodology, a voice communication service is required to ensure the successful operations of sUAS vehicles at LaRC. The Data Flow Model of the RBO also highlights the voice communications needs within the ROAM UAS Operations Center. During early requirements elicitation with subject matter experts and stakeholders, the Voice Comms Service would need to accomplish the following requirements:

- Reliable voice communication shall be provided between Actors to support simulation and live flight operations for sUAS vehicles across locations.
- Actor locations would include at a minimum the CERTAIN Range, the ROAM UAS Operations Center, the vehicle simulation located in SIVL, and the AOL and AVAL facilities at ARC.
- Participating Range Safety Officer(s) shall have the ability to communicate with Langley Air Force Base Tower Control.
- The Voice Comms Service shall be scalable, based on required vehicle operations and number of participating Actors.

The establishment of the Voice Comms Service met these requirements in phases, aligned with data collection activities conducted by the AAM-HDV subproject for single-vehicle extended line of sight, multi-vehicle extended line of sight, and single-vehicle beyond line of sight. For safe conduct of live vehicle flight operations on the CERTAIN range, a Flight Safety Channel and a Flight Operations Channel were initially established [7]. The Flight Safety Channel allows for flight critical and safety calls to me made by authorized personnel so that every individual part of the flight operation can hear any announcement. Announcements also include when a vehicle is ready for takeoff and when it is expected to land. The other primary channel, the Flight Operations Channel, may include briefings on the upcoming flight with actions required, capture information being shared on vehicle state during flight, and any planned changes to test scenario or vertiport conditions during flight.

As flight operations expand from single vehicle to multi-vehicle flight operations, the need for a separate Vehicle Channel per vehicle is established to support crosschecks between the Field and Remote personnel. This had the intended consequence of separating individual vehicle crews going through extensive pre-flight checklists without crosstalk contamination. Expanding into simulation needs, the Simulation Control Channel is established for the Simulation Director to communicate with hardware and software engineers supporting simulation activities. Finally, a separate channel is established for the control of the ROAM UAS Operations Center to maintain an independent voice channel for the ROAM Operations Engineer, ATOL Operations staff, and researchers during simulation and live vehicle flight activities. These independent channels and the communication link required to KLFI Tower Control are presented with the current Actor Inventory in Table 13. Individual cells of the table present whether an Actor on a particular channel can transmit and receive (TXR), receive only (R), optional use (O), or not applicable (N/A).

Table 13: Communication Plan Summary for Multi-Vehicle Operations in LVC Environment

Actor		**Communications Channel**					
		KLFI Tower Control	**Flight Safety**	**Flight Operations**	**Vehicle$_n$ Control**	**ROAM Control**	**Simulation Control**
Internal Operator	**RSO**	TXR	TXR	TXR	O	O	N/A
	GCSO$_n$	O	R	TXR	TXR	O	O
	FTM	O	R	TXR	TXR	TXR	N/A
	SD	N/A	N/A	TXR	TXR	TXR	TXR
	ASM	O	R	TXR	R	O	N/A
	RO	O	R	TXR	R	O	N/A
	VM	O	R	TXR	R	O	O
	ROE	O	R	R	R	TXR	TXR
	Researcher	O	R	R	R	TXR	R
	VNP	O	R	R	O	O	O
External Operator	**SP**	O	TXR	TXR	TXR	O	N/A
	KLFI Tower	TXR	N/A	N/A	N/A	N/A	N/A
	FM	O	R	TXR	R	O	O
	TC	O	R	R	O	O	O
	VSC	O	R	R	TXR	O	N/A
	VO	O	TXR	TXR	O	O	N/A
	Simulation Engineer	N/A	N/A	R	R	TXR	TXR
	MACS Operator	O	R	R	R	TXR	TXR

Legend: TXR = Transmit/Receive O = Optional Receive Subscript *n* denotes multiple vehicles
R = Receive N/A = Not Applicable

The information contained in Table 13 serves both simulation and flight activities at full implementation of the Voice Comms Service using the Clear-Com Voice Communications system described in the next subsection. The table also includes the assumption that the Range Safety Officer and Ground Control Station Operator positions located in the Field have been relocated into the ROAM UAS Operations Center for flight testing activities. The subscript “n” for the Vehicle Channel denotes that multiple separate vehicle channels can exist, dependent on the operation. The “N/A” label primarily indicates the difference in the communication plan between live flight and simulation operations since some Actor roles do not exist in both types. Since KLFI Tower Control only have a communication exchange with the Range Safety Officer, the “N/A” label applies to all channels for that external operator. Voice Comms between the Range Safety Officer and KLFI Tower Control currently uses an Over-the-Air Radio (described in Section 6.7.3) and was connected within the Clear-Com Voice Communication system. The Radar Operator and Airspace Surveillance Manager Actors are initially collocated with the Range Safety Officer within the ROAM UAS Operations Center, and some communications may be verbal within the room and not over a specified communication channel. Likewise, communication between a Visual Observer and Safety Pilot of a vehicle may be verbal during portions of flight operations because they may be collocated together in the Field. Finally, since activities in simulation and flight may include human factors assessments of selected roles, certain voice channels can be limited during data collection.

6.7.1 Clear-Com Voice Communications

The most complex but feature-rich source for the Voice Comms Service is the Clear-Com Voice Communication System [38] installed within the ROAM UAS Operations Center, the CERTAIN range, and SIVL. The system provides a solution identified to resolve existing difficulties in basic communication between the Field and Remote locations, a solution with expansion capabilities for additional end users and location, and highly developed functions to tackle future challenges for flight operations on the CERTAIN range. Unlike existing options with multi-user conference calling, the selected Clear-Com system provides a full-duplex communication platform centralizing wired, wireless, virtual (computer based), and bridged radio communications, eliminating missed announcements from crosstalk and customization of channels for expanding needs. The system is flexible, enabling an increase in the type of communication paths used, and scalable to support an increasing number of users during operations at varied locations. As currently implemented, Clear-Com supports sUAS simulation and flight operations at LaRC across multiple endpoints with a planned expansion to include externals operators like researchers and participants at ARC.

The complete and detailed Clear-Com implementation architecture is beyond the scope of this document, but Figure 37 illustrates a simplified diagram of the Voice Communication system established for flight operations at LaRC beginning in 2023. Independent aeronautical radio links are maintained between KLFI Tower Control and the location of the Range Safety Officer—either in the ROAM UAS Operations Center or on the CERTAIN range. Facilities within each center communicate over digital voice comms with each other over their respective enterprise networks and those networks can communicate together over the NASA Enterprise Network. The sources and devices used for the current implementation follows.

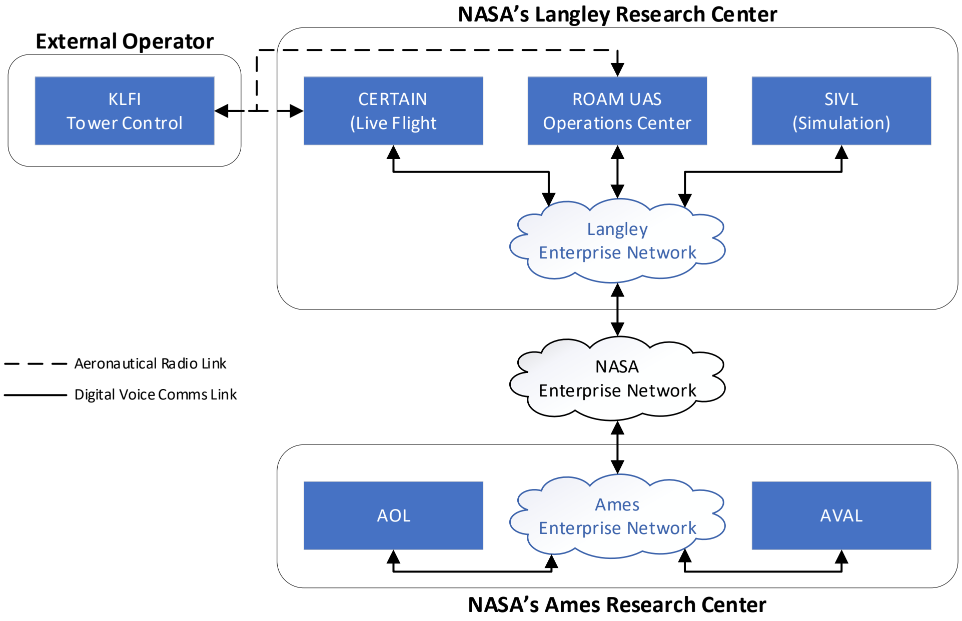

Figure 37: Simplified Conceptual Voice Communication Architecture Using Clear-Com

To implement a complete system successfully for the EVLOS and BVLOS flight operations within the CERTAIN Range at LaRC only, the listing of Clear-Com components presented in Table 14 are required. Not included in the listing are rechargeable batteries and charger docking stations for the beltpack units, cabling, rack installation hardware for the backend equipment, and headsets for users of the equipment. It is possible to expand coverage in the Field at other Vertiport locations with additional sets of Clear-Com FreeSpeak II Transceiver, Base Station, and LQ Internet Protocol (IP) Interface devices with associated power and network connectivity.

Table 14: Implemented Clear-Com Hardware Supporting Flight Operations

Part No.	Description	Quantity	Associated Actor(s) or Installed Location
Location: Field			
FSII-BP19-X4	FreeSpeak II Beltpack	8	RSO, SP, VO, VSC
FSII-TCVR-19	FreeSpeak II Transceiver	2	Vertiport #1 on CERTAIN Range
FS-Base-II-5-X5	FreeSpeak II Base Station	1	Vertiport #1 on CERTAIN Range
LQ-R2W4-4W4	LQ IP Interface	1	Vertiport #1 on CERTAIN Range
Location: Remote			
ECLIPSE-HX-DELTA-32P	Eclipse HX Delta Matrix[28]	1	ROAM Experiment Control[29]
V12LDDX4-IP	V-Series Desk Panel Unit	7	RSO, FTM/SD, ASM, RO, GCSO, VM, ROAM Experiment Control
FSII-BP19-X4	FreeSpeak II Beltpack	3	RSO, ROE
SC-IC	Station IC	13	All ROAM Workstations
LQ-R2W4-4W4	LQ IP Interface	1	ROAM Experiment Control
FSII-TCVR-19	FreeSpeak II Transceiver	1	ROAM Experiment Control
FS-Base-II-5-X5	FreeSpeak II Base Station	1	ROAM Experiment Control
Location: External			
SC-IC	Station IC	1	SIVL

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[28] A permanent Clear-Com Eclipse HX Delta Matrix was installed and configured in Spring 2024.

[29] The ROAM UAS Operations Center Experiment control is located just outside of ROAM-I in room 1089B in building complex 1286 at LaRC.

Presented in Figures 38 and 39 is the end-user Clear-Com equipment used by Actors in ROAM and in the Field. The Desk Panel unit provides a large format and tactile interface at a ROAM workstation for an Actor to access any number of preprogrammed channels with granted access over a wired connection. The desk unit can be used with a gooseneck microphone and speaker or headset (preferred option). The Beltpack unit is wireless interface into the voice communications network via a locally installed transceiver, permitting Actors to be mobile within ROAM or in the Field. The other user interface (Station-IC) is software based and described in further detail in Section 7.2. All Clear-Com equipment allows end-users to control the volume, select on/off channels, and select talking or receiving of individual channels.

Figure 38: Clear-Com Equipment – Desktop Panel

Figure 39: Clear-Com Equipment – Beltpack

6.7.2 Microsoft (MS) Teams

An important source to the Voice Communications Service that has been in use for all data collection activities within the ROAM UAS Operations Center is the cloud-based team collaboration software called Microsoft Teams. An integrated component of the Office 365 suite of software, MS Teams is a familiar product to many resulting from the global COVID-19 pandemic that provides at its core a group calling and chat function. MS Teams is supported across the LaRCnet and allows for real-time collaboration and communication between Actors that are internal and external to ROAM—a useful platform that has enabled information sharing between LaRC and ARC simulation and flight test teams (see Figure 40). MS Teams as a platform has several key features used within ROAM during data collection for simulation and flight test activities:

- chat-based messaging
- designated breakout rooms for side conversations (i.e., troubleshooting)
- screen sharing
- external collaboration capabilities
- link and file sharing within chat-based messaging (useful during debugging)

An interesting finding during the early flight test operations for the AAM-HDV subproject was the drawback of an auto-selected dominant voice when two or more individuals are talking at the same time, causing voice information to be lost. This unexpected outcome highlighted the need for a full-duplex voice communications during critical moments of flight test with multiple sUAS on the CERTAIN range. Until the Clear-Com voice communication system was established in early 2023, critical exchange of information between safety pilots and Ground Control Station Operators during flight operations would take place using existing telecommunication equipment within ROAM.

MS Teams also allows for the use of external microphone/speaker devices that enable entire room audio to be captured. The selected device used was the Jabra Speak 710 and is shown in Figure 41. During both simulation and flight test operations starting in Spring of 2023, a single Jabra Speak 710 was used within each room of ROAM to capture the audio in the room and share across MS Teams to enhance the shared situation awareness between the facilities at the two NASA centers.

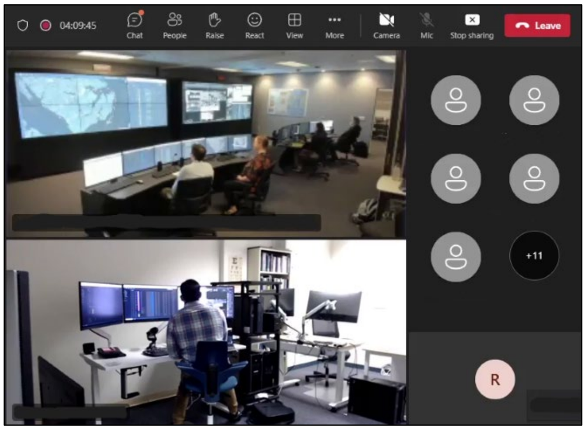


Figure 40: Microsoft Teams Group Calling Feature

Figure 41: Jabra Speak 710

6.7.3 Over-the-Air (OTA) Radio

Existing voice communications on the CERTAIN range prior to the development of the ROAM UAS Operations Center used handheld Very High Frequency (VHF) radios among team members in the Field, with a specific unit used by the Field Range Safety Officer for communication with local Langley Air Force Base tower control. To move the Range Safety Officer position from the field and establish them as a permanent role within ROAM, an Over-the-Air Aeronautical Radio was installed to establish and maintain direct two-way communication with KLFI Tower and to be able to monitor traffic within and near the local airspace of the CERTAIN range. The OTA radio is located at the Range Safety Officer's workstation in ROAM and allows only that individual to communicate to Tower Control. Mimicking the field handheld unit, the OTA Radio provides the required situation awareness of local, non-participating aircraft while located in the windowless environment of ROAM. The selected aeronautical radio is the Icom IC-A120 VHF Air Band Transceiver Base Station with handset and is pictured in Figure 42. Although currently a separate device in ROAM dedicated for use by the Range Safety Officer, integration of the OTA Radio into the Clear-Com communication system is planned to provide all users the ability to hear the same communications that the Range Safety Officer hears, if desired.

Figure 42: Over-the-Air Aeronautical Radio for Range Safety Officer in ROAM

6.7.4 Voice Over Internet Protocol (VoIP)

A final supporting source for the Voice Communications Service was the Voice over Internet Protocol (VoIP) telephones (see Figure 43) that were made available at each desk in the ROAM UAS Operations Center. The VoIP telephones are supported across the LaRCnet, and they also allow for real-time collaboration and communication between Actors that are internal and external to ROAM. In its most basic form, the VoIP telephone uses the network to transmit voice data between users instead of traditional transmission lines (i.e., copper). These devices include the benefits of constant uptime and availability, cost savings over specialized communication systems given widespread implementation, and the ability to integrate with various other communications tools and accessories.

Initially, VoIP telephones were planned as backup devices between Field and Remote operations within ROAM but the first full test of using the MS Teams platform for communication for all Actors during a flight test indicated the need for segregated voice channels for critical moments during flight preparation and mission planning. Until the Clear-Com communication system was fully operational, the VoIP telephones served as the direct communication link between the Safety Pilot in the Field and the same vehicle Ground Control Station Operator within ROAM, ensuring safety of flight during the early flight tests for the AAM-HDV subproject. The handset of the VoIP phone could be used for infrequent communication, but often a single, over-the-ear headset connected to the unit would be used for extended durations.

Figure 43: VoIP Telephone in ROAM UAS Operations Center

6.8 Weather

A product of the Weather Service is the display of weather information that is important to several Actors within the ROAM UAS Operations Center and for the safe operation of sUAS vehicles on CERTAIN. Limited for flight operations and documented for the AAM-HDV subproject in Reference [7], are connections to the real-time values of wind speed, temperature, airspace ceiling, and visibility. To provide a comprehensive look into the current and forecasted weather for a given day, the flight operations team uses information from several sources including local weather sensors, regional weather sensors, and mesoscale forecasts.

A brief description of each weather source follows. Weather information from these sources is displayed in the software application described in Section 7.8 or supplemented by access to an online application accomplished with a web browser installed locally to a ROAM workstation. The web browser may be Google Chrome, Microsoft Edge, or Mozilla Firefox; any of which run on a Microsoft Windows operating system.

6.8.1 Local Weather Sensors

Prior to the first flight commanded from the ROAM UAS Operations Center, the Safety-Critical Avionics Systems Branch (D320) at LaRC created a network of local weather sensors within the CERTAIN range to provide real-time information for meteorological parameters like wind speed and direction, temperature, humidity, and air pressure. Figure 44 presents the location of currently active sensors within the CERTAIN range, with the number designation next to the marker representing its sequence in the location of sensors over time. From this figure, a sense of the coverage availability of these sensors highlights areas of frequent flights in CERTAIN I and more concentrated portions of buildings and people at LaRC in CERTAIN II and III. For flight testing operations, weather information from these sensors provides additional situation awareness to the current wind speed and direction at one or more vertiports, crucial during the takeoff and landing phase of sUAS vehicles. Within ROAM, the local weather sensor information is used in decision-making by the Range Safety Officer, Ground Control Station Operator, and the Flight Test Manager.

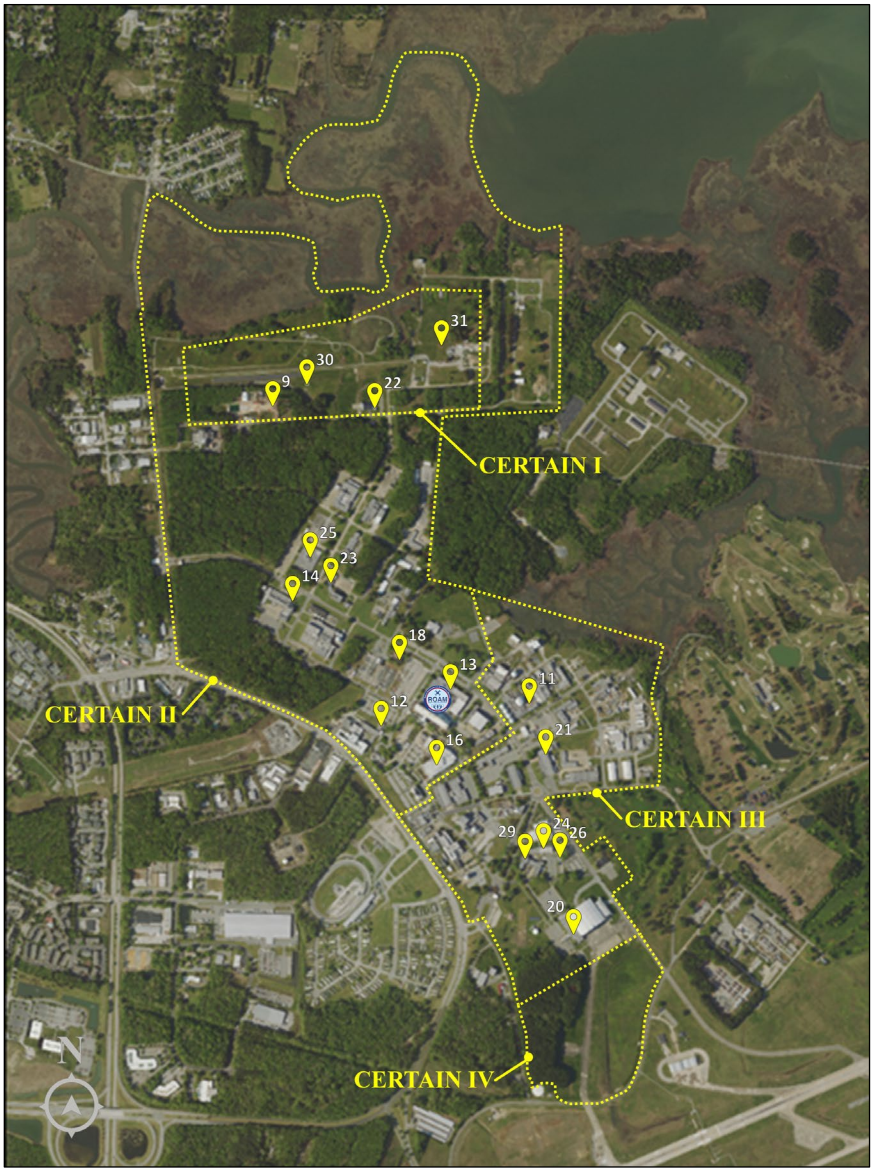


Figure 44: Local Weather Sensor Locations on CERTAIN

The weather sensors currently connected the LaRCnet are the Vaisala Weather Transmitter WXT530 Series [39], providing these real-time measurements with maximum, minimum, and average values in a data log message format that can be displayed within a web browser interface, over a Transmission Control Protocol (TCP) link, with a graphical interface connected to an IoT MQTT data message broker, or a customized software application for a user in ROAM. Data from local and regional weather sensors is an input for the software application described in Section 7.8.

Figure 45: Vaisala Weather Transmitter WXT530 Series

In addition to these weather parameters, the local weather sensors also measure and track the rain accumulation in millimeters since first measured, rain duration in seconds, and rain intensity. The sensor also reports hail accumulation, duration, and intensity. To simplify the user interface, rain data is only displayed to a user when reviewing the raw log message and hail data is not displayed.

6.8.2 Regional Weather Sensors

Where the Local Weather Sensors provide a close-in assessment of the conditions on the CERTAIN range, data from Regional Weather Sensors provide information further away from the LaRC campus that is standardized and maintained by non-NASA resources. Supporting the Weather Service for the Regional Weather Sensors are weather products like the Meteorological Aerodrome Report (METAR), the Terminal Area Forecast (TAF), and Radio Detection and Ranging (RADAR) displays of precipitation. Each of these weather sources is used by the Range Safety Officer and may also be used by the Ground Control Station Operator and Flight Test Manager during flight operations. The following information describes each of the current sources for the Regional Weather Sensors.

The METAR presents a regularly updated weather information that is typically used by aircraft pilots and meteorologists. A METAR is presented in a World Meteorological Organization (WMO) approved format (see Section A, Subsections FM-15 and FM-16 of Reference [40]). These data are collected and accessible through the Aviation Digital Data Services (ADDS) provided by the National Weather Service (NWS). A METAR may contain temperature, dew point, humidity, pressure, visibility conditions, wind speed and wind direction, ceiling, clouds, and a summary weather statement. A TAF is issued for airports and some weather stations, written in a standardized textual format, and may be issued at a six-hour interval, up to four times per day. A TAF is also presented in a WMO approved format (see Section A, Subsections FM-51 of Reference [40]). A TAF typically includes forecasted wind speed and wind direction, visibility, ceiling, type of precipitation expected, and the type of weather phenomenon expected while being valid up to thirty-hours from time of release. Figure 46 presents an example of METAR and TAF data for the source location at Langley Air Force Base.

METAR

```
KLFI 250155Z 18008KT 10SM OVC048 16/11 A3033 RMK AO2A SLP277 T01620113 $
```

TAF

```
TAF KLFI 250200Z 2502/2608 17009KT 9000 BR SCT015 SCT020 QNH3035INS
  BECMG 2505/2506 17009KT 8000 BR BKN007 OVC014 510073 QNH3032INS
  BECMG 2511/2512 18009KT 8000 BR OVC010 QNH3016INS
  BECMG 2523/2524 20009KT 6000 -SHRA OVC005 QNH3013INS
  BECMG 2602/2603 19009KT 8000 BR OVC005 QNH3005INS TX14/2519Z TN10/2502Z
```

Figure 46: Example METAR and TAF Data for Langley Air Force Base

The RADAR product matched to the METAR and TAF data is presented to a user within the NASA WxWidget software application. Within the WxWidget, RADAR information is a georeferenced composite image product from the NWS Next Generation Weather Radar (NEXRAD) Level III products. The image display presents the composite reflectivity estimating precipitation for the surrounding area of the selected weather station for the application. Composite reflectivity is a display of maximum reflectivity for the total volume within the range of the RADAR. These products reveal the highest reflectivity in all echoes, examine storm structure features, and determine the intensity of storms. The specific product has ground clutter and non-precipitation echoes removed. Further information on the creation of the RADAR product can be found at Reference [41].

Data from regional weather sensors like METAR, TAF, and RADAR are displayed in the NASA WxWidget (see Section 7.8) at individual workstations and the forward video wall within ROAM.

6.8.3 Mesoscale Weather Information and Forecasts

In consideration of longer duration flights, part of the Weather Service may include Mesoscale Weather Information and Forecasts. Mesoscale refers to the geographic size a weather system(s) may cover, ranging in horizontal dimensions starting around fifty miles to several hundred miles. A typical mesoscale weather system may be categorized as a squall line of a passing front, a convective complex (thunderstorm), or a convective system (an organized complex of thunderstorms). This further reaching information source is primarily used by the Range Safety Officer position and even the Flight Test Manager when considering flight operations of longer distance and durations.

Several sources of a mesoscale weather information and forecasts can be considered but for the current implementation within the ROAM UAS Operations Center display of this information, weather information from the National Weather Service is provided to the users. Selected Internet sites include the NWS RADAR at Reference [42] and the NWS Geographic Information System (GIS) Viewer at Reference [43]. Access to an online application is accomplished with a web browser installed locally to a ROAM workstation. The web browser may be Google Chrome, Microsoft Edge, or Mozilla Firefox; any of which run on a Microsoft Windows operating system.

7. Primary Software Applications

To accomplish their objectives based on specific roles, Actors within the ROAM UAS Operations Center use a variety of common and specific software applications that are installed or connected to the workstations within the facility. The following subsections describe at high level the applications that are listed within the Network Architecture Design presented in Figure 17 of Section 5.3. One additional software application is included in the listing that is critical to data collection operations within the facility—the NASA ROAM Workstation Control. A full listing of other supporting and underlying software applications is beyond the scope of this report but can be found in the latest version of Reference [9].

7.1 ADS-B Display

Operation of live sUAS vehicles on the CERTAIN range at LaRC requires members of the flight operations team to be aware of vehicles that may be in or could potentially enter the airspace above CERTAIN. Part of the Surveillance digital service, an ADS-B display is required by the Range Safety Officer Actor within the ROAM UAS Operations Center and is beneficial for other roles for situation awareness. The current choice of an ADS-B display within ROAM is from https://globe.adsbexchange.com. ADS-B Exchange is a public facing website for tracking ADS-B equipped and broadcasting aircraft and it offers a simplified map view of aircraft with data tags (see Figure 47) that meets the functional needs of the Range Safety Officer. Although there is an expected latency present with the information displayed on a public webpage, content within the ADS-B display and other information data sources within the Surveillance digital service provide a more comprehensive display to the actors within ROAM.

Display of direct local sources of ADS-B transmitted information ("raw data") requires additional software applications to be developed for the ROAM environment. Beyond current engineering displays that are used to check the quality and frequency of data from equipment sensors on CERTAIN, no other display format has been created that meets the needs of the actors within ROAM. However, it will be noted that ADS-B sensor data along with other surveillance source data is fused into an integrated display of local vehicle positions and history.

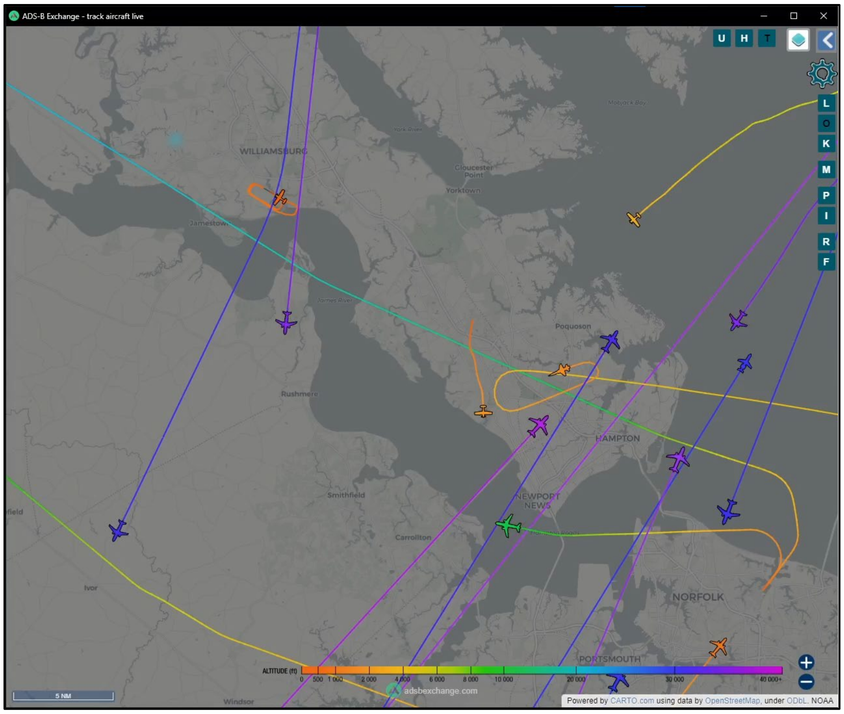
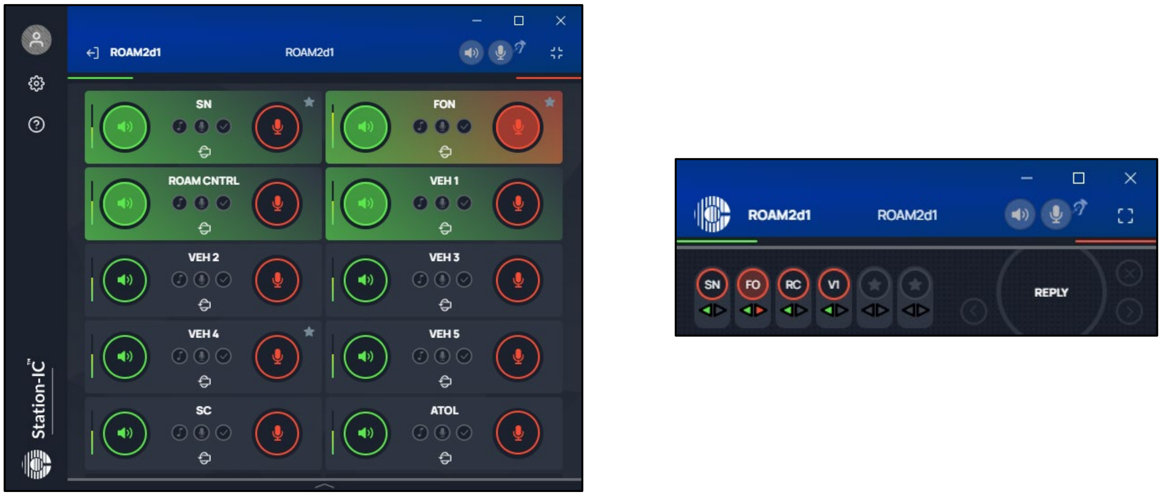


Figure 47: ADS-B Display Option – ADS-B Exchange

Access to this online application is accomplished with a web browser installed locally to a ROAM workstation. The web browser may be Google Chrome, Microsoft Edge, or Mozilla Firefox; any of which run on a Microsoft Windows operating system.

7.2 Clear-Com Station-IC

For voice communications within the ROAM UAS Operations Center and between Actors located in the Field and other External locations, the Clear-Com voice communication system described in Section 6.7.1 is used during integration testing and data collection for simulation and flight operations. The most widely used interface for Actors to this system and cost-effective utility for voice communications is the Clear-Com Station-IC software application. Station-IC [44] is installed on the ROAM workstations as a desktop client connected to the primary Clear-Com Eclipse Delta Matrix allowing full access to connected resources at LaRC. Individual voice channels (see Section 6.7) can be monitored or communicated by using the basic application and simple over-the-ear headsets connected to the workstation. Users of Station-IC have a choice of different volume levels based on individual channels allowing them to focus on key communication lines while only needing to "monitor" others avoiding over-saturation of information during multiple vehicle operations. Figure 48 presents the full user interface and the reduced display size of the Station-IC software application.



(a) Full Interface (b) Reduced Display Size

Figure 48: Clear-Com Station-IC User Interface

7.3 HDV Client

The HDV Client (also referred to as eXtensible Traffic Management (xTM) Client in some publications [45-47]) is a cloud-based research-software that has been under continued development by the AAM-HDV subproject that is built for fleet management of UAS vehicles. The online software application is used by Actors like the Ground Control Station Operator, Vertiport Manager, Fleet Manager (external to ROAM), Simulation Director, and Flight Test Manager within data collection activities for simulation and flight operations. The HDV Client allows digital-based communication between the Ground Control Station Operator and remote Fleet Manager for determining and allocating a timeslot and associated flight plan for the planned scenario and displays vehicle position information for the fleet of vehicles [48] that participate in the LVC environment. Two selected views of the user interface of a Ground Control Station Operator for the HDV Client is presented in Figures 49 and 50. A typical view used by the Vertiport Manager of HDV Client is presented in Figure 51.

To locate vehicle position information of sUAS that are controlled by a Ground Control Station Operator in ROAM, a software data telemetry module application (see Section 6.3) is required at the Ground Control Station Operator workstation to transmit connected vehicle state data to the backend of the provider of services hosted by ARC. This allows the vehicles controlled, both in simulation and live flight, from ROAM to be displayed with other simulated vehicle traffic by ARC within the HDV Client to all Actors connected in the system. The HDV Client provides multiple views to the operator—Map, Operations, Schedule, Vertiport, and connected systems status.

Access to this online application is accomplished with a web browser installed locally to a ROAM workstation. The web browser may be Google Chrome, Microsoft Edge, or Mozilla Firefox; any of which run on a Microsoft Windows operating system.

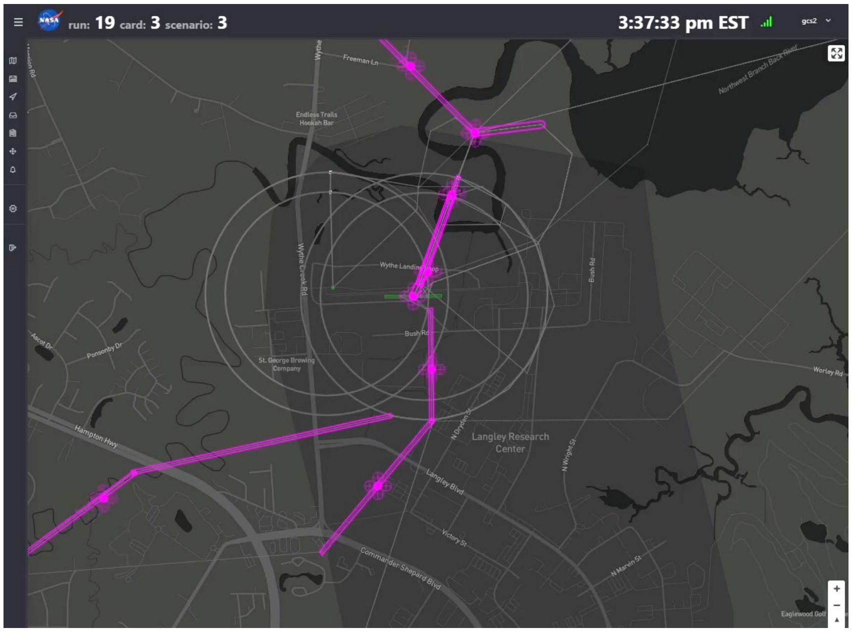
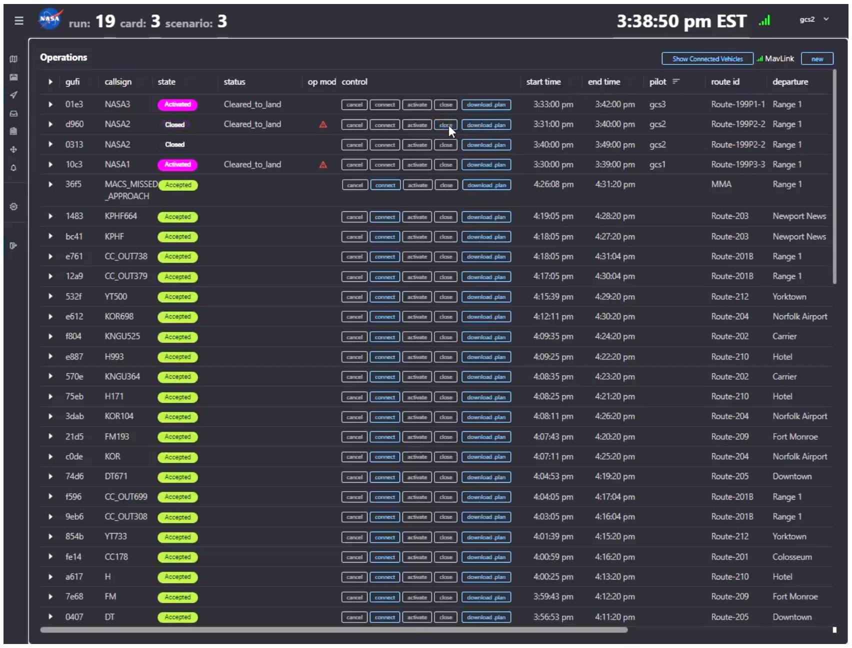


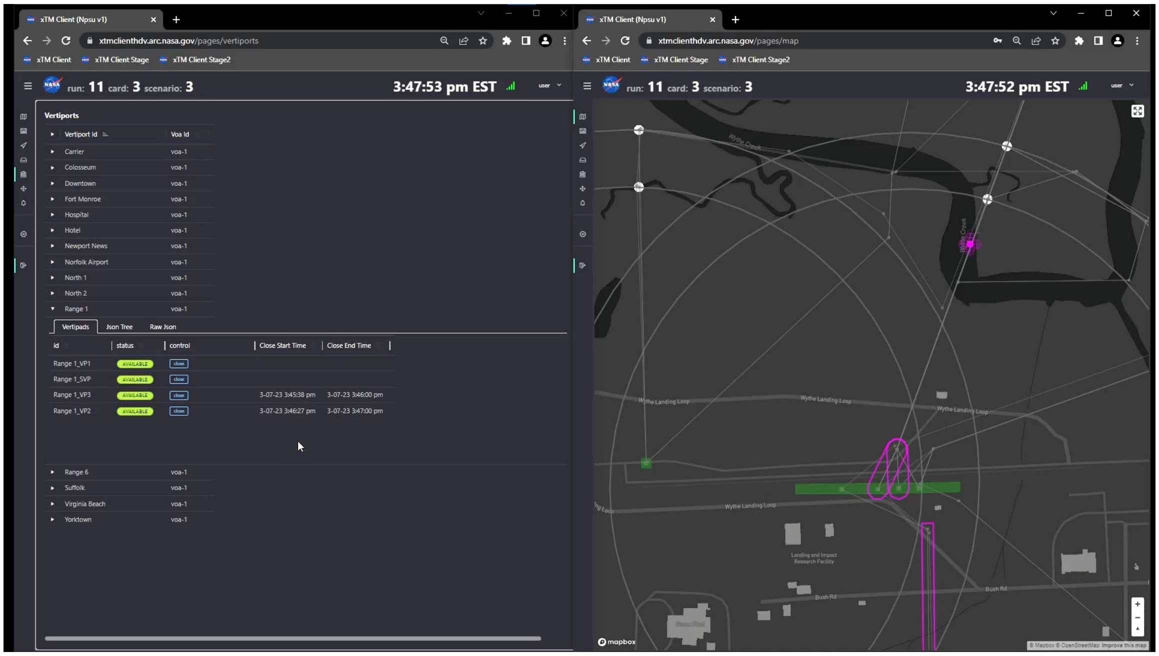
Figure 49: NASA HDV Client User Interface – Map View



Operations

gufi	callsign	state	status	op mod	control	start time	end time	pilot	route id	departure
01e3	NASA3	Activated	Cleared_to_land		cancel connect activate close download plan	3:33:00 pm	3:42:00 pm	gcs3	Route-199P1-1	Range 1
d960	NASA2	Closed	Cleared_to_land	⚠	cancel connect activate close download plan	3:31:00 pm	3:40:00 pm	gcs2	Route-199P2-2	Range 1
0313	NASA2	Closed			cancel connect activate close download plan	3:40:00 pm	3:49:00 pm	gcs2	Route-199P2-2	Range 1
10c3	NASA1	Activated	Cleared_to_land	⚠	cancel connect activate close download plan	3:30:00 pm	3:39:00 pm	gcs1	Route-199P3-3	Range 1
36f5	MACS_MISSED_APPROACH	Accepted			cancel connect activate close download plan	4:26:08 pm	4:31:20 pm		MMA	Range 1
1483	KPHF664	Accepted			cancel connect activate close download plan	4:19:05 pm	4:28:20 pm		Route-203	Newport News
bc41	KPHF	Accepted			cancel connect activate close download plan	4:18:05 pm	4:27:20 pm		Route-203	Newport News
e761	CC_OUT738	Accepted			cancel connect activate close download plan	4:18:05 pm	4:31:04 pm		Route-201B	Range 1
12a9	CC_OUT379	Accepted			cancel connect activate close download plan	4:17:05 pm	4:30:04 pm		Route-201B	Range 1
532f	YT500	Accepted			cancel connect activate close download plan	4:15:39 pm	4:29:20 pm		Route-212	Yorktown
e612	KOR698	Accepted			cancel connect activate close download plan	4:12:11 pm	4:30:20 pm		Route-204	Norfolk Airport
f804	KNGU525	Accepted			cancel connect activate close download plan	4:09:35 pm	4:24:20 pm		Route-202	Carrier
e887	H993	Accepted			cancel connect activate close download plan	4:09:25 pm	4:22:20 pm		Route-210	Hotel
570e	KNGU364	Accepted			cancel connect activate close download plan	4:08:35 pm	4:23:20 pm		Route-202	Carrier
75eb	H171	Accepted			cancel connect activate close download plan	4:08:25 pm	4:21:20 pm		Route-210	Hotel
3dab	KOR104	Accepted			cancel connect activate close download plan	4:08:11 pm	4:26:20 pm		Route-204	Norfolk Airport
21d5	FM193	Accepted			cancel connect activate close download plan	4:07:43 pm	4:20:20 pm		Route-209	Fort Monroe
c0de	KOR	Accepted			cancel connect activate close download plan	4:07:11 pm	4:25:20 pm		Route-204	Norfolk Airport
74d6	DT671	Accepted			cancel connect activate close download plan	4:04:53 pm	4:19:20 pm		Route-205	Downtown
f596	CC_OUT699	Accepted			cancel connect activate close download plan	4:04:05 pm	4:17:04 pm		Route-201B	Range 1
9eb6	CC_OUT308	Accepted			cancel connect activate close download plan	4:03:05 pm	4:16:04 pm		Route-201B	Range 1
854b	YT733	Accepted			cancel connect activate close download plan	4:01:39 pm	4:15:20 pm		Route-212	Yorktown
fe14	CC178	Accepted			cancel connect activate close download plan	4:00:59 pm	4:16:20 pm		Route-201	Colosseum
a617	H	Accepted			cancel connect activate close download plan	4:00:25 pm	4:13:20 pm		Route-210	Hotel
7e68	FM	Accepted			cancel connect activate close download plan	3:59:43 pm	4:12:20 pm		Route-209	Fort Monroe
0407	DT	Accepted			cancel connect activate close download plan	3:56:53 pm	4:11:20 pm		Route-205	Downtown

Figure 50: NASA HDV Client User Interface – Operations View



Vertiport Id	Voa Id
Carrier	voa-1
Colosseum	voa-1
Downtown	voa-1
Fort Monroe	voa-1
Hospital	voa-1
Hotel	voa-1
Newport News	voa-1
Norfolk Airport	voa-1
North 1	voa-1
North 2	voa-1
Range 1	voa-1
Range 6	voa-1
Suffolk	voa-1
Virginia Beach	voa-1
Yorktown	voa-1

id	status	control	Close Start Time	Close End Time
Range 1_VP1	AVAILABLE	close		
Range 1_SVP	AVAILABLE	close		
Range 1_VP3	AVAILABLE	close	3-07-23 3:45:38 pm	3-07-23 3:46:00 pm
Range 1_VP2	AVAILABLE	close	3-07-23 3:46:27 pm	3-07-23 3:47:00 pm

Figure 51: NASA HDV Client User Interface – Vertiport Manager (Typical)

7.4 Integrated Airspace Display (IAD)

Inputs into the Surveillance Service include feeds from multiple radar sources, ADS-B, ground-based FLARM, and positioning of the sUAS vehicles under control of operators in ROAM. The need for shared situation awareness of the airspace in the CERTAIN range is provided by the Integrated Airspace Display (IAD) and is primarily interpreted by the Airspace Surveillance Manager and Range Safety Officer, with occasional use by the Flight Test Manager. A data fusion sub-system designed to integrate multi-sensor information and provide a comprehensive display of the operational environment is currently provided by the Anra Smart Skies CTR (SS CTR). The fusion algorithm within the IAD takes inputs from multiple sources, fuses corollary tracks, and displays them as a single vehicle track. The IAD can also display raw track files from the sources and the airspace boundaries of interest around the CERTAIN range.

Early within the IAD fusion algorithm assessment, the Airspace Surveillance Manager evaluated the IAD's ability to merge corollary track data from the different ground sources into the single fused track for targets of interest while comparing it to individual source displays and an ADS-B display as mentioned in Section 7.1. The intent of the fused surveillance capability is to be used in both simulation and flight test data collection activities. During the simulation, all simulated airspace traffic and HHITL vehicles are inputs into the IAD from the HDV Client positional reports, even though fusion was not required for the same sourced data. Fused surveillance is more critical during live flight operations when the IAD is connected to all sources on CERTAIN. The IAD options under evaluation throughout the 2023 data collection activities from the ROAM UAS Operations Center included the Anra SS CTR and SkyGrid (late entry).

Figure 52 presents the user interface of the IAD during a flight operation with fused tracks of target vehicles around LaRC. Different iconography relates to different identified vehicle types and trailing paths from the vehicle's location is the fused flight path. Sources not fused (i.e., single source of data) are the solid, orange-colored circles.

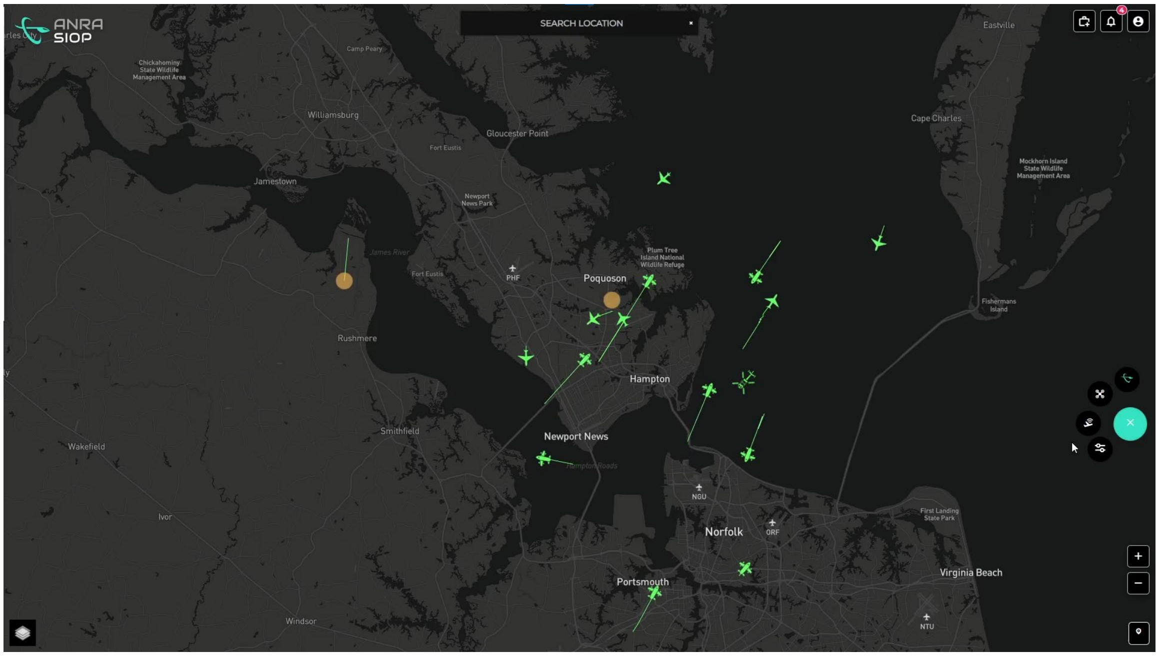


Figure 52: Integrated Airspace Display User Interface

Access to this locally hosted online application is accomplished with a web browser installed locally to a ROAM workstation. The web browser may be Google Chrome, Microsoft Edge, or Mozilla Firefox; any of which run on a Microsoft Windows operating system.

7.5 Microsoft Office365 (O365)

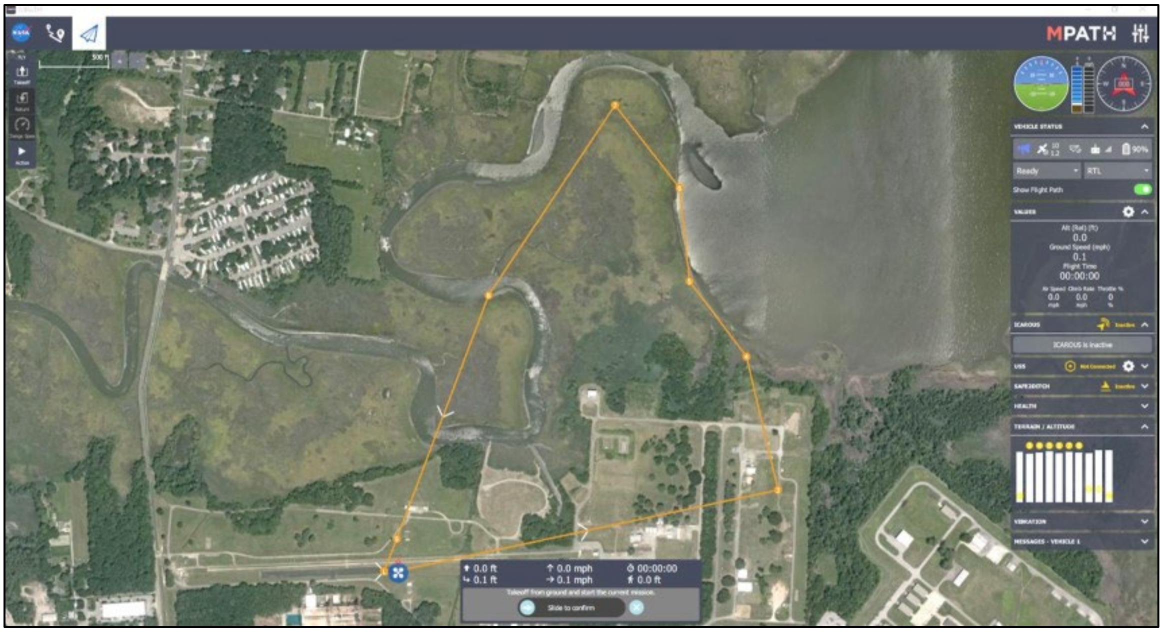
To increase collaboration and productivity across all NASA organizations and teams, both large and small, NASA provides Microsoft Office365 (O365), now labeled as Microsoft 365 [49], to all agency users. This allows Actors within the ROAM UAS Operations Center and others during a data collection activity to actively share in near real-time information within O365 applications. Information displayed on the forward video walls in a “test card” uses Microsoft PowerPoint, remote vehicle pilots use Microsoft Excel for first flight of day and recurrent mission checklists, and Microsoft Teams is used to share video sources and workstations display screens while providing a chat capability among Actors within and external to ROAM. In early 2022, Microsoft Forms was introduced by researchers to collect human factors questionnaire information in a quicker and more efficient format, thereby increasing the speed and feedback to researchers over hand-written paper or other formatted digital questionnaires. As capabilities mature within ROAM and requirements for information sharing evolve, the Microsoft Office software applications may be replaced by custom NASA applications to remove dependencies on specific user security credentials.

Access to this online application with secure user credentials is accomplished with a web browser installed locally to a ROAM workstation. The web browser may be Google Chrome, Microsoft Edge, or Mozilla Firefox; any of which run on a Microsoft Windows operating system.

7.6 Measuring Performance for Autonomy Teaming with Humans (MPATH)

For the Ground Control Station Operator workstation, the primary focus is the Measuring Performance for Autonomy Teaming with Humans (MPATH) GCS software [50]. Modified from the open-source QGroundControl software [51], MPATH is a software application developed by NASA (TTT-RAM) for controlling MAVLink-enabled sUAS. The primary user interface for MPATH is presented in Figure 53.

MPATH was designed to improve baseline QGroundControl usability by facilitating close spatial proximity of related information, increasing automation transparency, and supporting routine human factors data collection by logging user interaction data. With MPATH built upon the framework of QGroundControl, NASA has leveraged existing functionality, safety, and testing to provide a platform for research into human-autonomy teaming concepts in a remote vehicle operations center environment [50].



Alt (Rel) (ft) 0.0
Ground Speed (mph) 0.1
Flight Time 00:00:00
Air Speed 0.0 mph
Climb Rate 0.0 mph
Throttle % 0 %

ICAROUS is inactive

0.0 ft
0.1 ft
0.0 mph
0.1 mph
00:00:00
0.0 ft

Takeoff from ground and start the current mission.

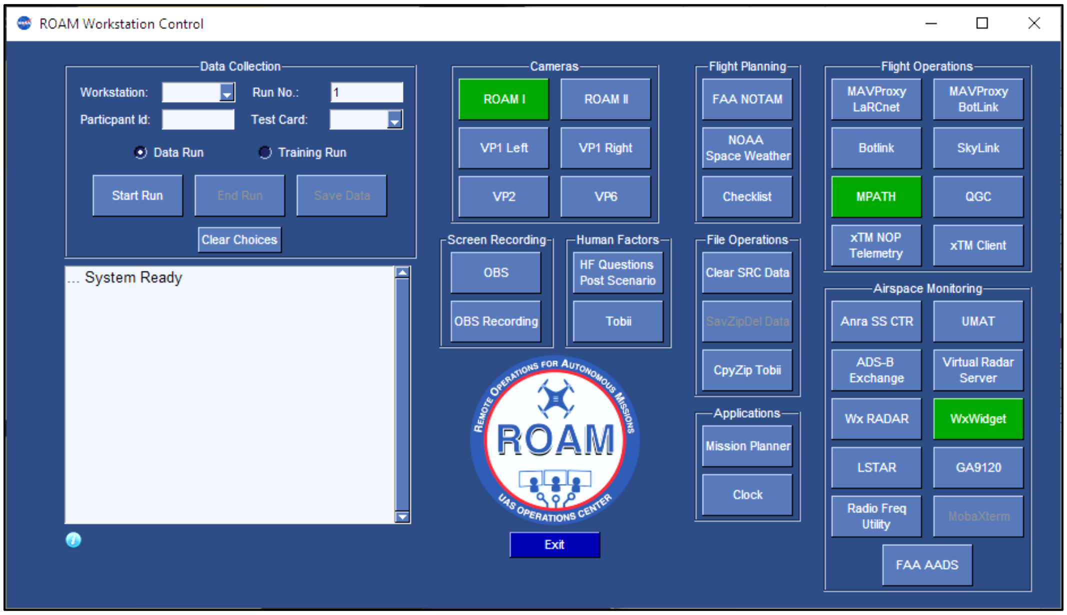
Figure 53: MPATH Ground Control Station User Interface

Often within ROAM for data collection activities in both simulation and flight operations, the display of MPATH is coupled with a Tobii Pro Nano eye tracker mounted on the display monitor with MPATH. This eye tracker allows researchers to measure the Ground Control Station Operator's eye movements (see Reference [52] for eye tracker specifications) for that display only giving insight into areas of interest by the operator throughout flight scenarios. Eye movements are recorded at a sampling rate of 60 Hz and analyzed after data collection activities with Tobii Pro Lab [53]. Because this is an off-body eye tracker, the Ground Control Station Operator can freely move around at the ROAM workstation without restriction. The goal of the eye tracking data is to explore naturalistic eye gaze behaviors of Ground Control Station Operators in ROAM. This unobtrusive approach allows the Ground Control Station Operator to move freely, look away from the MPATH GCS screen, and modify the configurations of the display elements. Past eye tracking results for Ground Control Station Operators from operations in ROAM can be found in Reference [54] and [48].

7.7 NASA ROAM Workstation Control

The NASA ROAM Workstation Control is a prototype software tool designed to provide the user an interface to control a selected group of the workstation's running applications. The ROAM Workstation Control provides a minor function of informing the user of current application status (on/off) on a workstation running a Windows operating system while also providing a central point to assist in the data collection from these applications during simulated and live flight operations.

The software was developed because of the number of applications needed to monitor a vehicle (simulated or live) or other conditions (local airspace, weather, etc.) are numerous and some must be started in a particular sequence to prevent data connection errors. To simplify the process, the software provides a simplified interface for application status and data collection (see Figure 54). Under application status, the monitored applications are indicated with an updated button color to green (application running), to default blue (application closed or not started), and grayed button text (application or function disabled). This provides the user at a quick glance to see that all necessary applications are operational for a data collection activity to begin. The other part of the interface is used for data collection, allowing the user to set four parameters: workstation label, participant label, run number, and test card number. Applications based on workstation role are initialized with the 'Start Run' button. At the conclusion of an operation, the applications are terminated with the 'End Run' button. And a third button allows the user to initiate a copy/archive data action with a 'Save Data' button to a collocated directory structure.



Run No.: 1

● Data Run

... System Ready

Figure 54: ROAM Workstation Control User Interface

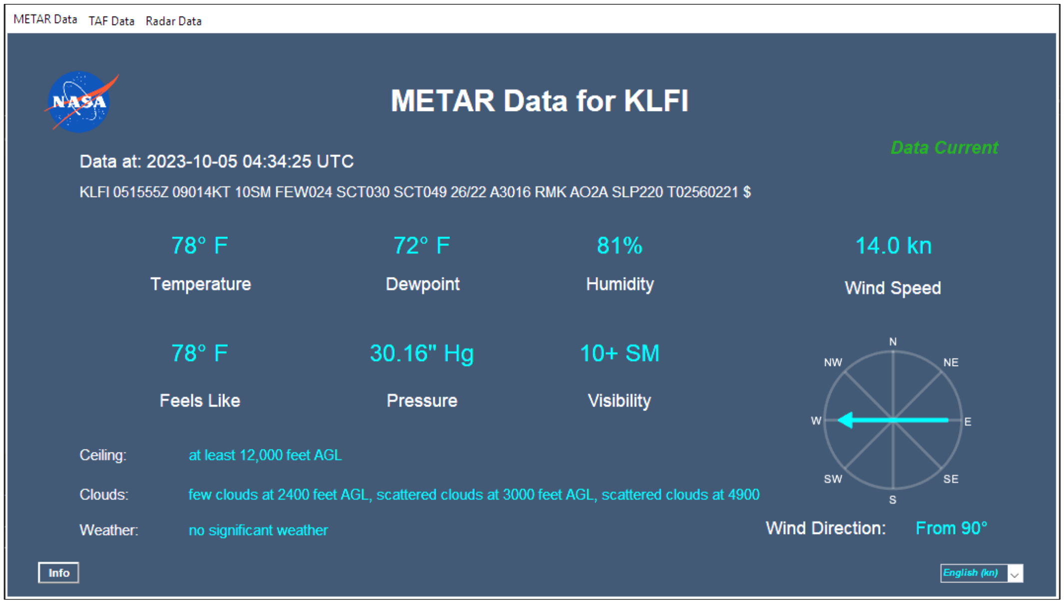
Application Notes:

- The software user interface is intended for display on the computer workstation for a single user and not for display on the video wall located within the operations center.
- The software does not collect any data from or transmit any data to an external source not operated by NASA.
- If the software was to fail, all basic applications on the computer continue to run and can be terminated manually at the end of an operation.
- This software is not used in a safety-critical system, to monitor a safety-critical system, to verify or validate a safety critical system, or to make safety decisions.

7.8 NASA WxWidget

The NASA Weather Widget (WxWidget) is a prototype software tool designed to collect publicly available weather data and present it to a user in a more friendly to read format for a selected weather station source. The tool is intended for display on computer workstations and a video wall within the ROAM UAS Operations Center supporting data collection activities for simulations and live flight operations. WxWidget provides as a minor function of serving data from one place to another. WxWidget runs on a workstation that is fully connected to the LaRCnet.

The WxWidget (see Figures 55-59) is capable of a Macro screen that displays regional weather data and a Micro screen that displays local weather data from weather sensors around LaRC. The Macro WxWidget connects to the public portal sources of METAR, TAF, and NEXRAD mosaic data. The Micro WxWidget connects to a website for the weather sensors at to download meteorological log messages produced at these micro weather stations. The software periodically checks for updated content and download when appropriate. While multiple instances of the WxWidget can run at once, the user can switch tabbed content within a single macro graphical user interface between METAR, TAF, and RADAR data. The micro user interface currently only supports one tab view or a “smaller” view to support multiple sensors sites at one time on a screen.



METAR Data for KLFI

Data Current

Data at: 2023-10-05 04:34:25 UTC

KLFI 051555Z 09014KT 10SM FEW024 SCT030 SCT049 26/22 A3016 RMK AO2A SLP220 T02560221 $

78° F Temperature

72° F Dewpoint

81% Humidity

14.0 kn Wind Speed

78° F Feels Like

30.16" Hg Pressure

10+ SM Visibility

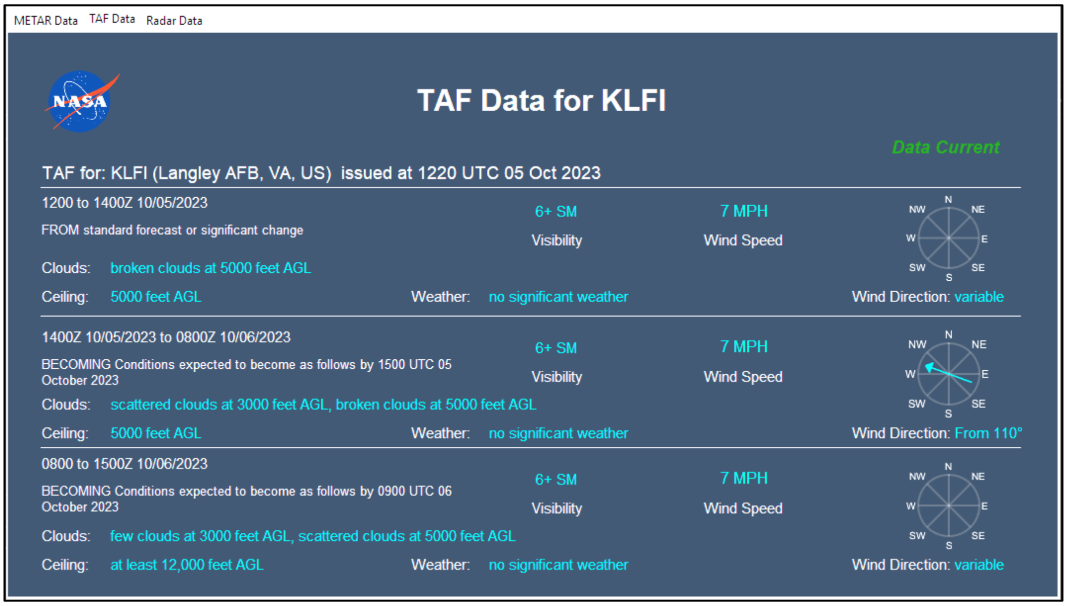
Ceiling: at least 12,000 feet AGL

Clouds: few clouds at 2400 feet AGL, scattered clouds at 3000 feet AGL, scattered clouds at 4900

Weather: no significant weather

Wind Direction: From 90°

Figure 55: NASA WxWidget – METAR Data



TAF Data for KLFI

Data Current

TAF for: KLFI (Langley AFB, VA, US) issued at 1220 UTC 05 Oct 2023

1200 to 1400Z 10/05/2023

FROM standard forecast or significant change

6+ SM Visibility

7 MPH Wind Speed

Clouds: broken clouds at 5000 feet AGL

Ceiling: 5000 feet AGL

Weather: no significant weather

Wind Direction: variable

1400Z 10/05/2023 to 0800Z 10/06/2023

BECOMING Conditions expected to become as follows by 1500 UTC 05 October 2023

6+ SM Visibility

7 MPH Wind Speed

Clouds: scattered clouds at 3000 feet AGL, broken clouds at 5000 feet AGL

Ceiling: 5000 feet AGL

Weather: no significant weather

Wind Direction: From 110°

0800 to 1500Z 10/06/2023

BECOMING Conditions expected to become as follows by 0900 UTC 06 October 2023

6+ SM Visibility

7 MPH Wind Speed

Clouds: few clouds at 3000 feet AGL, scattered clouds at 5000 feet AGL

Ceiling: at least 12,000 feet AGL

Weather: no significant weather

Wind Direction: variable

Figure 56: NASA WxWidget – Terminal Area Forecast Data

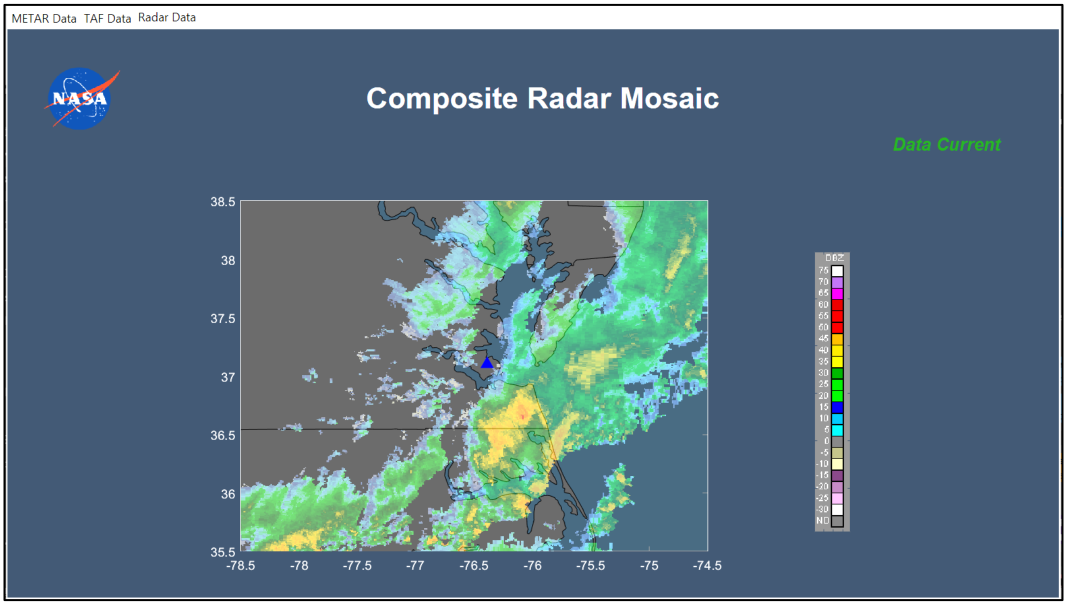
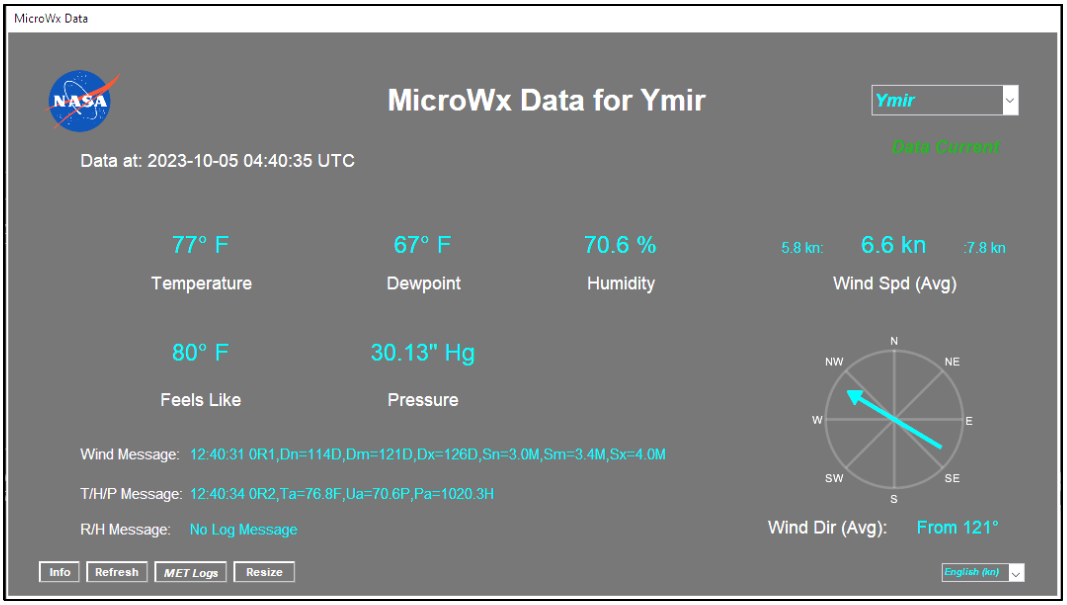


Figure 57: NASA WxWidget – Radar Data



MicroWx Data for Ymir

Data at: 2023-10-05 04:40:35 UTC

77° F Temperature

67° F Dewpoint

70.6 % Humidity

5.8 kn: 6.6 kn :7.8 kn Wind Spd (Avg)

80° F Feels Like

30.13" Hg Pressure

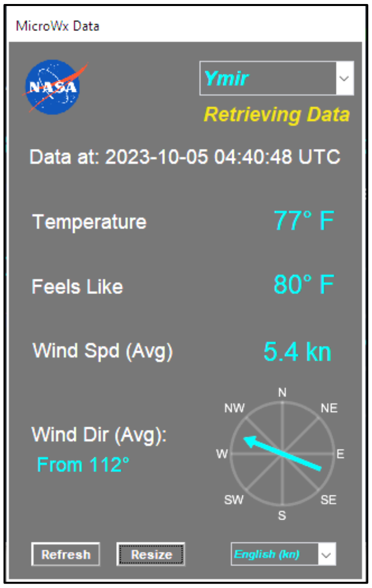
Wind Message: 12:40:31 0R1,Dn=114D,Dm=121D,Dx=126D,Sn=3.0M,Sm=3.4M,Sx=4.0M

T/H/P Message: 12:40:34 0R2,Ta=76.8F,Ua=70.6P,Pa=1020.3H

R/H Message: No Log Message

Wind Dir (Avg): From 121°

Figure 58: NASA WxWidget – Local Weather Sensor Data (Full Size)



MicroWx Data

Ymir

Retrieving Data

Data at: 2023-10-05 04:40:48 UTC

Temperature 77° F

Feels Like 80° F

Wind Spd (Avg) 5.4 kn

Wind Dir (Avg): From 112°

English (kn)

Figure 59: NASA WxWidget – Local Weather Sensor Data (Small Size)

Application Notes:

- WxWidget is a prototype only intended for internal research use for NASA to inform users with current and forecasted weather station data and has no safety-critical impact.
- The WxWidget provides non-critical weather data to the user.
- The presentation of METAR data; which includes temperature, dew point, humidity, pressure, visibility conditions, wind speed and wind direction, ceiling, clouds, and a summary weather statement; the presentation of TAF data—forecast information for the weather station, and the presentation of precipitation from RADAR data, are not used for any safety critical decision making.
- This software is not used in a safety-critical system, to monitor a safety-critical system, to verify or validate a safety critical system, or to make safety decisions.

7.9 Radar Display

A display of radar information directly from the data source(s) is important to the functional tasks of the Radar Operator in the ROAM UAS Operations Center. In these initial development cycles of flight operations on the LaRC CERTAIN range, the Radar Operator needs to be aware of the operational state and health of the radar equipment. Currently, there is a deployment of a single LSTAR Radar unit and a pair of GA9120 Radar units on CERTAIN that the Radar Operator monitors.

Each individual data source has a separate display application and user interface. The LSTAR Radar has a standalone software application that connects directly to the unit over the LaRCnet, allowing access to device health, radiating state, and configuration controls for both detection of vehicle traffic and display of information. Figure 60 presents the LSTAR software application in a configuration for display of detected vehicular traffic (white triangles follow by magenta trails) in and around LaRC. Like the LSTAR, the user interface for the GA9120 radar (see Figure 61) displays detected vehicular traffic (blue solid circles) and offers additional configuration management and control, but data access is not provided by a standalone software application. A thin web-client interface is used with user access controls to provide the display of data from the pair of GA9120 radar units.

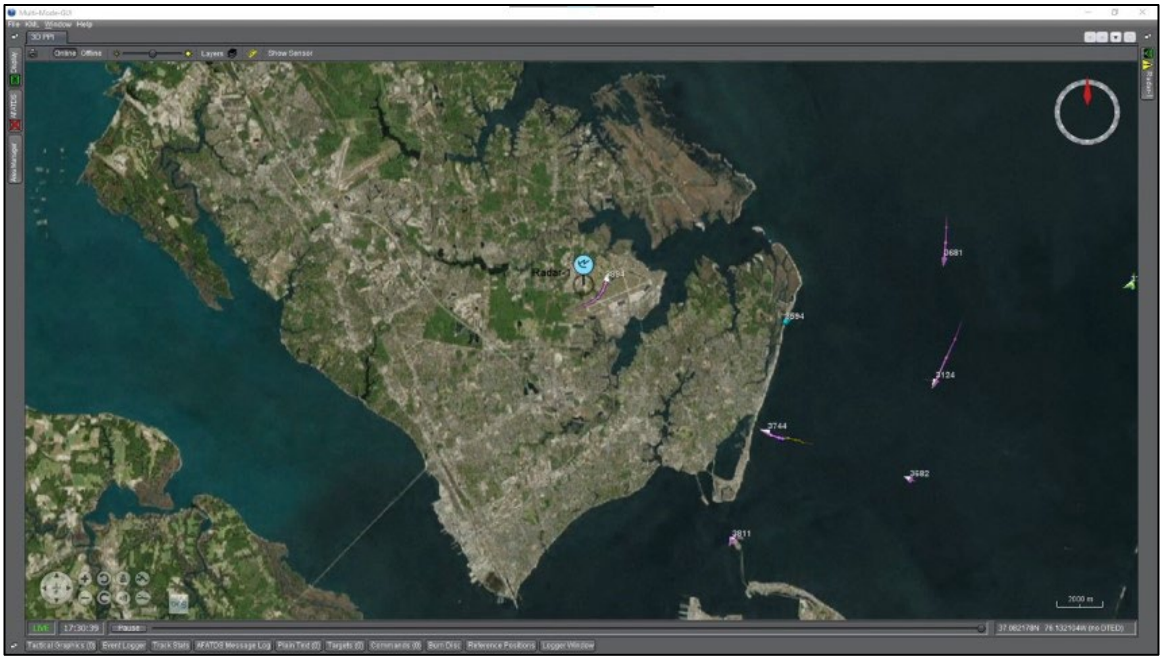


Figure 60: LSTAR Radar User Interface

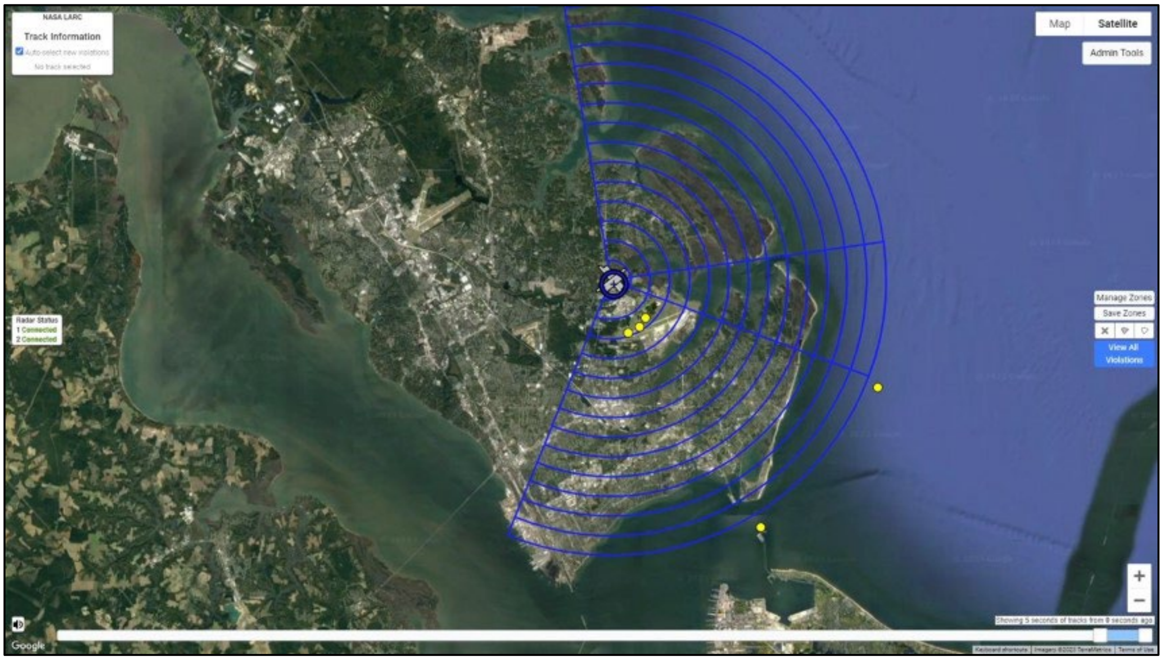


Figure 61: GA9120 Radar User Interface

Access to the display of the vehicle targets for the GA9120 radar is accomplished with a web browser installed locally to a ROAM workstation connecting to a local service running for this radar unit to process the data. The web browser may be Google Chrome, Microsoft Edge, or Mozilla Firefox; any of which run on a Microsoft Windows operating system.

7.10 UAS Mission Analysis Tool (UMAT)

The UAS Mission Analysis Tool (UMAT) was developed at LaRC by the Simulation Development and Analysis Branch and Metis Flight Research Associates to aid UAM and UAS operators to visualize flight missions and avoid obstacles and/or adverse conditions. Detailed UAS mission planning is accomplished with precise three-dimensional models including terrain, manmade structures, and vegetation; predicted weather; and predicted spatially distributed GPS signal quality. In addition to planning activities, UMAT can also monitor UAS mission execution in real-time for simulated and live vehicle traffic, providing live wind sensor data, and traffic position with intent.

UMAT can consider adverse conditions for flight that include poor weather, high winds, poor GPS coverage, and other vehicles operating in the area. This visual tool aims to include all obstacles larger than six inches, including buildings, sidewalks, roads, curbs, power lines, signage, utility poles, vegetation, and other structures. The UMAT tool extends on the capabilities of commercially available products by integrating live data from GPS, weather and ADS-B sources and presents this data on a single display in a high fidelity three-dimensional visual database. Finally, UMAT allows a mission planner to create a flight path in three-dimensional space to evaluate this flight path for possible interference, obstructions, or unsafe conditions either before the vehicle leaves the ground, or while the vehicle is in the air. The tool is also capable of allowing the mission planner to specify flight paths for multiple vehicles at the same time and allows the planner to evaluate possible conflicts between the vehicles.

Figure 62: UAS Mission Analysis Tool (UMAT) Primary User Interface

For operations conducted in the ROAM UAS Operations Center, the UMAT software (see Figure 62) is used generally by the Vertiport Manager and Flight Test Manager Actors to visually see the vehicle position (yellow triangular icons) in three-dimensional space relative to other vehicles and the geofence boundary (white transparent border). Also represented in the UMAT interface is the approach and departure paths into and out of the vertiports used during flight operations. The UMAT application connects into the Vertiport Automation System to receive vehicle telemetry information.

8. Roles and Responsibilities

With the Digital Services and key Software applications defined, the last component within the Network Architecture Design presented in Figure 17 of Section 5.3 is the role played by the Actors within the remote vehicle operations center. This section describes the roles, responsibilities, and basic communications between Actors (as described in Table 1) in the Field, the ROAM UAS Operations Center, and external participants at ARC and Langley Air Force Base (KLFI) Tower Control. The ROAM UAS Operations Center (*Remote*) supports the LaRC and ARMD program needs with the monitoring and command and control of simulated and live flight operations of small-UAS and future UAM vehicles at the CERTAIN Range (*Field*). Multiple workshops were held with existing users to refine the definition, validation of assumptions, identification of anything missed regarding the specific user's role and responsibilities, including services/functionalities to enable BVLOS operations, identification if emphasis or priority was being placed in the wrong areas for a user, and an open and honest assessment of the design for each user. The role descriptions presented are written in general terms and may not be comprehensive to other duties as assigned during the development of live and simulated flight operations. If applicable, guiding regulations or governing bodies of a particular role have been identified.

Following the description of the internal and external operators to the ROAM UAS Operations Center, the responsibility hierarchy is presented. For both the live and simulated flight operations that ROAM supports, the hierarchy of the roles, including the Field, ROAM, and External operators is discussed.

8.1 Internal Operators

Internal Operators are defined as Actors within the Organization Model that are located within the ROAM UAS Operations Center. These Actors may interact with other Internal Operators within ROAM and External Operators that may be either located on the CERTAIN Flight Range at LaRC, at ARC, or the local airspace control from Langley Air Force Base.

8.1.1 Range Safety Officer (RSO)

The Range Safety Officer is responsible for safety during a range flight operation. A Range Safety Officer has the authority to hold or abort the operation, or take a risk mitigation action, based on real-time events, which includes terminating the flight. The Range Safety Officer provides oversight for UAS vehicle operations by monitoring range airspace for potential risks with vehicle operations while monitoring a vehicle(s) [state, trajectory, and intention] in real-time, monitoring Field airspace for other aircraft by remote means, and monitoring Field current and forecasted weather conditions. The Range Safety Officer performs pre-flight briefings, including weather, safety procedures, and roles and responsibilities to ensure concurrence. The Range Safety Officer monitors UAS airspace prior to flight, during flight, and ensures completion. The Range Safety Officer may make real-time operational decisions when required for maintaining flight safety operations. The Range Safety Officer ensures proper safety mitigations are enacted in the field as outlined in the hazard analysis and files a Notice to Airmen (NOTAM) for flight operations. The Range Safety Officer maintains situation awareness of all local sUAS vehicles and is empowered to make any decision necessary to maintain range safety, including grounding all aircraft and directing the termination of a flight vehicle. Should an incident occur, the Range Safety Officer follows established accident reporting and investigation plan protocol.

- One position within CERTAIN.
- One position within the ROAM UAS Operations Center.
- RSO in ROAM priority is secondary to the RSO located in the Field during early data collection activities for the HDV subproject in FY21 and FY22. The secondary RSO coordinates with primary RSO in the field to ensure status. In subsequent operations, the RSO in ROAM becomes primary, relying on Visual Observers in the Field for confirmations.
    - Verifies operation is safe to proceed prior to flight or at each phase of flight.
- Guiding regulations for the responsibilities of the RSO:

  - NPR 8715.5B [55]
  - NPR 79003.D [56], Sec. 5.1.4.7
  - LPR 1710.16J [57], Sec. 5.1.5.7, 5.8.2.3 and 5.8.2.4
  - NASA-STD-8719.25 [58], Sec. 7.2
- Communication Description:
  - The RSO communicates with the SP(s), GCSO(s), VO(s), and FTM.
  - Communicates with Air Traffic Control (ATC) before, and during active operations on a professional level.
    - Ensures notification of completion at the end of the flight activity.
- Prototype Workstation Design:

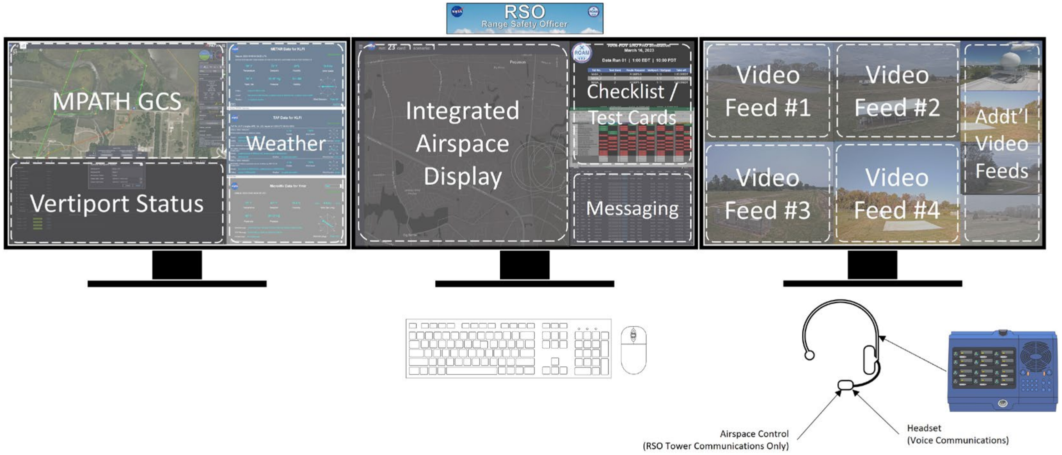


Figure 63: Prototype Workstation Design – Range Safety Officer

8.1.2 Ground Control Station Operator (GCSO)

The Ground Control Station Operator, using a connection to the UAS vehicle, monitors a vehicle [state, trajectory, and intention] in real-time and monitors Field current weather conditions. The Ground Control Station Operator reviews and approves flight trajectories from the PSU. The Ground Control Station Operator may also visually monitor local airspace and operations by remote means and supports vehicle setup, checkout, and shutdown.

The Ground Control Station Operator is also the primary point of interest for the human subject research. The Ground Control Station Operator is located within the ROAM UAS Operations Center and is responsible for all preflight, inflight, and post flight activities associated with the communication to the simulated vehicle. Associated run data logs are retrieved from the workstations and saved locally until the end of the day. If the Ground Control Station Operator is a human subject participant, they are responsible for answering questionnaires after each scenario run.

- Multiple positions within the ROAM UAS Operations Center. Dependent on the scenario type to be executed by NASA subproject management.
- GCSO in ROAM priority is secondary to the GCSO of the same vehicle located in the Field during initial testing with ROAM; later the GCSO in ROAM priority is primary to the GCSO of the same vehicle located in the Field, with the Field position eventually eliminated.
- The GCSO is a member of the Flight Crew.
- Guiding regulations for the responsibilities of the GCSO:
  - NPR 79003.D [56], Sec. 5.1.4.2 & 5.1.4.3
  - LPR 1710.16J [57], Sec. 5.5.1.4

- Communication Description:
  - The GCSO communicates with the SP, VSC, FTM, and SD.
  - The GCSO only communicates with Researchers after an operation.
- Prototype Workstation Design:

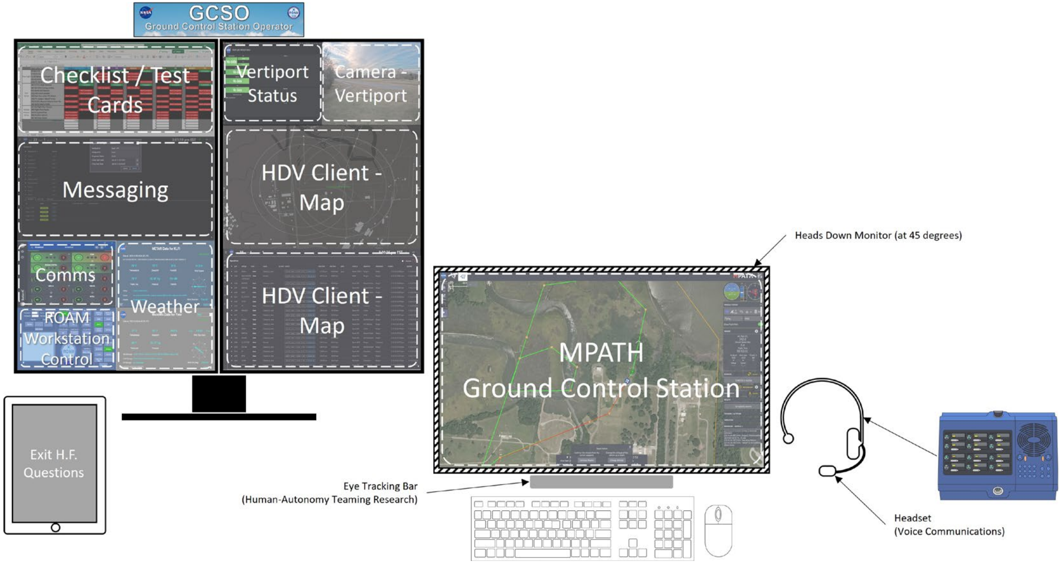


Figure 64: Prototype Workstation Design – Ground Control Station Operator

8.1.3 Flight Test Manager (FTM)

The Flight Test Manager (also identified as Mission Commander in many referenced publications) manages and coordinates flight crews and vehicle flights to conduct the test scenario(s) properly while monitoring a vehicle(s) [state, trajectory, and intention] in real-time and monitoring Field current and forecasted weather conditions. The Flight Test Manager may also visually monitor local airspace and operations by remote means.

- One position within the ROAM UAS Operations Center.
- FTM in ROAM priority is secondary to the FTM located in the Field during initial testing with ROAM; later the FTM in ROAM priority is primary with the Field position eliminated.
- Guiding regulations for the responsibilities of the FTM:
  - NPR 79003.D [56], Sec. 5.1.4.5 (acting as Mission Commander for multi-UAS operations)
  - NASA ER-ARB
  - NASA Advisory Implementing Instruction (NAII) 7900.3 [22], Sec. 4, App. E
  - NASA Subproject Management
- Communication Description:
  - The FTM communicates with the RSO, SP(s), GCSO(s), VM, ROE, ATOL Ops, and the FM.
- Prototype Workstation Design:
  - The workstation design for the FTM shares a similar design based on the role of the RSO. See Figure 63 for a workstation design that supports the FTM.

8.1.4 Simulation Director (SD)

The Simulation Director is the central point of contact and communications for the research team, simulation support staff, and ATOL Operations staff. The Simulation Director is located within the ROAM UAS Operations Center. The Simulation Director troubleshoots any scenario issues and determines if a run is valid or if a re-run of a scenario is necessary. The director is also responsible for ensuring all runs are complete before ending a data collection run or capturing data. The director ensures all participants are at the correct location in a timely manner and is responsible for maintaining the pace of the schedule. The Simulation Director ensures the correct scenarios are being used prior to the start of each run. The Simulation Director leads the execution of simulation studies within the ROAM UAS Operations Center while monitoring a vehicle(s) [state, trajectory, and intention] in simulation.

- One position within the ROAM UAS Operations Center.
- SD in ROAM priority is primary with no companion SD located in the Field during simulated flight operations.
- Guiding regulations for the responsibilities of the SD:
  - NASA Subproject Management
- Communication Description:
  - The SD communicates with the GCSO(s), FM, VM, Simulation Hardware Engineer, MACS Operator, TC, ROE, and ATOL Ops.
- Prototype Workstation Design:
  - The workstation design for the SD shares a similar design based on the role of the RSO. See Figure 63 for a workstation design that supports the SD.

8.1.5 Vertiport Manager (VM)

The Vertiport Manager monitors incoming/outgoing vehicle [state, trajectory, and intention] to a vertiport in real-time, monitors Field current weather conditions and may work directly with the Fleet Manager. The Vertiport Manager supervises the overall status (including closures due to hazards), services, and connectivity to the PSU Network within the vertiport in addition to overseeing arrival, surface taxi, departure, parking, and other vertiport services on the airside. The Vertiport Manger works with the Vertiport Automation System which provides resource management information (vertipad status and schedule) and risk management information (hazards on or around the vertipad, weather, etc.). The Vertiport Manager uses networked sensors to the VAS of a vertiport, such as weather, cameras, vertiport schedule and risk management services, and surveillance sensors consisting of an integrated and fused display of vehicle positions in the local airspace. The Vertiport Manager may use a conformance monitoring capability from a system like HDV Client and the independent surveillance display. Communications to the vehicle operators and fleet operators may be accomplished by voice, text-based automation, or a hybrid solution. The Vertiport Manager may also visually monitor local airspace and operations by remote means. If the Vertiport Manager is a human subject participant, they are responsible for answering questionnaires after each scenario run.

- One position within the ROAM UAS Operations Center. Additional, non-interfering, positions may be located at ARC.
- Guiding regulations for the responsibilities of the VM:
  - NASA Subproject Management
- Communication Description:
  - The VM communicates with the GCSO, FM, FTM, and SD.
  - The VM only communicates with Researchers after an operation.

- Additional descriptive resources:
    - NASA Advanced Air Mobility (AAM) project High Density Vertiplex – SAO Planning Discussion, Dr. Marcus Johnson, 2022
    - NUAIR – CLIN 3 Final Report – Vertiport Automation Software Architecture and Requirements, July 26, 2021
    - NUAIR – CLIN 3 Vertiport Automation System – Functional Requirements, July 2021
    - NUAIR – CLIN 3 Vertiport Automation System – Software Trade Study, July 2021
    - NUAIR – CLIN 3 Vertiport Automation System UI Design Concepts and Examples, July 2021
    - Vertiport Automation System Preliminary Design Review, Brian K. Hutchinson – NASA Langley, May 19, 2022
- Prototype Workstation Design:

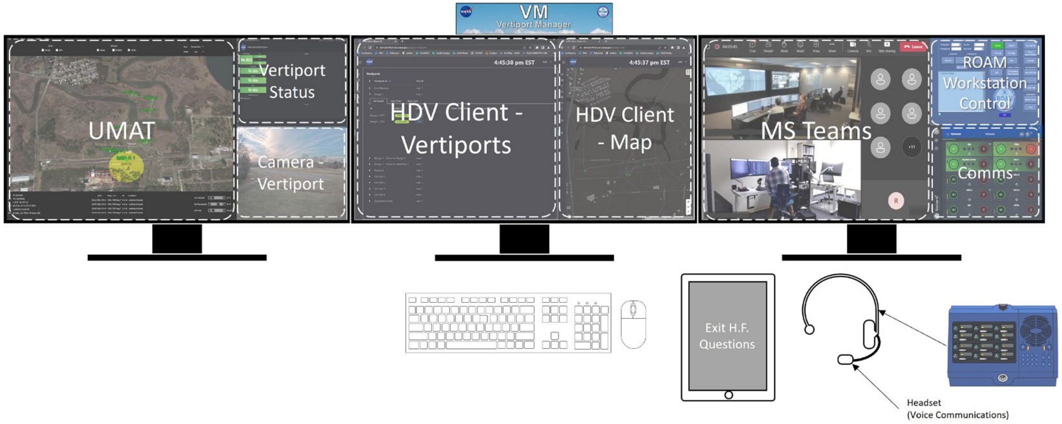


Figure 65: Prototype Workstation Design – Vertiport Manager

Future responsibilities considerations: The Vertiport Manager in its early instantiation may monitor and manage more than one vertiport with multiple vertipads and additional vertistops. As the number of vehicles increases in either simulation or live flight operations, the role of the Vertiport Manager may focus on single Vertiport or Vertiport area. This concentration of responsibilities may lead to the development of a Vertiplex Manager to manage the multiple vertiports within a define airspace and their relevant Vertiport Managers.

8.1.6 Radar Operator (RO)

The Radar Operator monitors state and health of radar systems that are present on CERTAIN at LaRC and any other radar systems that may be externally connected. The Radar Operator monitors incoming data from individual surveillance systems for validity checking and ensures fused target solutions are good. Provides troubleshooting of surveillance equipment remotely and source signals. The Radar Operator may work directly with the Airspace Surveillance Manager during initial integration of a fused surveillance display of local airspace vehicle traffic. One or more individuals may initially be needed to operate and fine tune displays from the LSTAR and GA 9120 radars.

- One position located within the ROAM UAS Operations Center but may be located elsewhere within LaRC. There is no companion Radar Operator located in the Field during operations.
- Guiding regulations for the responsibilities of the RO:
    - NASA Subproject Management
- Communication Description:
    - The RO communicates with the RSO, ASM, FTM, and SD.

- Prototype Workstation Design:

Figure 66: Prototype Workstation Design – Radar Operator

Future responsibilities considerations: The responsibilities of the Radar Operator may be merged with that of the Airspace Surveillance Manager at first, and eventually with the Range Safety Officer located in ROAM at a future date as determine by the Uninhabited Aerial Systems Operations Office (UASOO) at LaRC. The position of the Radar Operator may also be replaced as a service in the future.

8.1.7 Airspace Surveillance Manager (ASM)

The Airspace Surveillance Manager[30] reviews the fused surveillance display that contains the LSTAR radar, GA9120s radar, Skyler radar (external partner), ground ADS-B, and ground FLARM information. The Airspace Surveillance Manager works directly with the IAD. The Airspace Surveillance Manager monitors the airspace of interest and inform the Range Safety Officer and impacted vehicle flight crew of intruder traffic or UAS deviations from a planned flight route. The Airspace Surveillance Manager is also responsible for monitoring the performance of the fusion algorithm to ensure raw data (radar, ADS-B, FLARM) is being represented accurately on the IAD. The addition of the role for the Airspace Surveillance Manager is a risk mitigation to support the Range Safety Officer until the merging algorithms for the fused display of information have been confirmed to be acceptable and allows the opportunity to understand the workload the Range Safety Officer may have in performing their role and working with the separate displays required for the Airspace Surveillance Manager.

- One position within the ROAM UAS Operations Center, but not required. There is no companion ASM located in the Field during operations.
- ASM in ROAM provides input information to the RSO; located in the Field, ROAM, or both locations. Initially, the ASM works closely with the Radar Operator.
- Guiding regulations for the responsibilities of the ASM:
  - NPR 79003.D [56], Sec. 5.1.5.2
  - NASA Subproject Management
- Communication Description:
  - The ASM communicates with the RSO, RO, FTM, and SD.
- Prototype Workstation Design:

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[30] The Airspace Surveillance Manager is referred to as the Airspace Monitor (AM) in the *Safety Case for sUAS BVLOS Operations at NASA Langley Research Center* [7].

Figure 67: Prototype Workstation Design – Airspace Surveillance Manager

Future responsibilities considerations: The responsibilities of the Airspace Surveillance Manager may be merged with that of the Range Safety Officer located in ROAM at a future date as determine by the UASOO at LaRC.

8.1.8 ROAM Operations Engineer (ROE)

The ROAM Operations Engineer (ROE) directly supports and manages portions of the development, integration testing, and conduct of operations (simulated and live) within the ROAM UAS Operations Center. The ROAM Operations Engineer prepares the facility for daily operations in conjunction with ATOL Operations, ensure operator knowledge of the ROAM workstations and connected systems, provides necessary troubleshooting, manages the data collection from multiple workstations, and closes out systems at the end of each day of operations. The ROAM Operations Engineer may be a member of the research team.

- Minimum of one position within the ROAM UAS Operations Center. There is no companion ROE located in the Field during operations.
- Guiding regulations for the responsibilities of the ROE:
    - LaRC D318 Study/Experiment Review Policy: LMS-BP-5364, Revision B [59]
    - NASA Institutional Review Board (IRB)[31] for Human Factors Research
    - NASA Subproject Management
- Communication Description:
    - The ROE is not a direct participant during simulated and live vehicle flight operations; but is a support and troubleshooting role for the systems and resources within the ROAM UAS Operations Center.
    - ROE communicates with all users within ROAM UAS Operations Center as needed and may communicate with external operators in the Field and other connected facilities.

8.1.9 Researcher

Researchers from sponsor projects like AAM-HDV and TTT-RAM shall be available and are responsible for observation, feedback, and data gathering regarding Human Factors in ROAM. Data gathering involves

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[31] The NASA IRB is a committee panel that reviews all proposed research involving human subjects at NASA to ensure the safe, ethical, and equitable treatment of the participants. The IRB is guided by the Common Rule [77], NASA Policy Directive (NPD) 7100.8 [78], NPD 7170.1 [79], and NPR 7100.1 [80].

handwritten, digital, or tablet surveys used to question the subject Ground Control Station Operator, Vertiport Manager, and Fleet Manager after each scenario as well as researcher notes.

- Multiple positions located at LaRC and ARC.
- Guiding regulations for the responsibilities of the Researchers:
    - LaRC D318 Study/Experiment Review Policy: LMS-BP-5364, Revision B [59]
    - NASA IRB, where a new application for human subjects' research must be prepared and submitted for approval with each new data collection activity.
    - NASA Subproject Management
- Communication Description:
    - Researchers can hear any of the communication channels but are not able to communicate with any positions within the system during critical phases of high workload for flight operations.
- Prototype Workstation Design:

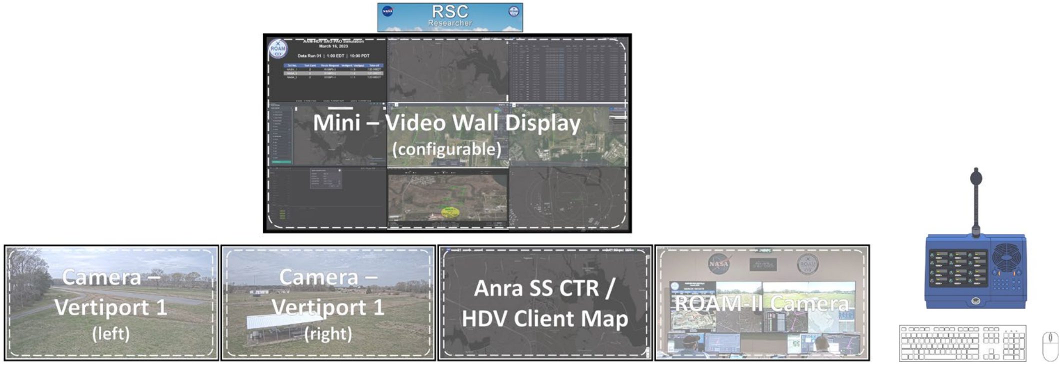

Figure 68: Prototype Workstation Design – Researcher

8.1.10 ATOL Operations (ATOL Ops)

The experimental specialists of ATOL Operations (ATOL Ops) supports flight operation (live or simulated) within the ROAM UAS Operations Center by managing equipment startup and shutdown, troubleshooting, data collection from operations, and management of Video Wall presentation of content. The experimental specialists prepares the ROAM Operations Center, monitors data collection activities, and uploads digital data to the storage facility. Other necessary duties related to the operations of the ROAM are completed as approved by the lab manager. The system administrator is available as a stand-by member to troubleshoot any failures or breakages in the facility.

- One lead position (Experiment Specialist) within the ROAM UAS Operations Center. Other support personnel may be present onsite during operations within ROAM.
- ATOL Operations in ROAM priority is primary with no companion located in the Field during operations.
- Guiding regulations for the responsibilities of ATOL Operations:
    - LaRC D318 Study/Experiment Review Policy: LMS-BP-5364, Revision B [59]
- Communication Description:
    - ATOL Operations communicates with all users within ROAM UAS Operations Center as needed.

8.1.11 Visitor / Non-Participant (VNP)

A Visitor/Non-Participant (VNP) in the ROAM UAS Operations Center/AOL/AVAL/SIVL/CERTAIN may be accommodated during the simulation or live flight to obtain familiarity with the operations. The Visitor/Non-Participant shall be directed to not influence operations (i.e., no workstation, no decision making during a run) and may be asked to move to an observation section of the facility/grounds. The Visitor/Non-Participant is a position of non-interference.

- There may be multiple visitors or non-participants present during operations within the ROAM UAS Operations Center/AOL/AVAL/SIVL/CERTAIN.
- Guiding regulations for the responsibilities of visitors or non-participants within ROAM:
    - LaRC D318 Study/Experiment Review Policy: LMS-BP-5364, Revision B
    - NASA Subproject Management
- Guiding regulations for the responsibilities of visitors or non-participants within CERTAIN:
    - Direction is provided by the Range Safety Officer at start of an operation to new visitors or non-participants.
- Communication Description:
    - Position of non-interference with simulated and/or live operations.

8.2 External Operators

External Operators are defined as Actors within the Organization Model that are located away from the ROAM UAS Operations Center. These Actors may interact with other External Operators and with Internal Operators within ROAM.

8.2.1 Pilot-In-Charge (PIC) and Safety Pilot (SP)

The Safety Pilot (SP) operates an uncrewed aircraft by means of a remotely located, manually operated radio-controlled flight management system (direct control by means of stick-to-surface interface). The Safety Pilot also may perform crewmember duties of a safety (or external) pilot who acts as a fail-safe to an uncrewed aircraft system that is normally controlled by a pilot-operator or Ground Control Station Operator.

If more than one vehicle is in operation at a given time, a single individual is designated as the Pilot-In-Charge (PIC) for lead decision making of all vehicles in flight.

- Position is in the Field. There is no position within the ROAM UAS Operations Center.
- SPs and PIC are members of Flight Crew.
- Guiding regulations for the responsibilities of the SP and PIC:
    - NPR 79003.D, Sec. 5.1.4.1
    - LPR 1710.16, Sec. 5.5.1.3
- Communication Description:
    - The SP communicates with the RSO, SP(s), GCSO(s), and FTM.

8.2.2 Ground Control Station Operator

The Ground Control Station Operator, using a connection to the UAS vehicle, monitors a vehicle [state, trajectory, and intention] in real-time and monitors Field current weather conditions. The Ground Control Station Operator reviews and approves flight trajectories from the PSU. The Ground Control Station Operator may also visually monitor local airspace and operations by local or remote means and supports vehicle setup, checkout, and shutdown.

The Ground Control Station Operator is responsible for all preflight, inflight, and post flight activities associated with the communication to the vehicle.

- Up to three positions planned in the Field for initial AAM-HDV subproject activities.
- GCSO in the Field priority is primary to the GCSO of the same vehicle located in ROAM during initial testing with ROAM; later the GCSO in ROAM priority is primary to the GCSO of the same vehicle located in the Field, with the Field position eventually eliminated.
- The GCSO is a member of the Flight Crew.
- Guiding regulations for the responsibilities of the GCSO:
    - NPR 79003.D [56], Sec. 5.1.4.2 & 5.1.4.3
    - LPR 1710.16J [57], Sec. 5.5.1.4
- Communication Description:
    - The GCSO communicates with the SP and FTM.
    - The GCSO only communicates with Researchers after an operation.

8.2.3 Airspace Control, KLFI Tower

Approves request for the opening of airspace at the CERTAIN range and confirms the request for the closure of the same airspace. When necessary, KLFI Tower issues NOTAMs and broadcasts alerts on the Automated Terminal Information System (ATIS) identifying that uncrewed vehicles are operating in the local area. Through a Letter of Agreement, KLFI Tower will limit other traffic at or above 900 feet over the CERTAIN range during sUAS operations.

- Single generalized position, External to the ROAM UAS Operations Center.
- KLFI Tower Control is a passive participant in live flight operations on the CERTAIN range.
- Guiding regulations for the responsibilities of KLFI Tower Control:
    - Federal Aviation Administration (FAA) Order JO 7110.65 [60] – Air Traffic Control
- Communication Description:
    - KLFI Tower only communicates with the RSO.

8.2.4 Fleet Manager (FM)

The Fleet Manager is responsible for management of individual and groups of aircraft, schedules the vehicles and supporting resources, and communicates with the Vertiport Manager(s). The Fleet Manager monitors each vehicle [state, trajectory, and intention] in real-time, monitors Field current weather conditions, and may work directly with the PSU. The Fleet Manager may issue altitude or speed change commands to vehicles in the area and manages information regarding a missed approach by a vehicle. The Fleet Manager provides flight trajectory adjustments to the PSU while monitoring multiple sUAS vehicles during a flight operation (live and simulated). The Fleet Manager coordinates with the Ground Control Station Operator to work through the active scenario and potentially provide an updated flight plan to the Ground Control Station Operator for upload to the vehicle. The Fleet Manager provides oversight for virtual aircraft in the simulation and flight operations. The Fleet Manager is located within AVAL at ARC. Further information on the Fleet Manager role and their interfaces can be found in Reference [21].

- One position External to the ROAM UAS Operations Center, located at ARC.
- Guiding regulations for the responsibilities of the FM:
    - NASA Subproject Management
- Communication Description:
    - The FM communicates with the GCSO(s), VM, FTM, and SD.

8.2.5 Test Coordinator (TC)

The Test Coordinator (TC) is a position explicit to AAM-HDV data collection activities that serves as the ARC point of contact to ensure that all systems are functioning and communicating properly and at the end of each run/day assess that all data has been received and documented. The main location of the Test Coordinator is in the AVAL at ARC.

- One position External to the ROAM UAS Operations Center, located at ARC.
- Guiding regulations for the responsibilities of the Test Coordinator:
    - NASA Subproject Management
- Communication Description:
    - The Test Coordinator communicates with the FM and SD.

8.2.6 Vehicle Service Crew (VSC)

Consisting of one or more individuals, the Vehicle Service Crew (VSC) is responsible for the maintenance, inspection, and visual pre-flight of the vehicle while it is on the ground. The Vehicle Service Crew is stationed at the vertiport takeoff and landing sites and are responsible for prepping and positioning of the vehicle for takeoff. After landing, they are responsible for removing the vehicle from the vertiport to perform servicing activities. The Vehicle Service Crew individuals also may perform crewmember duties of a Safety (or external) Pilot or Visual Observer while the vehicle is in flight and within sight of the Vehicle Service Crew's location.

- One or more positions External to the ROAM UAS Operations Center located within CERTAIN.
- Guiding regulations for the responsibilities of the VSC:
    - NASA Subproject Management
- Communication Description:
    - The VSC communicates with the RSO, SP(s), and GCSO(s). The VSC may also communicate with the FTM.

8.2.7 Visual Observer (VO)

Consisting of one or more individuals, the Visual Observer (VO) is responsible for the viewable airspace in and around the takeoff and landing areas of the vertiport. A Visual Observer ensures noninterference between the sUAS vehicle(s) and nonparticipating aircraft by means of see and avoid and notifies the flight operations team when nonparticipating aircraft are observed. When able, the Visual Observer visually tracks the research vehicle(s) and determines its proximity to other sUAS and hazards such as terrain, weather, and structures. The Visual Observer notifies members of the flight test team when they have or lose visual contact with the vehicle. Additionally, the Visual Observer(s) notifies the flight test team of any major observed deviations from the planned flight path and provides navigational awareness, as able, when the sUAS are within VLOS.

- One or more positions External to the ROAM UAS Operations Center located within CERTAIN.
- Guiding regulations for the responsibilities of Observers:
    - NPR 79003.D, Sec. 5.1.4.4
    - LPR 1710.16, Sec. 5.5.1.5
    - Title 14, Code of Federal Regulations (CFR) [61], Section 107.33
    - FAA Order 8900.1A [62], Volume 16, Chapter 1, Section 2
- Communication Description:
    - The Visual Observers communicates directly with the RSO, SP(s)
    - The Visual Observers communicate indirectly with the FTM and GCSO(s).

8.2.8 *Simulation Hardware Engineer*

The Simulation Hardware Engineer serves as the point of contact for development, setup, and troubleshooting the hardware-in-the-loop simulated aircraft. The Simulation Hardware Engineer may be one or more individuals located within the SIVL facility at LaRC. The individual(s) actively participate in startup and shut down of each of the simulation runs and assures functioning hardware and software. The Simulation Hardware Engineer coordinates the timing of the playback vehicle and other vehicles in simulation. The Simulation Hardware Engineer is responsible for local data collection from the hardware and may interact directly with the VAS for troubleshooting purposes.

- One position External to the ROAM UAS Operations Center, located at LaRC within the UAS Systems Integration and Validation Lab.
- Guiding regulations for the responsibilities of the Simulation Hardware Engineer:
  - NASA Subproject Management
- Communication Description:
  - The Simulation Hardware Engineer communicates with the GCSO, SD, and FM.

8.2.9 *Multi Aircraft Control System (MACS) Operator*

The Multi Aircraft Control System (MACS) [63] Operator serves as the point of contact for troubleshooting and startup of the MACS simulated aircraft. The operator coordinates with the Test Coordinator and is not required to be directly in the loop of the simulation scenarios. The MACS Operator is in the AOL at ARC. The MACS Operator is responsible for controlling the demand of the arrivals/departures and for documenting and logging data associated with the MACS system.

- One position External to the ROAM UAS Operations Center, located at ARC.
- Guiding regulations for the responsibilities of the MACS Operator:
  - NASA Subproject Management
- Communication Description:
  - The MACS Operator communicates with the FM and SD.

8.3 Operators No Longer Applicable

Throughout the design lifecycle of the ROAM UAS Operations Center, some operators are defined as Actors within the Organization Model that are no longer involved in the current operation model of the system. These Actors are included here for the purpose of reference.

8.3.1 *xTM Operator (xTMO)*

The xTM Operator is the central point of contact and communications for troubleshooting the HDV Client (also referred to as the xTM Client earlier in its life cycle) at LaRC. The xTM Operator is located within the ROAM UAS Operations Center. The xTM Operator actively works with the Fleet Manager at ARC to assure flight paths are compatible with GCS software and do not conflict with other flight paths prior to being uploaded by the Ground Control Station Operator to the vehicle during the simulation. The xTM Operator reviews flight trajectory approvals from the PSU while monitoring multiple UAS vehicles during a flight operation (live and simulated).

- One position within the ROAM UAS Operations Center. The xTMO in ROAM priority is primary with no companion xTMO located in the Field.
- Guiding regulations for the responsibilities of the xTMO:
  - NASA Subproject Management
- Communication Description:

- The xTMO communicates with the SP and GCSO of a vehicle, and the FM.

This position was removed as an Internal Operator during AAM-HDV AOA Simulation, September 2021.

8.4 Responsibility Hierarchy

To conduct live flight operations, simulated studies, or a hybrid mix, it takes a coordinated army of individuals playing key roles during the process. From the start, there must be a responsibility hierarchy that is established to maintain control of the operation in a safe and orderly method to guarantee the success and safety of vehicle flights. Table 15 presents the responsibility hierarchy for live vehicle flight operations. Live vehicle operations require additional thought in planning and safety considerations for people and property. In these missions, the Range Safety Officer is top priority in the command structure regarding the safety of operating the mission and is defined by the NASA regulations of the role. The Flight Test Manager is top priority in the same command structure to achieve Mission Objectives. Other roles work down from these positions, but everyone is responsible for safety. A similar approach to the responsibility hierarchy for simulation studies is presented in Table 16. Common positions between both tables are included, but if the role is not relevant, it is presented in gray text.

Table 15: Responsibility Hierarchy – Live Vehicle Operations

Responsibility	"Field"	ROAM	AOL/AVAL	SIVL
Airspace Management	① RSO VO$_n$	② RSO ASM RO	---	---
Mission Objectives	① FTM	② FTM SD	TC	---
Tactical Vehicle Management	① PIC / SP$_1$ ② SP$_n$	---	---	---
Strategic Vehicle / Fleet Management	①GCSO$_n$	② GCSO$_n$ VM	FM	---
Mission Support	VSC	ROE ATOL Operations	MACS Operator	Simulation Hardware Engineer
	Researchers VNP	Researchers VNP	Researchers VNP	---

Note:
①, ② Priority for Duplicate Positions within Category of Responsibility
Subscript *n* denotes multiple vehicles or positions

Table 16: Responsibility Hierarchy – Simulated Vehicle Operations

Responsibility	"Field"	ROAM	AOL/AVAL	SIVL
Airspace Management	RSO VO$_n$	RSO ASM RO	---	---
Mission Objectives	FTM	FTM ① SD	② TC	---
Tactical Vehicle Management	PIC / SP$_1$ SP$_n$	---	---	---
Strategic Vehicle / Fleet Management	GCSO$_n$	② GCSO$_n$ ① VM	③ FM	---
Mission Support	VSC	ROE ATOL Operations	MACS Operator	Simulation Hardware Engineer
	Researchers VNP	Researchers VNP	Researchers VNP	---

Note:
①, ②, ③ Priority within Category of Responsibility
Subscript *n* denotes multiple vehicles or positions

9. Implementation and Use of a Remote Vehicle Operations Center

The ROAM UAS Operations Center was implemented using the Role-Based Ontology introduced in Section 4 to define a logical and structured methodology that created as an outcome the overall facility design based on the roles and responsibilities of personnel expected to use the operations center. The Role-Based Ontology approach for designing ROAM was purposefully applied iteratively and recursively. To that end, as more unique roles were identified to be included in ROAM, the workstations, layout, and data sources available were extended. Additional services allow for a more enriched research environment to support human factors data collection for operations (live and simulated) conducted within ROAM.

At LaRC, the concept of a small-UAS operations center has been an evolutionary process beginning with a simple desk setup to monitor a remote vehicle's telemetry from inside a research complex building [64]. This early "remote Ground Control Station Operator" was able to observe live operations at CERTAIN, which laid the foundation for future needs and capabilities to be explored. As the AAM-HDV subproject gained experience in its early development, the need for a larger facility to support more remote operators and to study their needs and role was required, leading to this first command and control instantiation of the ROAM UAS Operations Center.

To date, data collected within ROAM have been used to explore different roles and responsibilities of remote operators managing autonomous vehicles, with the goal of exploring human-autonomy teaming concepts that enable *m:N* operations (i.e., *m* operators managing *N* vehicles). With workstations capable of supporting multiple roles, the remote command and control of sUAS vehicles, and interconnectivity with resources at ARC and the CERTAIN Flight Test Range resources, ROAM is an environment that can support both the collection of human factors data and the command and control of remote vehicles in BVLOS conditions. Multiple simulations and flight test operations, including several "firsts" for LaRC in simultaneous remote vehicle flight, have been completed from ROAM since 2021.

The following subsections present the implementation of a remote vehicle operations center at LaRC and its use for multiple NASA aeronautics activities. Figure 69 presents a timeline of ROAM with the role of Actors (Internal Operators) within the facility for various activities, the establishment of services, and the initial operating capability (IOC) of software applications. This figure directly illustrates an implementation over time of the Role-Based Ontology design methodology in a crawl, walk, run concept for the ROAM UAS Operations Center with product software applications being updated overtime after introduction. The symbology and nomenclature of the figure is designed to closely match and be relatable to the Network Architecture Design presented in Section 5.3 and Figure 17, the Services discussed in Section 6, and the Software described in Section 7.

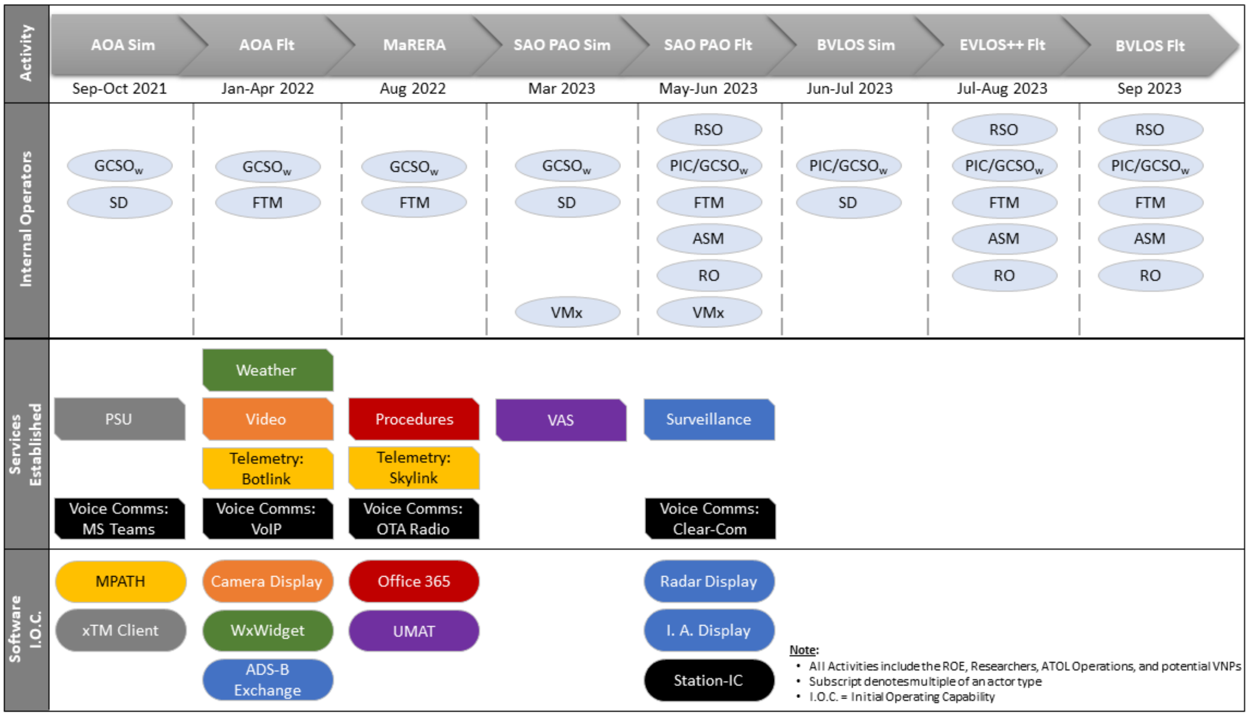

Figure 69: Implementation and Use Timeline of the ROAM UAS Operations Center

9.1 AAM-HDV AOA Simulation (Fall 2021)

The Advanced Onboard Automation (AOA) spiral wrap of the AAM-HDV subproject HHITL activity verified developed system-in-test software using a simulated environment to determine gaps and validate assumptions made regarding the HDV system-in-test design. Furthermore, data from the first verification tests support an initial safety risk assessment for BVLOS operations on the CERTAIN range using integrated onboard vehicle automation and human-autonomy teaming techniques as primary safety mitigations. Approval for BVLOS operations is a highly significant achievement, even more so considering that a runaway UAS has potential to escape the CERTAIN range and physically impact nearby Air Force F-22 operations, causing millions of dollars of damage with the potential for loss of life.

The AOA Simulation [45] was the first fully involved activity for the ROAM UAS Operations Center, pushing the initial limits and data connections established over the Summer of 2021. This simulation data collection activity ran for twelve (12) days between September 30 and October 19, 2021, taking approximately 115 work hours, with six (6) Ground Control Station Operators as participants (one at a time) from LaRC and three (3) Fleet Manager participants from ARC. Nine (9) different scenario types were tested with varying usage of technology components within the HDV system. The HHITL activity successfully completed 108 scenarios between training and data collection runs for a total of 15 hours of simulated vehicle flight time.

Figure 70 presents the final layout of the ROAM UAS Operations Center for AOA Simulation, focused on a four-desk layout for the Ground Control Station Operator, xTM Operator, Simulation Director, and ROAM Operations Engineer. Late in the process of preparing for the data collection effort, the xTM Operator workstation was eliminated leaving room for the Simulation Director to be closer to the participant and freeing a desk area for a supplemental researcher from ARC. Figure 71 is a photo of a Ground Control Station Operator participant in ROAM during AOA Simulation.

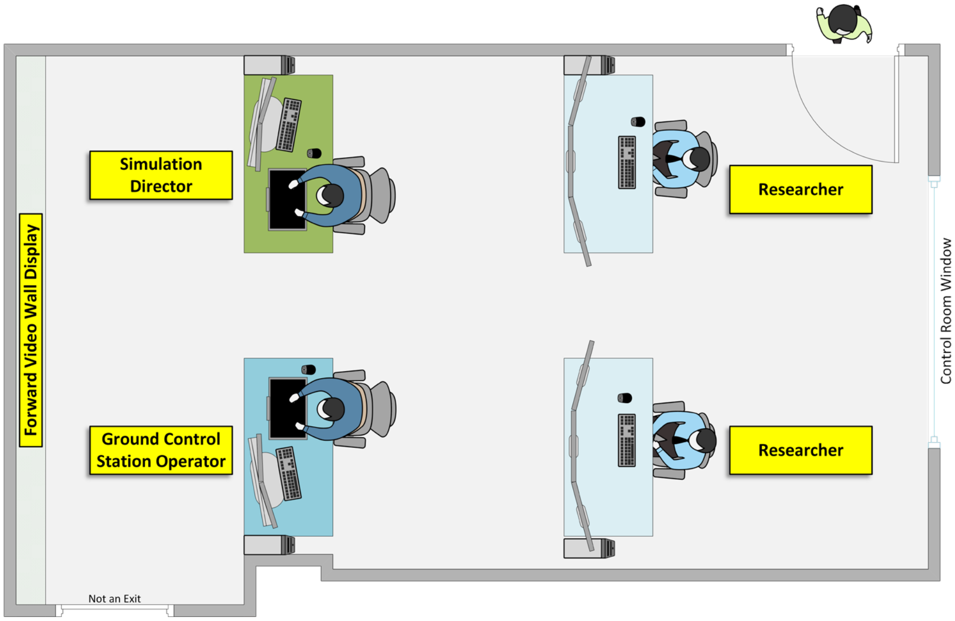

Figure 70: ROAM Layout for AAM-HDV AOA Simulation (Fall 2021)

Figure 71: Users in ROAM for AOA Simulation (Fall 2021)

9.2 AAM-HDV AOA Flight (Spring 2022)

The AOA Flight activity [65] complements and expands select capabilities of the air mobility ecosystem that were first explored within AOA Simulation and the prototype assessment with small-UAS surrogate aircraft. Furthermore, this activity expands the operations in consideration to mitigate risk for future BVLOS flight at LaRC. Flight operations utilized the ROAM UAS Operations Center, AOL, and the AVAL. AOA Flight Operations began in January of 2022, and concluded in April of the same year; typically flying two to three days every week. The AOA Flight activity was conducted with a modified subset of AOA Simulation scenarios and included participation from ARC with varying usage of technology components within the HDV system. The data collected supported NASA technology development, flight operations and procedures development, and human factor analysis on participants and their role. Data from participants of both AOA Simulation and Flight data collection activities on the usability of the operations center is presented in Reference [66] and further human factors analyses is presented in References [48, 50, 54, 67].

Figure 72 presents the final layout of the ROAM UAS Operations Center for AOA Flight, with a six-desk arrangement for the Ground Control Station Operators, Flight Test Manager, ROAM Operations Engineer, and a Researcher. The workstation where a researcher was sitting could be used for a Range Safety Officer. The primary change from AOA Simulation in 2021 was the addition of two Ground Control Station Operator workstations, and the rearrangement of several workstation monitors. Figure 73 is a photo of a three Ground Control Station Operator participants in ROAM during AOA Flight.

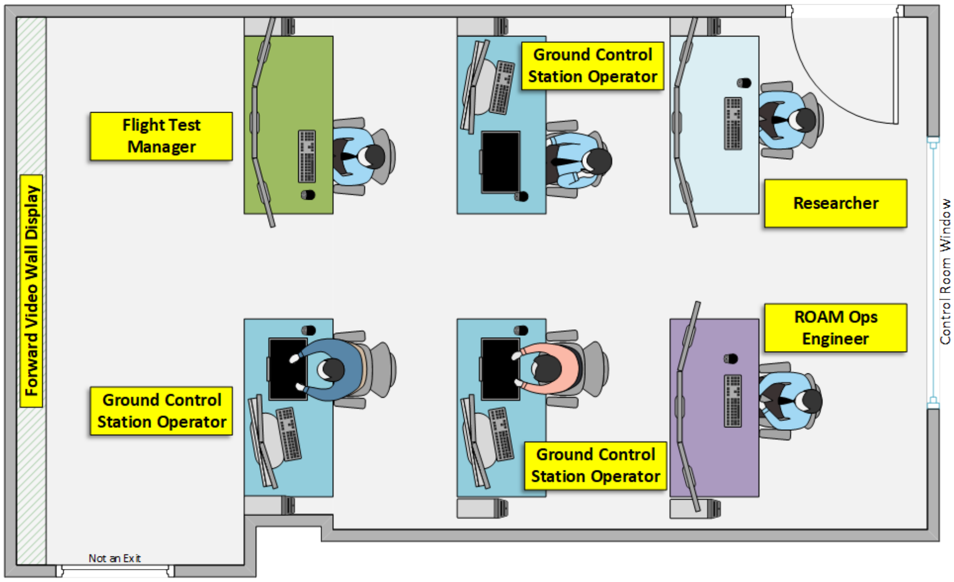

Figure 72: ROAM Layout for AAM-HDV AOA Flight (Spring 2022)

Figure 73: Users in ROAM for AAM-HDV AOA Flight (Spring 2022)

9.3 MaRERA Collaboration (Late Summer 2022)

The NASA Multi-aircraft Remote Emergency Response Assessment (MaRERA) Collaboration [68, 69] was a CAS bridge activity that directly supports the needs of wildland fire response teams for small-UAS vehicle coordination in EVLOS and BVLOS conditions. Although not directly connected to the AAM-HDV subproject, this small, but impactful data collection activity culminated in a final flight demonstration in August 2022, for NASA and the United States Forest Service, showcasing water package delivery using a small-UAS with command and control from ROAM. This was also a first successful example of a *m:N* (small number of humans [*m*] supervising many autonomous aircraft [*N*]) demonstration of an operator controlling a live and simulated vehicle from the ROAM UAS Operations Center with vehicle control handoff between operators. The operation concept demonstrated package delivery logistics of potable water to front-line wildland firefighters and potential scalability using small-UAS vehicles.

The flight assessment spanned several weeks and was conducted in the ROAM UAS Operations Center by a single human operator using the MPATH GCS software to remotely control two aircraft simultaneously. This flight assessment employed a hybrid configuration in which one vehicle was real (EVLOS operation) and one vehicle was simulated. More specifics on the multi-aircraft control flight assessment are described in Reference [50], including the initial usability results of the MPATH software and ROAM for these types of operations.

In addition to the prototype development of an *m:N* operation and testing of a link to the MQTT Broker for the NASA IoT Platform, the UAM Flyer was incorporated into the use case scenario allowing for manual and automatic remote control of a simulated vehicle from ROAM. This activity was also the initial test for a shared checklist between remote operator and field personnel. Finally, a new telemetry communication link to the remote vehicle was tested and proved viable using the uAvionix SkyLink application from the ROAM UAS Operations Center.

A layout diagram is not presented given the basic needs of the activity and a sole Ground Control Station Operator. Figure 74 presents a single Ground Control Station Operator at the forward-left most GCS Workstation in ROAM I and the forward video wall in the background supplying additional situation awareness of field and vehicle status during the final demonstration of the MaRERA activity.

Figure 74: Multi-Vehicle Operator in ROAM for MaRERA Flight Demonstration (Summer 2022)

9.4 AAM-HDV SAO PAO Simulation (Early Spring 2023)

The SAO Prototype Assessment Operations (PAO) Simulation [47, 70] is another HHITL activity, building from the achievements of AOA Simulation and Flight. The activity verified system-in-test software and hardware, connectivity, and human performance using a simulated environment to determine gaps and verify assumptions made in the AAM-HDV design for the SAO schedule work package. A key part of SAO PAO Simulation was the initial role assessment for the newly defined Vertiport Manager in conjunction with the development of automation and displays. The activity continued to support the collection of Human Factors data on participants and results from this simulation informed the research questions and evaluate the scenarios being developed for future studies within HDV.

SAO PAO Simulation ran for six (6) days between March 1 and March 16, 2023, taking approximately 42 work hours. The simulation activity included nine (9) Ground Control Station Operators and three (3) Vertiport Manger participants from LaRC and three (3) Fleet Manager participants from ARC. Other positions included the Simulation Director and ROAM Operations Engineer. Five (5) different scenario types were tested with varying degrees of complexity for vertiport loading within a prototype AAM ecosystem. The HHITL activity successfully completed 22 Scenarios per participant between training and data collection runs for a total of 7 hours of simulated vehicle flight time.

Figure 75 presents the final layout of the ROAM UAS Operations Center for the SAO PAO Simulation, featuring a six-desk arrangement for the Ground Control Station Operators, Vertiport Manager, Simulation Director, and ROAM Operations Engineer. This simulation activity included the three Ground Control Station Operator participants in every scenario tested with the addition of the emerging role of the Vertiport Manager. While the Ground Control Station Operators continued to work with MPATH as their primary GCS application and the HDV Client application for flight plan initialization, the Vertiport Manager used multiple windows of the HDV Client to monitor incoming and ongoing simulated flight operations, simulated faux video camera resources, and the UMAT software application—an exocentric full-view control to maintain situation awareness for vertiport operations. Figure 76 is a photo of a participants in ROAM during the SAO PAO Simulation.

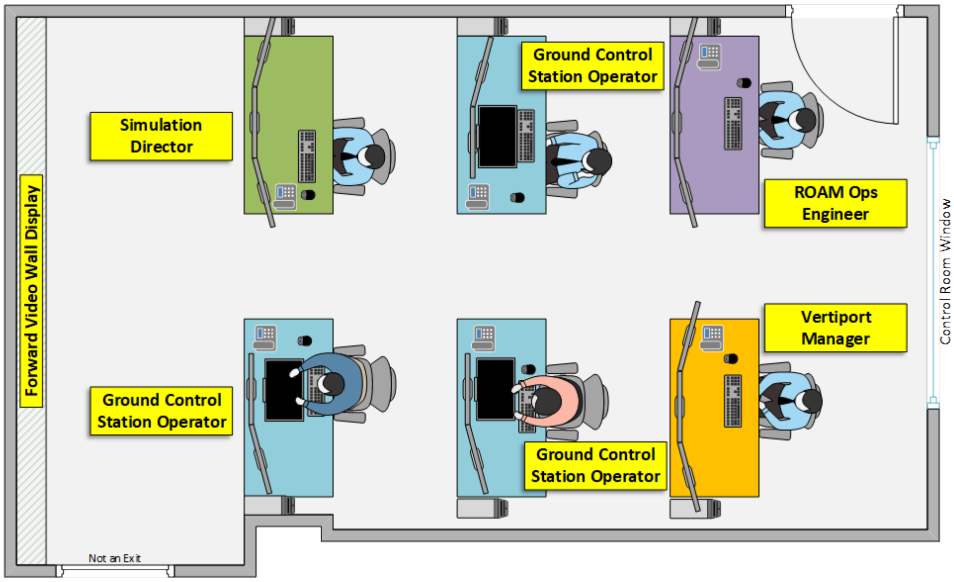

Figure 75: ROAM Layout for AAM-HDV SAO PAO Simulation (Early Spring 2023)

Figure 76: Users in ROAM for AAM-HDV SAO PAO Simulation (Early Spring 2023)

9.5 AAM-HDV SAO PAO Flight (Late Spring 2023)

The SAO PAO Flight Test [21, 71, 72] objectives demonstrated the SAO scenarios in flight in a relevant environment (the UAM ecosystem) with a buildup approach. AOA Flight began to bring operations into the ROAM UAS Operations Center and extended from visual line of sight to operations where the pilot did not have visual of the aircraft (EVLOS); whereas SAO Flight expanded on that and progress towards BVLOS operations where only personnel were in the field are setting up the vehicle (pre-flight and post flight). Flight operations utilized the ROAM UAS Operations Center, the AOL, and the AVAL. SAO PAO Flight Operations began in May of 2023, and concluded in June of the same year; typically flying two to three days every week. The SOA Flight activity was conducted with a modified subset of SOA PAO Simulation scenarios and included participation from ARC with varying usage of technology components within the HDV system. The data collected supported NASA technology development, flight operations and procedures development, and Human Factor analysis on participants and their role.

Figure 77 presents the final layout of the ROAM UAS Operations Center for SOA PAO Flight, with a six-desk arrangement for ROAM I that included the Flight Test Manager, Radar Operator, Range Safety Officer, Airspace Surveillance Manager, and Vertiport Manager. ROAM II, an extension of ROAM located adjacent to the original facility location, included up to five Ground Control Station Operators and the ROAM Operations Engineer. Figure 78 is a photo of a five Ground Control Station Operator participants in ROAM during a coordinated five-vehicle simultaneous flight for SAO PAO Flight.

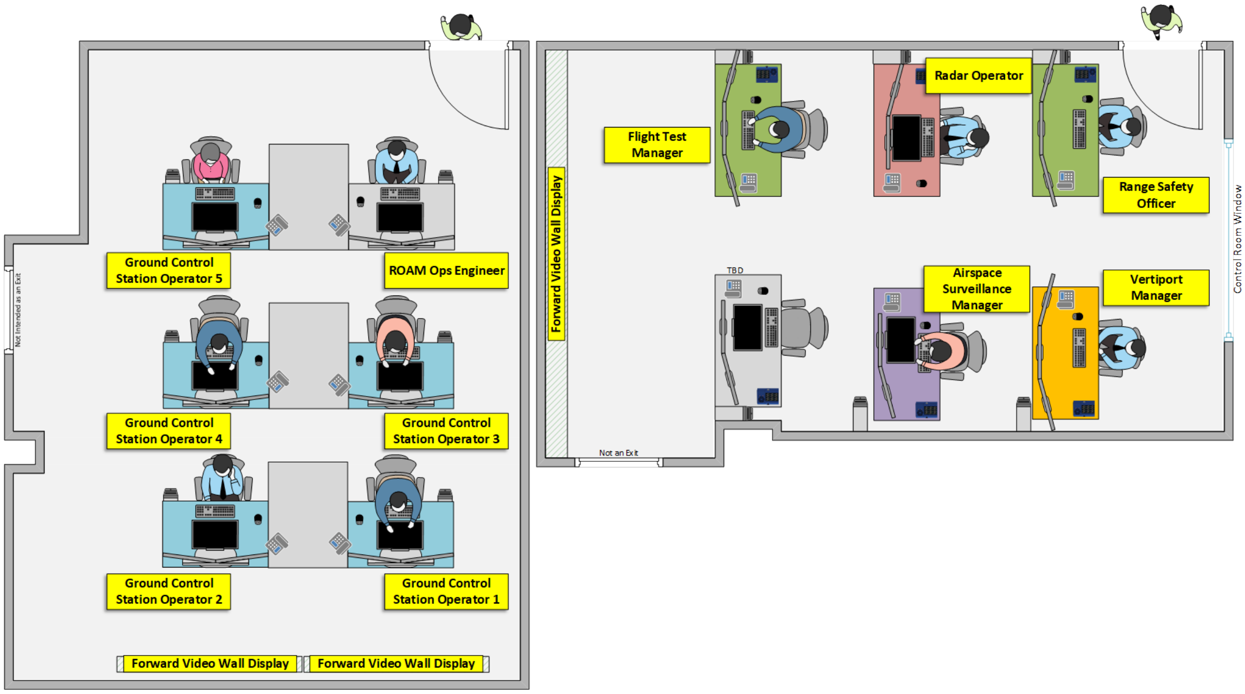

Figure 77: ROAM Layout for AAM-HDV SAO PAO Flight (Late Spring 2023)

Figure 78: Participants in ROAM for AAM-HDV SAO PAO Flight (Late Spring 2023)

9.6 AAM-HDV SAO BVLOS Simulation (Summer 2023)

To move the previous SAO PAO Flights towards true BVLOS flights, the AAM-HDV subproject sought both training for specific pilot-in-command responses to vehicle and system faults (e.g., lost vehicle link, motor failure, other vehicle conflict, etc.) and a simulation to test the effectiveness of the training when the pilot-in-command is the sole individual responsible for a vehicle during BVLOS scenarios. The BVLOS Simulation ran for five (5) days between June 29th and July 12th, taking approximately 32 work hours. Simulation activity included five (5) Ground Control Station Operators individually as participants from LaRC. With the goal to test ten (10) different scenario types to exercise BVLOS training in a data collection environment, BVLOS Simulation also introduced a capability to record audio of participants to support the human factors technique of "think aloud." BVLOS Simulation was critical to certify remote pilots to be capable of completing future live BVLOS flights on Center. The data collection activity successfully completed 50 scenarios across all participant collection runs for a total of 5.25 hours of simulated vehicle flight time.

Figure 79 presents the layout of the ROAM UAS Operations Center for SOA BVLOS Simulation, with an arrangement for ROAM I that only included the Simulation Director and ROAM II only including a single Ground Control Station Operator and the ROAM Operations Engineer. Figure 80 is a view of the forward video wall display from the Simulation Director's workstation. Separation of the Actors was done purposefully to create an immersive environment for the Ground Control Station Operator.

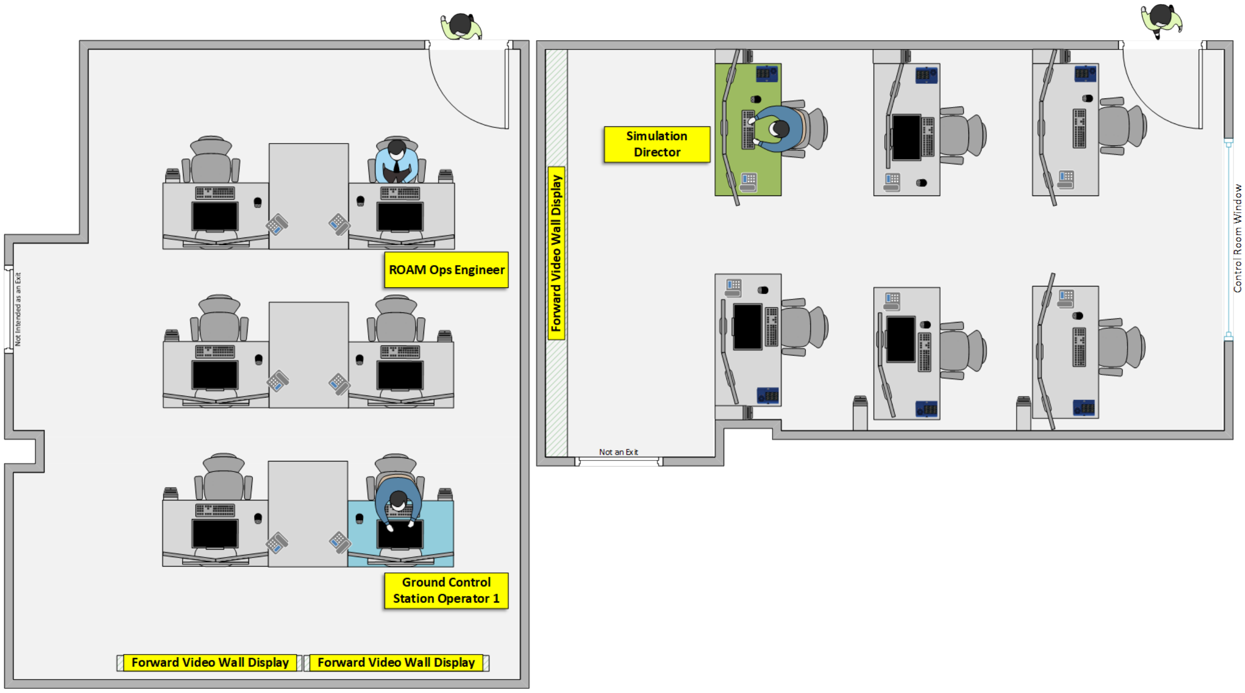

Figure 79: ROAM Layout for AAM-HDV BVLOS Simulation (Summer 2023)

AAM-HDV SAO BVLOS Sim
June 29, 2023

Data Run 08 – Test Card - 04

GCS	Vehicle	Skystation	Route	Vertiport - Vertipad	Take-off
1	Sim	X	BVLOS 3	V2 - P1	03:06

Figure 80: Flight Test Manager Position in ROAM for AAM-HDV BVLOS Simulation (Summer 2023)

9.7 AAM-HDV SAO EVLOS++ Flight (Summer 2023)

Flight testing activities continued for the AAM-HDV subproject throughout the Summer of 2023, with a continued focus on vertiport operations and autonomous systems to support them. Building from the EVLOS flights and BVLOS Simulation activities presented in Section 9.5 and 9.6, the next series of flight testing was an extension of both and labeled as EVLOS++. In a methodical step towards BVLOS operations, the EVLOS++ flights and data collection activity received approval for the removal of the Safety Pilot from the field location, a first for LaRC and the subproject, but continued to maintain the visual observer(s). EVLOS++ Flight ran for six (6) days between July 21 and August 18, 2023, taking approximately 36 work hours. Flight included multiple Ground Control Station Operators from LaRC (no human factors data was collected) with support roles provided by the Flight Test Manager and Range Safety Officer. The data collection activity tested four (4) different scenario types with varying degrees of complexity for vertiport loading within a prototype AAM ecosystem. The activity successfully completed 26 scenarios with data collection for an approximate total of 4 hours of vehicle flight time.

Figure 81 presents the final layout of the ROAM UAS Operations Center for SOA EVLOS++ Flight, with a six-desk arrangement for ROAM I that included four desks for the Flight Test Manager, Radar Operator, Range Safety Officer, and Airspace Surveillance Manager. During the flight activity, ROAM II was only required to support a single Ground Control Station Operator with the ROAM Operations Engineer to maintain separation of situation awareness from the Flight Test Manager. Figure 82 is a photo of the Flight Test Manager in ROAM I with the forward video wall in the background with repeated displays from the Ground Control Station Operator position in ROAM II.

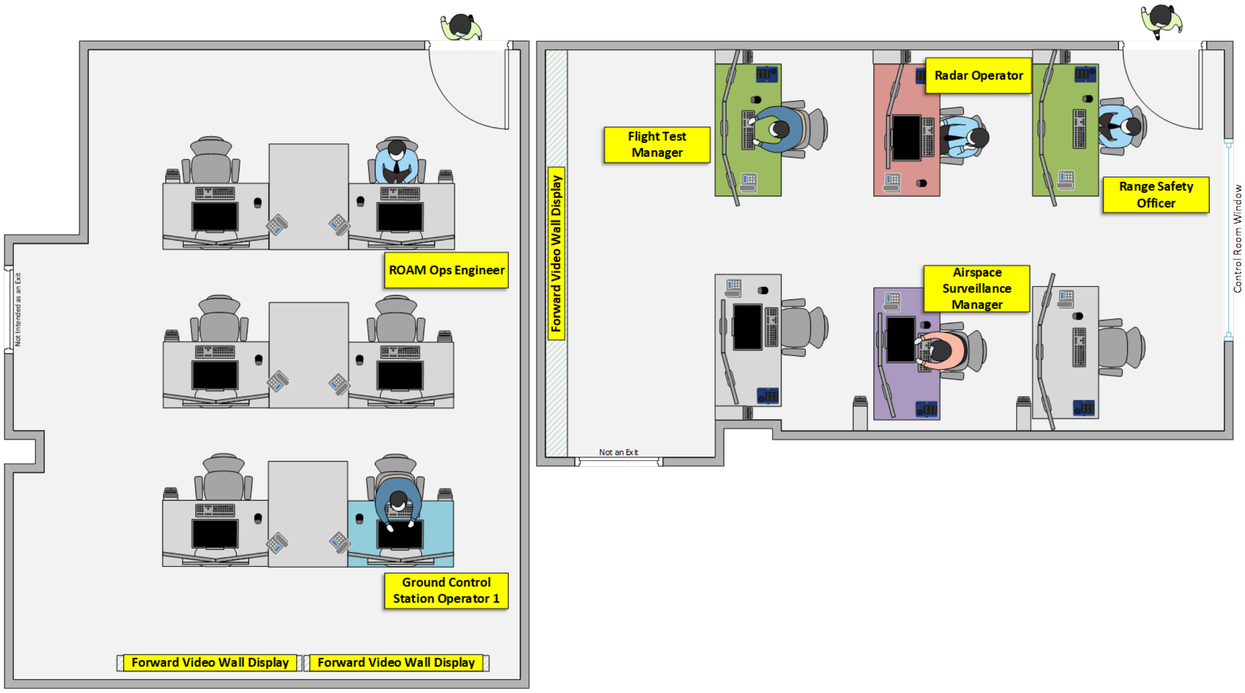

Figure 81: ROAM Layout for AAM-HDV SAO EVLOS++ Flight (Summer 2023)

Figure 82: Flight Test Manager in ROAM for AAM-HDV SAO EVLOS++ Flight (Summer 2023)

9.8 AAM-HDV SAO BVLOS Flight (Late Summer 2023)

The culmination of the SAO Schedule Work Package for the AAM-HDV subproject and the natural extension of the EVLOS++ flights, the BVLOS flights would not only eliminate the Safety Pilot from the field location, but Visual Observers as well—replacing them with ground-based surveillance systems. Prior to BVLOS Flight, additional remote pilot training was required that was developed at LaRC (see Reference [73]). With a BVLOS Certificate of Authorization (COA) from the FAA, a waiver for the provisions to meet the see and avoid requirement of 14 CFR 91.113(b), and a well-documented BVLOS Safety Case [7], the flight data collection activity ran for four (4) days between September 12 and September 21, 2023, taking approximately 28 work hours. Flight included three (3) Ground Control Station Operators as participants from LaRC with support roles provided by an Airspace Surveillance Manager, Radar Operator, Flight Test Manager, and Range Safety Officer. The data collection tested three (3) different scenario types with varying degrees of loss of sight from the take-off vertiport on the CERTAIN flight range. At the conclusion, a total of 10 BVLOS flights were successfully completed with data collection and human factors for a total of less than 1 hour of vehicle flight time.

Figure 83 presents the final layout of the ROAM UAS Operations Center for SOA BVLOS Flight, with a six-desk arrangement for ROAM I that included four desks for the Flight Test Manager, Radar Operator, Range Safety Officer, and Airspace Surveillance Manager. During the flight activity, ROAM II was only required to support a single Ground Control Station Operator with the ROAM Operations Engineer to maintain separation of situation awareness from the Flight Test Manager. Figure 84 is a photo showing ROAM I from the perspective of the Range Safety Officer with the other actors present in the room and the forward video wall in the background providing shared situation awareness for the execution of the flight tests.

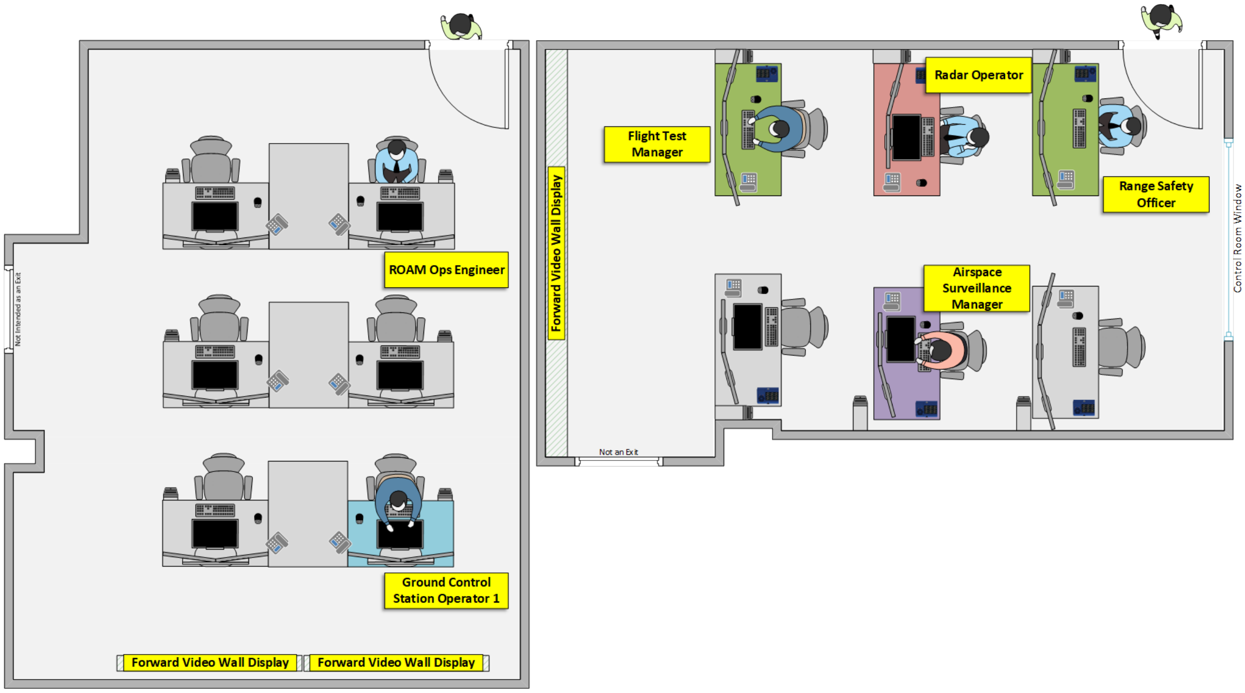

Figure 83: ROAM Layout for AAM-HDV SAO BVLOS Flight (Late Summer 2023)

Figure 84: ROAM I during AAM-HDV SAO BVLOS Flight (Late Summer 2023)

9.9 Supported Operation Use Case Scenarios

The examples of implementation and use of the ROAM UAS Operations Center that have been presented so far have been focused on the research and development capabilities that support NASA subprojects like AAM-HDV and TTT-RAM AS Human-Autonomy Teaming. The use case scenarios that a remote vehicle operations center can support could include more extensive control and monitoring of vehicles (air-, sea-, and ground-based vehicles), inspections and surveillance, and emergency response operations. The following figures present a potential expansion of the benefits a fully developed and connected operations center can provide to government, businesses, and academia with the management of remote vehicles.

- Multi-vehicle operations in BVLOS conditions, working jointly or independently to support mission needs of the stakeholder.

Figure 85: Use Case – Multi-Vehicle Operations

- Building and roof-top inspections allow for preventative maintenance to be identified early on with potential cost-savings benefits to the stakeholder. Identification of parts of an aging facility that need repair can extend its usability. A remote vehicle can quickly reach heights and vantage points that would be difficult for an inspection team.

Figure 86: Use Case – Building and Roof-Top Inspections

Figure 87: Use Case – Aging Facility Inspections (Insulation Loss)

- Interior facility inspections into difficult to reach areas or areas that take specially trained individuals considerable time to prepare to reach.

Figure 88: Use Case – Interior Facility Inspections

- Property/fence line and environmental inspections can be made on a more frequent basis, allowing for a timely and better prepared response by the stakeholder.

Figure 89: Use Case – Property Line and Environmental Inspections

Whether it is a research-focused facility like ROAM or an operations-focused facility like MOSAIC, an operations center that is connected to appropriate data sources and services that supports the roles of its users can perform a mix of the above use cases or can be specialized to focus on a single area. Simulation and training should always be considered in part of the process of setting up for the more complex flight operations. Preparing the operators of the facility with experiences enables them to respond quickly and efficiently in use cases like emergency wildland fires, disaster response, and humanitarian aid missions.

10. Extensibility of a Remote Vehicle Operations Center for UAM Research

The systems that the ROAM UAS Operations Center connects into is part of an ever-evolving ecosystem, supporting the needs of researchers and flight operations for projects at LaRC. The development of this prototype remote vehicle operations center with its capabilities and impacts described herein is extensible to other research activities in AAM that seek to study a future airspace system and that needs to explore human-autonomy teaming enabled *m:N* operations. Many entities in government, industry, and academia are currently conducting research in this domain. The development of remote vehicle operations centers such as ROAM provides the backbone necessary to conduct research into current and future domains while informing evolving aviation regulations. In its current form, the ROAM UAS Operations Center enables the maturation of technology and concepts in simulation and flight to support the continued development of new and emerging UAM and AAM operations and technologies. The Role-Based Ontology design method using a human-centered design process enables clear definition of multiple user roles, so they can perform remote sUAS operations safely and efficiently. ROAM also enables the full end-to-end hardware- and human-in-the-loop simulation testing with simulated sUAS, providing connections for an LVC environment. With ROAM, NASA researchers can leverage the established flow of simulation-to-flight and therefore lower the transfer risk of new ideas and technologies with this type of research and development environment.

10.1 Future Technical Development

With the first simulation study completed in the Fall of 2021 [45, 46, 54, 74] and a series of subsequent live vehicle operations and simulation data collection activities having been conducted from ROAM (see References [21, 47, 48, 50, 65-68, 70-73, 75]), the evolutionary process of the facility continues. The systems that the ROAM UAS Operations Center connects into are part of an ever-evolving ecosystem, supporting the needs of researchers and flight operations for projects at LaRC. As the need shifts within NASA projects and industry to command and control more vehicles from a remote location (i.e., BVLOS), additional information may be required to substitute for the information that is available to operators when controlling a vehicle under visual line of sight conditions. The following is a list of areas of ongoing and future development that are connected to ROAM:

- Integrated Airspace Surveillance Display – additional capabilities
- Extension of Voice Communication System for Operations Support
- Extension of Video Surveillance Source for Operations Support
- Integration into the NASA IoT Platform

At LaRC, several simulation facilities and equipment capabilities exist that the ROAM UAS Operations Center could be connected to in the future, enabling a larger and more dynamic LVC environment. One such example that the NASA research team is currently exploring is a connection to the NASA UAM Flyer [29] as a crewed or uncrewed simulated vehicle that could be a part of the LVC environment and could be controlled by a Ground Control Station Operator within ROAM. A suite of these vehicles coupled with existing point-mass modeled vehicles and live-flight vehicles is a near-term technical development goal.

Near-term development plans in ROAM are focused on providing users with supplemental information to support initial multi-vehicle operations and more sophisticated onboard automation. Yet to achieve the level of scalability needed to enable mature AAM operations, a paradigm shift is required to allow significantly fewer human operators to manage more increasingly autonomous vehicles (i.e., *m:N*). In this construct, the role of the human needs to change substantially such that responsibility for and authority over individual vehicles shifts from the human to the autonomous (or highly automated) vehicle systems. This shift transforms the human's role from managing multiple vehicles to assisting many more vehicles at a much larger scale [76]. This paradigm shift in vehicle management to enable these types of operations has been identified by NASA's TTT-RAM subproject as a critical area of research into human-autonomy teaming. Indeed, an overarching goal of ROAM is to provide a research testbed that can evolve to support this paradigm shift.

10.2 Potential Research Activities

A remote vehicle operations center like ROAM enables research activities that would be prohibited in a mature operations center, such as those that must routinely conduct daily operational activities with fixed versioning of workstation and software applications. A remote vehicle operations center like ROAM described within this report can be used to conduct research into several specific areas of AAM, such as:

- **Technology Performance Studies.** New individual and pairings of AAM technologies and human-autonomy teaming concepts may be developed that require a facility supporting research, development, and technology (RD&T) environments. With a remote vehicle operations center like ROAM, various technology performance studies and benefits analyses could be conducted to justify adoption and inform evolving aviation regulations.
- **Procedure Development.** By equipping select Ground Control Station Operators within an operational scenario with one or more airspace services/technologies in a HITL study, procedures and interactions may be evaluated between the different actors of the operations center and external operators.
- **Human Factors Analyses.** By equipping select Ground Control Station Operators and other actors in an operational scenario with one or more airspace services/technologies in a HITL study, human factors data can be collected and evaluated to address various research questions. Data gathered from these studies may include both objective metrics (e.g., eye tracking data) and subjective metrics (e.g., subjective workload, situation awareness, and human-automation trust) to determine how humans interact within a remote vehicle operations center.
- **Integrated Simulation Studies.** By connecting the capabilities described for ROAM with external simulations and resources, integrated air-ground simulation activities with realistic operational scenarios may be conducted. This type of activity presents a unique opportunity to not only evaluate a given technology's performance or the procedures used to operate it within the context of a facility like ROAM, but to evaluate the interaction of multiple users and their roles in the command and control of remote vehicles while assessing human-autonomy teaming concepts within the emerging AAM ecosystem.
- **Performance Standards Development.** By developing and maturing new concepts and technologies within ROAM, these efforts can inform the refinement and development of performance standards for sUAS in BVLOS flight and GCS requirements. Research activities conducted within ROAM may help inform regulators like the FAA and industry working groups in their decision-making process.
- **Future Evolutions.** ROAM is part of an evolving ecosystem, supporting the needs of researchers and increasing the value of simulated and live flight operations. The design of ROAM supports the functional transition from current field control to future remote operations and management of sUAS while supporting the exploration of human-autonomy teaming enabled *m:N* operations. This type of facility should continue to evolve to support new user roles and responsibilities in AAM research.

11. Summary

The groundbreaking development of the Remote Operations for Autonomous UAS Operations Center, known as ROAM, is an exceptional contribution to the exploration of AAM operations through small uncrewed aerial systems vehicles. This world-class facility serves as the backbone for pushing the boundaries of current and future aerial transportation, laying the foundation for integrating remotely piloted vehicles into the National Airspace System in the years to come.

ROAM UAS Operations Center stands as a cutting-edge platform that facilitates the maturation of technology and conceptual advancements in simulation and flight. By doing so, it continuously supports the development of pioneering UAM and AAM operations and technologies. A key highlight of ROAM lies in its capability to enable full end-to-end HHITL simulation testing, connecting with simulated sUAS and creating a seamless LVC environment.

Through the implementation of ROAM, NASA researchers have gained unparalleled leverage, ensured a smooth flow of simulation-to-flight processes, and significantly reduced the transfer risk associated with testing new ideas and technologies. This invaluable research, development, and testing environment not only accelerates progress but also guarantees safety in the pursuit of groundbreaking innovations. Data collected within this extraordinary facility has paved the way for exploring diverse roles and responsibilities of remote operators managing increasingly autonomous vehicles. A major goal has been to investigate human-autonomy teaming concepts, enabling operations where multiple operators manage numerous vehicles (known as *m:N* operations). The implementation of a single pilot operating several sUAS aircraft in the ROAM facility would undoubtedly be a game changer, revolutionizing the way we approach and advance aviation technology.

Thanks to its versatile workstations, ROAM offers seamless remote command and control of sUAS vehicles, allowing for unparalleled interconnectivity with resources at ARC and the CERTAIN Flight Test Range. This dynamic environment not only facilitates the collection of crucial human factors data but also enables the command and control of remote vehicles in BVLOS conditions, pushing the boundaries of what was previously considered possible.

Since its inception in 2020, ROAM has achieved numerous milestones. Multiple simulations and flight test operations, some of which were pioneering endeavors for LaRC, have been successfully completed from this outstanding facility. Notably, ROAM played a pivotal role in orchestrating simultaneous remote vehicle flights and BVLOS flight of remote vehicles, further solidifying its position as a trailblazer in the field of AAM.

In conclusion, the development of the ROAM UAS Operations Center represents an exceptional achievement in the realm of AAM operations. The impact of ROAM goes beyond its physical capabilities, as it sets the stage for the future of aerial transportation and exploration.

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Appendix A. Full Organization Model

The following table presents the Organization Model developed for the Role-Based Ontology for the internal operators within the ROAM UAS Operations Center. The model layout of the information has been re-formatted to fit this document format. The Organization Model concept is explained in Section 4.2.

Appendix Table A-1: Organization Model – Range Safety Officer

Actor: Range Safety Officer (RSO)	
Priority[*]: • Secondary to the RSO located in the Field during early data collection activities for the HDV subproject in FY21 and FY22. • In subsequent operations, the RSO in ROAM becomes primary, relying on Visual Observers in the Field for confirmations.	
Location: Remote	**Workstation:** Range Safety Officer Station
Core Functions:	**Functional Tasks:**
• Provides safety oversight for flight operations by monitoring Range airspace for potential risks with vehicle operations	• Primary role for providing safety oversight for UAS operations. • Liaison support with other range safety organizations when operating at their sites • Limits the assessed collective risk associated with sUAS vehicle operations • Ensures that the probability of doing harm to equipment, personnel, or the public is not greater than the criteria established by NPR 8715.5 (Range Safety Program) • Reviews the plan of the vehicle(s) prior to the flights. Approves the flights are safe. • Conducts the safety briefing for each flight operation • Gives clearance for take-off of vehicle(s) • Communicates status for shared situation awareness on the Video Wall(s)
• Opens/ closes the airspace to flight operations. Contacts Tower Control	• Opens/closes the airspace to flight operations. Contacts Tower Control.
• Monitors a vehicle(s) [state, trajectory, and intention] in real-time	• Monitors the vehicle(s) position within the airspace of the Range • Monitors the vehicle(s) intended path within the airspace of the Range
• Monitors Field airspace for other aircraft	• Monitors airspace for other aircraft and ground traffic under flight operations • Monitors tower radio frequency for incoming aircraft and alerts
• Monitors Field current and forecasted weather	• Monitors Field weather conditions, including ceiling and wind/ gust limits.
• Visually monitors local airspace and operations by remote means	• Monitors local airspace by use of various Video sources
• Communicates with SP(s), GCSO(s), VO(s), FTM, ASM, RO, and Tower Control	• Communicates with Flight Crew in the Field and within the Operations Center
Guiding Regulations[†]	
• NPR 8715.5B • NPR 79003.D, Sec. 5.1.4.7 • LPR 1710.16J, Sec. 5.1.5.7, 5.8.2.3 and 5.8.2.4 • NASA-STD-8719.25, Sec. 7.2	

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[*] For an Actor with one or more priorities in different locations, the decision to "remove" a location for an Actor shifts the priority of the lesser location forward. For this initial Organization Model presented in this appendix, it is assumed that the Field location takes priority when more than one of the same Actor is in play.

[†] Guiding Regulations Specific Acronyms: ER-ARB: Eastern Region Airworthiness Review Board, LMS = Langley Management System, LPR = Langley Procedural Requirements, NAII = NASA Advisory Implementing Instruction, NPR = NASA Procedural Requirements

Appendix Table A-2: Organization Model – Ground Control Station Operator

Actor: Ground Control Station Operator (GCSO)	
Priority: • Secondary to the GCSO of the same vehicle located in the Field during early data collection activities for the HDV subproject in FY21. • In subsequent operations, the GCSO in ROAM becomes primary with the Field position eventually eliminated.	
Location: Remote	**Workstation:** Ground Control Station
Core Functions:	**Functional Tasks:**
• Monitors a vehicle [state, trajectory, and intention] in real-time	• Monitors the operation of an uncrewed aircraft by means of the remote GCS • Monitors the uncrewed aircraft autonomously by means of computer interface with an onboard flight management system (fly-by-mouse) through a command-and-control communications link • Support SP with readout of state and intent information where required from GCS.
• Support vehicle setup, checkout, and shutdown	• Creates and saves vehicle flight plan, geo-fence, and rally points • Connects to vehicle via multiple connection pathways • Supports pre-flight checks and vehicle shutdown. Saves data from vehicle when able
• Monitors flight trajectory approvals from the PSU	• Monitors flight trajectory approvals from the PSU via the HDV Client interface
• Visually Monitors Local Airspace and operations by remote means	• Monitors local airspace by use of various Video sources • Video feed provides confirmation of vehicle position and attitude • Monitor vehicle at T/O and Landing location by use of various Video Sources
• Monitors Field current weather	• Monitors Field weather conditions, particularly Vertiports
• Communicates with SP and VSC of a vehicle, RSO, FTM, and SD	• Communicates with SP and VSC of a vehicle in the Field and within the Operations Center, RSO, FTM, and SD • Only communicates with Researchers after an operation is completed
Guiding Regulations:	
• NPR 79003.D, Sec. 5.1.4.2 & 5.1.4.3 • LPR 1710.16, Sec. 5.5.1.5	

Appendix Table A-3: Organization Model – Flight Test Manager

Actor: Flight Test Manager (FTM)	
Priority: • Secondary to the FTM located in the Field during early data collection activities for the HDV subproject in FY21 and FY22. • In subsequent operations, the FTM in ROAM becomes primary with the Field position eliminated.	
Location: Remote	**Workstation:** Flight Test Manager Station
Core Functions:	**Functional Tasks:**
• Provides safety oversight for flight operations by monitoring Range airspace for potential risks with vehicle operations	• Controls simulation and training session from station (Start, Stop, Reset, Scenario and configuration selection) • Directs the sequence of events at the appropriate times • Manages the resources available • Selectable communications with the operations team (Field, Remote, External)
• Monitors a vehicle(s) [state, trajectory, and intention] in real-time	• Monitors the operation of vehicle(s) and ensures criteria of the test scenarios are met. • Monitors the vehicle(s) position within the airspace of the Range • Monitors the vehicle(s) intended path within the airspace of the Range
• Monitors Field current and forecasted weather	• Monitors Field weather conditions via RADAR and other internet data products
• Communicates with RSO, SP(s), GCSO(s), VM, ROE, ATOL Ops, and FM	• Communicates with the Flight Crews in the Field and within the Operations Center, with the ATOL Operations Experiment Specialists, and with the ROE.
Guiding Regulations:	
• NPR 79003.D, Sec. 5.1.4.5 (acting as Mission Commander for multi-UAS operations) • NASA ER-ARB • NAII 7900.3, Sec. 4, App. E • NASA Subproject Management	

Appendix Table A-4: Organization Model – Simulation Director

Actor: Simulation Director (SD)	
Priority: Primary	
Location: Remote	**Workstation:** Simulation Director Station
Core Functions:	**Functional Tasks:**
• Leads the execution of simulation studies within the ROAM	• Manages test scenarios, order of scenarios, and assignment of positions of remote pilots at a particular workstation • Coordinates execution of simulation with roles in SIVL, AOL, and AVAL • Coordinates success of a data collection run for a scenario with the TC.
• Monitors a vehicle(s) [state, trajectory, and intention] in simulation	• Monitors the operation of vehicle(s) and ensures criteria of the simulation scenarios are met. • Monitors the vehicle(s) position within the airspace of the Range • Monitors the vehicle(s) intended path within the airspace of the Range
• Communicates with GCSO(s), FM, VM, Simulation Hardware Engineer, MACS Operator, TC, ROE, and ATOL Ops	• Communicates with the Flight Crews within the Operations Center, the simulation support team, TC, ROE, and the ATOL Ops Experiment Specialists
Guiding Regulations:	
• NASA Subproject Management	

Appendix Table A-5: Organization Model – Vertiport Manager

Actor: Vertiport Manager (VM)	
Priority: Primary	
Location: Remote	**Workstation:** Vertiport Station
Core Functions:	**Functional Tasks:**
• Monitors a vehicle [state, trajectory, and intention] in real-time	• Monitors the operation of an uncrewed aircraft by means of multiple sources available like the HDV Client or Integrated Airspace Display • use a conformance monitoring capability from a system like HDV Client and the Integrated Airspace Display
• Manages resources within a Vertiport	• Manages one or more vertipads, vertiports, or vertistops
• Interfaces with a display of information from the VAS	• Supervises the overall status (including closures due to hazards), services, and connectivity to the PSU network within the vertiport • Oversees arrival, surface taxi, departure, parking, and other vertiport services • Interfaces with the VAS • Monitors networked sensors to the VAS of a vertiport like weather, cameras, vertiport schedule and risk management services, and surveillance sensors consisting of an integrated and fused display of vehicle positions in the local airspace
• Visually Monitors Local Airspace and operations by remote means	• Monitors local airspace by use of various Video sources • Video feed provides confirmation of vehicle position and attitude • Monitors vehicle at T/O and Landing location by use of various Video Sources
• Monitors Field current weather	• Monitors Field weather conditions, particularly Vertiports
• Communicates with the GCSO of a vehicle, FTM, SD, and FTM	• Communicates with the GCSO of a live or simulated vehicle, providing guidance on vertiport status including information on the opening or closure of an individual vertipad(s) or a vertiport • May communicate with the FTM, SD, or FM • Communications to the GCSO(s) and FM may be accomplished with voice, text-based automation, or a hybrid solution • Only communicates with Researchers after an operation is completed
Guiding Regulations:	
• NASA Subproject Management	

Appendix Table A-6: Organization Model – Radar Operator

Actor: Radar Operator (RO)	
Priority: Primary	
Location: Remote	**Workstation:** Radar Station
Core Functions:	**Functional Tasks:**
• Monitors a vehicle [state, trajectory, and intention] in real-time	• Monitors the vehicle(s) position within the airspace of the Range • Monitors the vehicle(s) intended path within the airspace of the Range
• Interfaces directly with sources of the Integrated Airspace Display	• Monitors state and health of radar systems that are present on the CERTAIN range and any other radar systems that may be externally connected • Monitors incoming data from individual surveillance systems for validity checking and ensures fused target solutions are good • Provides troubleshooting of surveillance equipment remotely and source signals
• Communicates with the RSO, ASM, FTM, and SD	• Communicates directly with the RSO, ASM, and potentially the Flight Crew in the Field and within the Operations Center. May communicate with FTM and SD.
Guiding Regulations:	
• NASA Subproject Management	

Appendix Table A-7: Organization Model – Airpsace Surveillance Manager

Actor: Airspace Surveillance Manager (ASM)	
Priority: Primary	
Location: Remote	**Workstation:** Airspace Surveillance Station
Core Functions:	**Functional Tasks:**
• Monitors a vehicle [state, trajectory, and intention] in real-time	• Monitors the vehicle(s) position within the airspace of the Range • Monitors the vehicle(s) intended path within the airspace of the Range
• Interfaces directly with the Integrated Airspace Display	• Reviews the fused surveillance display that contains the LSTAR radar, GA9120s radar, Skyler radar (external partner), ground ADS-B, and ground FLARM information • Monitors the airspace of interest and inform the RSO and impacted vehicle flight crew of intruder traffic or UAS deviations from a planned flight route • Monitors the performance of the fusion algorithm to ensure raw data (radar, ADS-B, FLARM) is being represented accurately on the Integrated Airspace Display
• Visually Monitors Local Airspace and operations by remote means	• Monitors local airspace by use of various Video sources • Video feed provides confirmation of vehicle position and attitude
• Communicates with the RSO, RO, FTM, and SD	• Communicates directly with the RSO, RO, and potentially the Flight Crew in the Field and within the Operations Center. May communicate with FTM and SD.
Guiding Regulations:	
• NPR 79003.D [34], Sec. 5.1.5.2 • NASA Subproject Management	

Appendix Table A-8: Organization Model – ROAM Operations Engineer

Actor: ROAM Operations Engineer (ROE)	
Priority: Primary	
Location: Remote	**Workstation:** N/A
Core Functions:	**Functional Tasks:**
• Manage the ROAM UAS Operations Center during operations	• Directly supports and manages portions of the development, integration testing, and conduct of operations (simulated and live) within the ROAM UAS Operations Center • Prepares the facility for daily operations in conjunction with ATOL Operations • Ensures operator knowledge of the ROAM workstations and connected systems • Provides necessary troubleshooting of systems and resources • Manages the data collection from multiple workstations • Works directly with Researchers to meet objectives of data collection activity • Closes out systems at the end of each day of operations
• Communicates with all users within ROAM	• Communicates with all users within ROAM as needed • May communicate with external operators in the Field and other connected facilities
Guiding Regulations:	
• LaRC D318 Study/Experiment Review Policy: LMS-BP-5364, Revision B • NASA IRB for Human Factors Research • NASA Subproject Management	

Appendix Table A-9: Organization Model – Researchers

Actor: Researchers	
Priority: Primary	
Location: Remote	**Workstation:** N/A
Core Functions:	**Functional Tasks:**
• Gather data on roles, facilities, and airspace environment from flight and simulation data collection activities	• Observes flight and simulated operations • Administers human factors related questionnaires to human subject participants meeting specific goals • Conducts one-on-one and group interviews with human subject participants and individual Actors as needed and after operations are completed.
• Observe operations within ROAM	• Position of non-interference during operations
• Listens to communications of Actors in the Field and the Operations Center	• Monitors communications of Actors in the Field and the Operations Center
Guiding Regulations:	
• LaRC D318 Study/Experiment Review Policy: LMS-BP-5364, Revision B • NASA IRB for Human Factors Research • NASA Subproject Management	

Appendix Table A-10: Organization Model – ATOL Operations

Actor: ATOL Operations	
Priority: Primary	
Location: Remote	**Workstation:** N/A
Core Functions:	**Functional Tasks:**
• Supports flight operations within ROAM by supporting equipment startup and shutdown, troubleshooting, data collection from operations, and management of Video Wall(s).	• Conducts startup/ shutdown of Operations Center equipment, including comms and network checkout • Provides troubleshooting of Operations Center equipment during operations • Executes and provides storage/archival of collected data from Operations Center machines during flight operations and simulated operations • Manages of Video Wall for shared situational awareness among users of Operations Center
• Communicates with all users within ROAM	• Communicates with all users within ROAM
Guiding Regulations:	
• LaRC D318 Study/Experiment Review Policy: LMS-BP-5364, Revision B	

Appendix Table A-11: Organization Model – Visitors / Non-Participants

Actor: Visitors / Non-Participants (VNP)	
Priority: N/A	
Location: Remote	**Workstation:** N/A
Core Functions:	**Functional Tasks:**
• Observe operations within ROAM	• Position of non-interference
• Listens to communications of Actors in the Field and the Operations Center	• Monitors communications of Actors in the Field and the Operations Center
Guiding Regulations:	
• LaRC D318 Study/Experiment Review Policy: LMS-BP-5364, Revision B • NASA IRB for Human Factors Research	