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UAS Live, Virtual, & Constructive (LVC) Strategy: An Approach for Uncrewed Aircraft System (UAS) Standards Development and System Validation

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1. Executive Summary

This document presents a candidate architecture for employing Live, Virtual, and Constructive (LVC) techniques in support of the NASA Pathfinding for Airspace with Autonomous Vehicles (PAAV) project and related efforts within the domain of the integration of Advanced Air Mobility (AAM) operational use cases into the National Air System (NAS). By linking live test assets with human-in-the-loop system surrogates (virtual) and fully synthetic (constructive) components, LVC allows for the creation of a blended-fidelity ecosystem – achieving high realism where needed to meet test objectives while simultaneously reducing cost, complexity, and risk. LVC is a fundamental aspect of live-testing complex airspace operations because it provides continuous safety assurance in theoretically high-risk operational scenarios, reduces the demand for valuable resources required for live testing activities, and maximizes the ratio of the value of test results to cost expenditures. This plan proposes a configurable, modular approach, employing standardized interfaces to enhance existing NASA testing capabilities to improve test organizer's ability to select the level of fidelity appropriate for key individual system components for their particular objectives.

The document begins by selecting the specific target use cases of focus for discussion, largely aligning to the addressing the key challenges described in the PAAV Concept Document that are most aligned to the benefits of LVC techniques. A common linguistic and conceptual framework for adapting LVC concepts to the context of the identified use cases is provided. This framework, along with a discussion of current capabilities, especially those currently part of NASA's existing LVC capabilities, and those of the "HollSafe" test ecosystem, are used to inform the design for an expanded LVC-enabled ecosystem, along with a proposed evolutionary path to realize the design.

This discussion is facilitated via a use-case by use-case level breakdown, where within the context of each identified use-case, desired research objectives are mapped to the specific LVC techniques that could be employed to provide the appropriate level of fidelity to most efficiently and safely achieve meaningful results. The proposed evolutionary pathway takes the form of a phased approach and is informed by an attempt to find efficient incrementations that make maximum use of existing capabilities, prioritize groupings of new capabilities that unlock the greatest amount of research value at each step for the level of required investment. Additionally, this timeline attempts to align with the externally driven need-dates of the identified use cases under test (e.g. standards, regulatory, and industry readiness that drives the need for the identified research use case).

Phases

- Phase 1: Enabling "core" use case testing, maximizing use of existing components with the addition of more robust distribution of position/track information and voice communications throughout the network. This phase unlocks significant additional testing capabilities with a minimal amount of additional investment.
- Phase 2: Additions required to enable testing to inform certification efforts for the automated regional cargo use case. Highlights include improved capabilities for test scenario coordination, C2 related components, airspace definition distribution, and weather components.

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- Phase 3: Enabling the first portion of “PAAV Next” objectives, expanding the supported use cases into AAM more broadly, facilitating introduction of an m:N coordinator concept, and components related to data comm, and initial vertiport integration concepts
- Phase 4: All remaining elements to allow full testing and research objectives of the PAAV next initiative

This document concludes with discussions of practical considerations for using and governing the system, as well as discussions of the unique risks to effective validation activities and how they may be mitigated.

2. Introduction

2.1. Background

As NASA conducts research relating to incorporating new Advanced Air Mobility operational concepts into the NAS, the techniques and lessons learned from the concept of "LVC" matured in the military training and simulation space provides a potential pathway to enhance NASA's testing capabilities to be more efficient, safe, and achieve a higher scale than by conventional methods alone.

The concept of "Live, Virtual, and Constructive" (LVC) is a taxonomy widely used within military and defense training to describe distributed simulation environments that integrate elements of different levels of simulation fidelity to create a single shared comprehensive synthetic environment. While many testing environments chose a single level of fidelity to the target environment (example "live" aircraft on a test range, or a fully simulated test conducted in simulators), the core concept of "LVC" testing is the intermingling of different elements along a spectrum of possible levels of fidelity. In this way, fully "live" systems can seamlessly interoperate alongside human in the loop simulators ("virtual") or fully scripted ("constructive") elements.

By doing so, the following benefits can be achieved:

- **Realism**: LVC can create realistic, complex scenarios that are difficult or impossible to replicate in a purely live environment.
- **Cost-Effectiveness**: LVC reduces the need for full-scale live exercises, which can be expensive and logistically challenging.
- **Scalability**: LVC allows for large-scale exercises involving many participants without the need for everyone to be physically present in the same location.
- **Flexibility**: Test directors can easily modify scenarios, repeat exercises, and introduce new variables on the fly.

Within the military context, the applications of LVC environments to a range of use cases have been explored. The primary motivation for the original LVC integration activities was cost savings anticipated from the reuse of existing simulation capabilities. While the original motivations may have proven naïve, LVC environments have shown their value in an array of applications, including:

- **Simulation-based Training**: LVC is extensively used for training military personnel in complex, multi-domain operations that involve air, land, sea, cyber, and space domains.
- **Event Rehearsal**: Particularly when integrated with command-and-control planning systems, LVC can provide mission rehearsal where specific operations are practiced before execution.
- **Experimentation and Research**: LVC environments can provide greater flexibility in testing new systems, technologies, and procedures while minimizing the risks associated with such testing.
- **Communications, Datalink and Sensor Subsystem Surrogates**: LVC can be used to replace or instrument subsystems, or entire function sets to assess the value of having (or improving) such a system.
- **Synthetic Injected to Live (SITL)**: By scrupulously adhering to interface standards, LVC can interpose novel system functionality, providing a simulation-based proxy for a proposed new system of function.

The integration of LVC is largely accepted as a critical component in modern systems engineering, enabling analysis and testing of systems concepts and engineering design a wide

range of scenarios in a controlled and adaptable environment. NASA itself has a history of LVC enabled research and brings significant existing LVC capabilities that serve as the starting point to an approach to conduct AAM enabling research and validation activities.

An expanded definition of “LVC” can be found in section 3.1.1 of this document.

2.2. Objective

This document proposes a phased approach to establish an LVC-enabled testing and validation ecosystem to facilitate the advancement of Advanced Air Mobility (AAM) and address the challenges of integrating autonomous vehicles in the National Airspace System (NAS).

This plan, here called the “LVC strategy,” is informed firstly by the objectives of the NASA PAAV program (focused around the use case of enabling automated regional cargo operations) as laid out in the PAAV Concept Document and subsequently expanded into adjacent areas of research to inform future efforts relating to the integration of other related AAM platforms into the NAS.

Structurally, the strategy consists of:

1. A selection of target “use cases” to be used in clarifying the scope of the LVC strategy. These use cases are informed by the PAAV Concept Document, focusing on key “challenges” encountered in enabling automated regional cargo, and evaluation of identified “technologies” that address those challenges. These challenges and key technologies are adapted to adjacent AAM use cases for the purposes of expanding the applicability of this strategy. This objective is the primary topic of the remainder of Section 2 (this section).
2. A conceptual framework for LVC, as those concepts apply within the context of the identified AAM use cases. This framework consists of definitions and techniques adapted to the identified “challenges” of the use cases of interest. This objective constitutes Section 3 of this document.
3. A discussion of the current capabilities available to NASA as the agency seeks to enable elements of the LVC framework. The primary portion of these consisting of the existing MACS/ADRS enabled LVC environment hosted at NASA Ames campus, with connections to various other NASA Centers. This content is the focus of Section 4.
4. A proposed phased approach to apply these techniques and supplement NASA capabilities to enable the identified use cases. This approach attempts to maximize the use of existing NASA and industry capabilities. It attempts to efficiently group the additional capabilities into phases in a way that unlocks the greatest amount of new functionality with the smallest investment, while also aligning the needed timing of key industry milestones. This objective is the primary topic for Section 5 of this document.
5. Isolated use-case by use-case vignettes that serve as starting points for how the LVC enabled ecosystem could be leveraged to address each identified use cases. Introductory material related to these vignettes is provided in section 6, with vignettes themselves making up Section 7 of this document.

6. Discussions relating to the administration, use, and evaluation of the success of such an approach. These elements can be found in sections 8 and 9 of this document.
7. Discussions of risks that may be encountered as these techniques are applied and as research is conducted, along with possible mitigations to those risks. This is the focus of section 10.

These elements are intended to provide common vocabulary and a reference framework that can be used to help facilitate discussions and planning of future efforts.

For the purposes of grounding the discussions around application and governance of these LVC techniques, these technical enhancements to existing capabilities are presented within the context of the “HollSafe” ecosystem, an ongoing effort aligned with the PAAV program and other NASA efforts that unites NASA LVC capabilities, primarily based out of the NASA Ames campus, with industry capabilities including representative AAM operations centers, platforms, and simulators, a Ground-Based Surveillance System (GBSS) network, and a reference Provider of Services for UAM (PSU) implementation, along with other support capabilities.

2.3. Use Case Selection

The basis for the discussions provided in this document is the selection of use cases for the proposed testing and validation environment to identify the types of research, testing, and validation activities that the proposed system is intended to facilitate. This scope prioritizes the following goals:

1. Align to NASA’s stated objectives relating to conducting research to enable AAM within the NAS
2. Utilize existing components and capabilities as the basis for the creation of the system, especially existing MACS based LVC infostructure.
3. Create a broad “ecosystem” that can mimic the scale and complexity needed to address the challenges of integrating AAM operational use cases in the NAS
4. Prioritize configurability and flexibility of the system design to enable a wide variety of research and testing activities
5. Maximize safety while containing costs

To start this process, we draw heavily from the approach taken by the NASA PAAV Concept document. This document focuses on enabling Automated Regional Air Cargo (for the rationale for this particular selection, see section 2 of the referenced document) within the NAS as an initial priority on the path to enabling “AAM” operational concepts more broadly. This document firstly identifies key “challenges” limiting the realization of Automated Regional Air Cargo operations, and then potential “solutions” that may address these challenges. Finally, the document attempts to find mappings between those solutions and the identified challenges.

2.3.1. TARGET AAM ENABLEMENT CHALLENGES

We have adopted (with light modification, re-prioritization, and additional interpretation) these challenges as the basis of understanding the specific types of problems we wish our LVC enabled system to solve. The identified “challenges” are:

1. **Communications Operations**: Adapting communication architectures to support remotely piloted aircraft (including the m:N remote operations concept), ensuring reliable, low-latency connections across multiple aircraft and control points.
2. **Separation and Flow Management**: Ensuring adequate separation between aircraft to maintain safety while optimizing airspace efficiency, particularly in congested environments.
3. **Flight Trajectory Planning**: Establishing efficient and safe flight paths that account for airspace restrictions, operational priorities, and environmental factors.
4. **Traffic Pattern Integration**: Addressing the complexities of coordinating UAS operations with visual flight rules (VFR) traffic in landing and departure patterns, especially near busy airfields.
5. **Contingency Management**: Managing off-nominal situations, such as system malfunctions or communication failures, to minimize risks and ensure the safety of operations.
6. **Taxi, Takeoff, and Landing Operations**: Overcoming challenges in ground navigation and transitions between ground and airborne phases of flight, including interaction with manned aircraft and surface vehicles.
7. **m:N Operations**: Resolving practical challenges of many-to-one (m:N) operations, where a single operator manages multiple vehicles, including workload balancing and decision-making scalability.

These challenges span technical, operational, and organizational domains, reflecting the complexity of creating a testing ecosystem capable of evaluating potential solutions against the challenges.

2.3.2. LVC PRIORITIZED FAMILIES FOR "SOLUTIONS" UNDER TEST

As NASA, along with industry partners, attempts to evaluate solutions addressing these challenges, a testing environment of suitable fidelity to the intended operational environment is required. For the purposes of narrowing in on the scope for this LVC strategy, first an awareness of what these potential solutions will be and what environments such solutions would require for adequate testing is required. Once these are understood, appropriate testing techniques and environments can be selected to achieve these ends. In some cases, conventional testing techniques may prove sufficient. However, many of the identified challenges and accompanying solutions require testing solutions emulating broad NAS level environments, with differing levels of fidelity required along the path of maturation of the solution. This type of broad testing environment is inherently complex, but many aspects of the environment are common across the testing needs of the different solutions. These types of solutions are prime candidates for a scalable LVC enabled testing environment.

With this in mind, we have selected the following target “solutions” for evaluation via this proposed LVC architecture. This list is based on the list provided in the PAAV concept described above, with selections and prioritization for those systems most aligned to the benefits of an LVC enabled testing environment.

The selected “families” of solutions, along with potential examples within each family are outlined below:

1) Reliable C2 solutions and network architecture
    a) Examples: command non-payload control (CNPC), dynamic frequency allocation, deterministic C2 network planning
2) Scalable voice communications architecture
    a) Examples: ED-137 compliant VoIP networks aligned to IPS principles, voice relay for remotely piloted aircraft
3) Data link
    a) Example: CPDLC with accompanying procedures for automated taxi, takeoff, traffic pattern integration, and landing
4) ATC Procedures
    a) Examples: Traffic pattern integration, traffic load-level control, procedures for lost communications
5) DAA & Automated hazard avoidance
    a) Examples: Do-365/DO-381 compliant Ground Based Detect and Avoid capabilities, ACAS-X variant tactical conflict mitigation capabilities
6) Trajectory management & Flight route optimization
7) m:N Operations and remote pilot control paradigm

2.3.3. USE CASES

2.3.3.1. Standards Validation

While the discrete testing activities enabled by this system may take many forms, a significant portion of envisioned efforts take the shape of conducting the initial work to inform the creation of AAM/UAS operational standards, as well as validating systems against those standards.

This framework is designed to simulate realistic and scalable airspace conditions, ensuring that standards governing AAM/UAS operations are practical, reliable, and compliant with regulatory requirements.

The strategy includes validating key standards related to command-and-control (C2) data links, detect-and-avoid (DAA) systems, ground-based surveillance, and emergency protocols. It extends to assessing interoperability between UAS/AAM systems and external airspace management infrastructures, and addressing environmental and operational challenges such as signal degradation, high traffic densities, and emergency scenarios.

Table 1 Selected Standards and Validation Use Cases

Standard	Title	Validation Objectives
RTCA DO-362	C2 Data Link MOPS	Validate C2 links under signal loss, latency, and interference. Evaluate recovery and resilience.
RTCA DO-365	DAA MOPS (Phase I & II)	Test detect-and-avoid capabilities in high-density and mixed-traffic environments.

Standard	Title	Validation Objectives
RTCA DO-366	Air-to-Air Radar (ATAR) Surveillance MOPS	Validate ATAR tracking accuracy in diverse airspace configurations.
RTCA DO-377	C2 Link Systems Supporting UAS Operations	Assess performance of C2 systems under varying operational and environmental conditions.
RTCA DO-381	Ground-Based Surveillance Systems MOPS	Validate ground-based radar and ADS-B tracking accuracy in diverse airspace configurations.
RTCA DO-386	Airborne Collision Avoidance System Xu MOPS	Evaluate collision avoidance algorithms in mixed manned and unmanned airspace.
RTCA DO-400	Lost Link Procedures for UAS	Test lost-link scenarios for compliance with automatic recovery and safe termination procedures.
ASTM F3623-23	Supplementary Data Service Provider (SDSP) Specification	Validate performance of SDSP systems in diverse system configurations.
ASTM F3673-23	Weather Information Provider (WIP) Specification	Validate weather sensor performance in diverse weather situations.

In addition to these standards, potential future standards relating to EO/IR for surveillance, MOPS for DAA for digital taxi, Autonomous taxi MOPS, cooperative surveillance MOPS, and C2CSP MOPS have been identified as potentially in scope.

2.3.3.2. Other Selected use cases

In addition to standards validation, selected use cases include:

- ATC Procedures for Automated Regional Cargo Research
- m:N Coordination for Regional Automated Cargo Research
- Spectrum Deconfliction/C2CSP CONOPS Development
- AAM Autonomous Passenger CONOPS Development
- Vertiport AMAN/DMAN CONOPS Development
- ATAR to GBSS Interoperability Concept Development
- GNSS – System Limitations for Automated Cargo
- Landing Systems with Approach Radar CONOPS development
- Data Comm/CPDLC

2.4. System Components

2.4.1. LVC SYSTEMS AND THEIR ROLES

The LVC Strategy for UAS Standards Development and Validation incorporates a range of systems, both internal and external to the LVC environment, to replicate operational conditions and validate emerging UAS standards. These systems span live, virtual, and constructive elements, offering a high-fidelity and scalable framework to assess standards across varying operational complexities, airspace densities, and environmental conditions. By integrating real-world systems, simulating critical subsystems, and hybridizing live and virtual data streams, the strategy provides robust testing, repeatability, and scalability.

The supporting systems are categorized based on their role in the validation process. Systems internal to the LVC environment are primarily simulated and constructive -- focused on replicating airspace configurations, CNS infrastructures, and UAS behaviors. Systems external to the LVC environment, such as existing NAS Infrastructures with which the LVC interoperates, are either integrated as live or hybridized systems or fully simulated to support specific validation objectives.

Table 2 Supporting Systems and Their Roles

System	Role in Validation	Integration Method
Airspace Models	Simulate dense, mixed-use airspace with UAS and manned aircraft.	Constructive/Simulated
Traffic Generators	Create scalable traffic densities to stress-test detect-and-avoid systems.	Simulated
CNS Infrastructure Simulations	Model communication, navigation, and surveillance (CNS) conditions, including latency and interference.	Simulated
Virtual ATC Systems	Emulate ATC interactions to validate operator responses and DAA compliance.	Simulated
Virtual UAS Systems	Simulate UAS flight behaviors, including C2, lost-link scenarios, and conflict avoidance.	Simulated
Weather and Environmental Models	Provide realistic environmental challenges, such as adverse weather and GPS denial.	Simulated

Ground-Based Surveillance Systems	Track UAS using radar, ADS-B, and other sensors to validate surveillance standards (e.g., DO-381).	Integrated (Live or Simulated)
GNSS Systems	Assess UAS navigation under nominal and degraded GPS conditions.	Simulated or Hybrid
C2 Networks	Validate resilience of live communication systems under variable operational conditions.	Hybrid (Live/Simulated Interfaces)
Airspace Management Systems	Test interoperability between UAS and manned operations in shared airspace.	Integrated (Live or Simulated)
Live UAS Platforms	Provide real-world performance data for validating lost-link and collision avoidance standards.	Integrated
ATC Systems (Human-in-the-Loop)	Support testing of operator interactions and system behaviors in realistic scenarios.	Integrated (Live with Simulated Traffic)
Weather Sensors and Data Feeds	Provide real-time or simulated weather inputs to test UAS resilience.	Integrated/Simulated

3. LVC Framework for AAM/UAS Enabling Research & Standards Validation

The Live, Virtual, and Constructive (LVC) framework is a structured approach for testing and validating potential solutions to identified key challenges to realizing AAM operational use cases. It integrates real-world systems, high-fidelity simulations, and synthetic scenarios into a cohesive environment to evaluate the performance, safety, and interoperability of UAS. By combining live systems for realism, virtual systems for controlled variability, and constructive systems for scalability, the framework verifies that standards are tested under realistic, scalable, and repeatable conditions. This approach enables key testing/research efforts and validation of standards governing command-and-control (C2), detect-and-avoid (DAA), surveillance, and emergency response procedures across diverse operational scenarios.

The framework consists of two components: a **linguistic and conceptual foundation**, and practical **applications** based on that foundation. The applications of the framework consist of three key elements: **infrastructure**, **systems integration**, and **validation methods**. These

components work together to create an environment that supports testing of UAS capabilities and standards under nominal and extreme operational conditions.

3.1. LVC Definitions and Key Concepts

3.1.1. "LVC" IN AN AAM/UAS ECOSYSTEM CONTEXT

The concept of "Live, Virtual, and Constructive" (LVC) is a taxonomy widely used within military and defense training to describe distributed simulation environments that integrate elements of different levels of simulation fidelity to create a single shared comprehensive synthetic environment. As we adapt these concepts to context of an AAM/UAS test ecosystem representing the NAS, we slightly modify the use of these terms to our particular context.

The Department of Defense Simulation Glossary[1] defines these constituent simulation fidelity categories as such:

1. Live Simulation: "Live simulation involves real people operating real systems. Military training events using real equipment are live simulations. They are considered simulations because they are not conducted against a live enemy."
2. Virtual Simulation: "A simulation involving real people operating simulated systems. Virtual simulations inject human-in-the-loop in a central role by exercising motor control skills (i.e., flying an airplane), decision skills (i.e., committing fire control resources to action), or communication skills (i.e., as members of a C4I team)."
3. Constructive Simulation: "A constructive simulation includes simulated people operating simulated systems. Real people stimulate (make inputs) to such simulations but are not involved in determining the outcomes. A constructive simulation is a computer program. For example, a military user may input data instructing a unit to move and to engage an enemy target. The constructive simulation determines the speed of movement, the effect of the engagement with the enemy and any battle damage that may occur."

The concept of LVC involves techniques that can be used to combine elements representing each of the constituent categories into a single distributed simulation environment in order to minimize costs/test complexity and maximize safety while still meeting all requires test or training objectives.

As NASA pursues research and testing objectives related to addressing the key challenges needed to enable regional automated cargo use cases, as well as AAM more broadly, this document proposes an adaptation of these concepts that can be applied to create a configurable reference ecosystem to complete a variety of related testing and validation activities. In applying LVC concepts to the automated regional cargo/AAM domains more broadly, this document defines the LVC constituent categories thusly:

1. **Live Simulation:** "Live simulation" involves real people operating real systems. That is, the actual systems or components that are intended to be used to execute the use case of concern. This includes physical AAM aircraft and their constituent sub-systems and

[1] https://www.acqnotes.com/Attachments/DoD%20M&S%20Glossary%201%20Oct%2011.pdf

the NAS infrastructure that supports that use case including ATC systems, radars, communications radios, network components, sensors, etc.
Note that not all systems necessarily require a human operator. Rather, this category represents the highest level of simulation fidelity and describes systems operating in ways that are very similar to the intended eventual realized use case. Elements of the "Live" category are often employed for the "system under test" or other areas of the system where a high level of fidelity is required in order to complete test objectives.

2. **Virtual Systems:** "Virtual simulation" involves real people operating simulated/surrogate systems. This includes the use of human-in-the-loop simulators as well as direct human use of surrogate systems. For example, real ATC controllers using a surrogate ATC control system.
   Systems in this category operate procedurally in very similar, but not identical ways to the eventual realized use case. This category represents the middle of the simulation fidelity continuum.
3. **Constructive Simulation:** This involves a digital or otherwise lower fidelity representation of a system within the LVC environment. While these entities may operate with some limited inputs from a human (such as receiving basic high-level tasking or configuration) during testing operations, they may also be fully scripted/deterministic.
   Constructive simulation elements can be used to achieve operational scale otherwise not cost-effectively obtainable with Live or Virtual elements, or to stand in for elements of the larger system that are peripheral for a particular test scenario. Examples in this category may include:
   a. A software-in-the-loop vehicle simulator operating on a pre-determined flight path
   b. Automated simplistic or otherwise pre-determined flight clearance issued by a script standing in for the ATC system
   c. Artificial weather data injected into the weather distribution system at a pre-determined time during a testing scenario

The exact demarcations between these categorizations are not always cleanly defined, but this ambiguity is acceptable for the purposes of this document. These categories help us conceptually create useful groupings of what is a nuanced continuum of simulation fidelity to the systems/components used in the end-state use case deployments. The ability to identify and employ the correct level of fidelity appropriate for each component and the ability to employ the LVC techniques required to allow the intermingling of these different levels of fidelity into a single distributed simulation environment that can efficiently and safely meet the objectives of a particular testing activity is the core foundation of this plan.

3.1.2. CONCEPT: SYNTHETIC ENVIRONMENT VS OBJECTIVE ARCHITECTURE

In this document, we refer to the "world" created by the merging of L, V, and C elements as the "**Synthetic Environment**," while the underlying elements and structure that enable the Synthetic Environment are collectively referred to as the "**Objective Architecture**." These linguistic distinctions help avoid confusion arising from terms such as "real" and "simulated" in a

blended environment consisting of differing levels of simulated fidelity and objective, tangible presence.

3.1.3. CONCEPT: GEOPROXY & OTHER METHODS OF OVERRIDING LIVE DATA

One important function of the LVC-enabled test environment is to present the system under test with problems or conditions that would otherwise be impractical or present unacceptable risk. For example, practical tests of a DAA system require that a non-cooperative aircraft (target) present a collision risk to the test vehicle. Presenting difficult scenarios for DAA has the potential of creating hazardous situations. These hazards can be avoided by replacing live aircraft, with simulation, or via LVC-augmented tracks. One example of this, used to mitigate the dangers of close-range flight, is known as geoproxy. In this model, as shown below, two aircraft can maneuver in close proximity (according to their shared data), without the hazards of physical proximity. In this example, the test aircraft and the target aircraft are separated by some fixed distance, corresponding to a safe “offset” between vehicles. Each vehicle receives a representation of the other, with that offset subtracted from the actual position of the other vehicle. This allows both vehicles to interact as if they are, for example, withing the DAA threshold range. This is just one example of how LVC can be used to present a more flexible and challenging test environment without a compromise to safety.

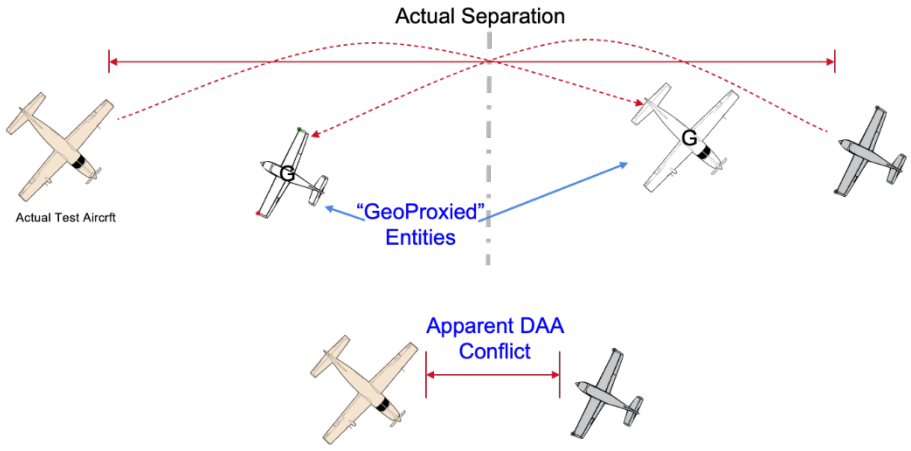


Figure: Geoproxy Concept

3.1.4. CONCEPT: CO-SIMULATION

“Co-simulation" is a technique by which complex systems can be decomposed into a series of smaller coordinated sub-simulations, rather than a single large simulation model. This allows the composite simulation environment to take maximum advantage of established simulation tools appropriate to particular aspects of the larger problem, and function with some degree of independence and modularity. Subsystems can be simulated in a distributed manner. Coupling methods are employed to provide synchronization and communication across subsystems at the level required for the composite environment to meet its objectives.

3.2. Applications of the Framework

3.2.1. INFRASTRUCTURE

The infrastructure forms the backbone of the LVC framework, enabling the interaction of live, virtual, and constructive systems in a unified environment. It provides computational resources, networking capabilities, and data management tools required to support complex simulations and real-time operations.

- Live infrastructure includes physical UAS platforms, communication networks, and ATC workstations, which provide real-world data and operational interactions. For example, live UAS and ground-based surveillance systems like radar and ADS-B are used to validate C2 reliability (DO-362) and ground-based tracking accuracy (DO-381).
- Virtual infrastructure includes high-fidelity simulations of airspace, environmental conditions, and aircraft behavior, allowing controlled and repeatable testing of edge-case scenarios such as degraded GPS performance or adverse weather conditions. These simulations are necessary for evaluating standards such as detect-and-avoid (DO-365) and SDSP (ASTM F3623-23).
- Constructive infrastructure includes synthetic environments and automated traffic generators, which simulate large-scale scenarios like congested urban airspace or dense multi-vehicle environments. These tools allow scalability and repeatability in testing, ensuring that standards like remote identification (DO-406) and airborne collision avoidance (DO-386) are validated for robustness under extreme conditions.

3.2.2. SYSTEMS INTEGRATION

Systems integration in LVC is the process of connecting live, virtual, and constructive components to form a cohesive and interoperable validation environment. This integration enables components that work seamlessly together to replicate real-world operations.

- Live systems, such as operational UAS, ground control stations, and live ATC workstations, interact directly with the environment to validate real-world interactions. For example, live systems are used to test lost-link recovery procedures (DO-400) and real-time collision avoidance systems (DO-386) in operationally relevant settings.
- Virtual systems simulate operational components like aircraft, traffic, and environmental conditions, providing flexibility to test scenarios that are difficult or unsafe to replicate in live operations. For instance, virtual simulations allow precise control over variables such as weather, traffic density, and GPS availability, ensuring that detect-and-avoid (DO-365) and SDSP (ASTM F3623-23) are tested across a range of conditions.
- Constructive systems generate synthetic environments and scenarios, such as high-density traffic or complex airspace configurations, to evaluate scalability and stress-resilience. These systems enable testing of cooperative and non-cooperative surveillance standards (DO-381) and conflict detection systems under extreme traffic conditions.

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3.2.3. VALIDATION METHODS

Validation methods define how the LVC framework is used to test UAS standards systematically and consistently. These methods provide meaningful, actionable results that contribute to the evaluation and refinement of standards.

Scenario-based testing replicates specific operational conditions to evaluate standards in realistic settings. For example, scenarios may include testing lost-link procedures (DO-400) in both urban and remote airspaces or evaluating C2 performance (DO-362) under conditions of network congestion and interference. Human-in-the-loop (HITL) testing involves real operators managing virtual or live systems to evaluate human interactions with UAS, such as ATC responses to detect-and-avoid advisories or operator decision-making during emergencies. Stress testing examines system performance under extreme conditions, such as dense airspace traffic, rapid conflict escalation, or degraded environmental factors. For example, stress tests are critical for ensuring that DAA systems (DO-365) can handle high levels of complexity and variability in airspace operations. Finally, iterative testing and refinement use feedback from initial tests to improve both systems and standards, ensuring that the framework evolves alongside advancements in UAS technology and operational requirements.

3.2.4. INTEGRATION OF LIVE, VIRTUAL, AND CONSTRUCTIVE FRAMEWORK COMPONENTS

The integration of live, virtual, and constructive systems within the LVC framework allow for comprehensive testing of UAS operations. Live systems provide realism by incorporating physical UAS, surveillance infrastructure, and ATC workstations. Virtual systems allow control over test conditions, enabling exploration of edge cases and environmental challenges without the risks incurred by live testing. Constructive systems add scalability and complexity, generating simulated environments to evaluate system performance in high-density or high-complexity scenarios.

4. NASA LVC Components

NASA has a diverse array of tools and technologies available to support the LVC framework, enabling testing and validation of UAS standards. The tools are designed to simulate realistic airspace scenarios, evaluate system performance, and facilitate the integration of live flights, virtual simulations, and constructive environments. These tools have capabilities ranging from high-fidelity air traffic simulations to human-in-the-loop evaluations and advanced data integration. By combining these resources with systems from FAA and industry, NASA Ames creates a federated testing environment that ensures interoperability, scalability, and comprehensive validation of UAS standards.

The table below provides an overview of the tools available at NASA Ames and their specific roles in the LVC framework.

Table 2 Representative Tools for LVC Testing at NASA

Tool	Description	Role in LVC Framework
MACS (Multi-Aircraft Control System)	High-fidelity simulation platform for evaluating air traffic operations and UAS performance.	Supports live, virtual, and constructive testing by modeling traffic flow, conflicts, and pilot actions.
ADRS (Aeronautical Datalink and Radar Simulator)	Information hub within the MACS simulation environment	Information and distribution hub for state and trajectory information from aircraft simulators across the system
HSID (Human Systems Integration Division)	Facility for human-in-the-loop simulations, focusing on operator interactions.	Evaluates workload, decision-making, and human-system performance in live and virtual tests.
HITL (Human-In-The-Loop) Simulators	Interactive simulation tools integrated into HSID and other environments.	Test human interaction with systems like ACAS-Xr or detect-and-avoid technologies.
HPC (High-Performance Computing)	Advanced computational resources for large-scale simulations.	Enables scalability testing and high-density airspace modeling for constructive tests.
VAMS (Virtual Airspace Modeling System)	Virtual airspace and weather modeling system.	Simulates environmental factors such as turbulence, wind, and airspace constraints.
Sensor Emulation Tools	Emulates ground-based radar, ADS-B, and satellite systems.	Provides synthetic tracking and surveillance data for virtual and constructive testing.

Tool	Description	Role in LVC Framework
LVC Simulation Integration Platform	Centralized framework for integrating live, virtual, and constructive components.	Ensures seamless interoperability and data synchronization across systems.
FAA ADS-B and Radar Systems	External real-time surveillance inputs from FAA infrastructure.	Integrates cooperative and non-cooperative traffic data into LVC scenarios.
UHF Communication Systems	Tools for testing UHF command-and-control (C2) links in collaboration with FAA.	Validates communication resilience, latency, and coverage.
Constructive Air Traffic Models	Synthetic scenarios generating high-density traffic patterns.	Stress-tests scalability and interoperability under diverse operational conditions.
Distributed Simulation Networks	Federated networks connecting NASA, FAA, and industry systems.	Ensures real-time data sharing and aligned testing across all contributors.

4.1. LVC Tool Federation and Interoperability

NASA interfaces its tools with external systems using a combination of defined protocols, secure gateways, and standardized data exchange formats to enable interoperability within the LVC framework. For example, the Distributed Simulation Gateway (DSG) facilitates connections between NASA's internal systems and external simulations, using High-Level Architecture (HLA) or Distributed Interactive Simulation (DIS) protocols to synchronize scenarios and ensure consistency across federated environments.

Data ingress and egress are managed through predefined formats such as XML, JSON, or binary telemetry streams, depending on the source and target systems. For example, live telemetry from FAA ADS-B systems is ingested into MACS simulations using a protocol adapter that translates raw radar and positional data into formats compatible with NASA's simulation models. Similarly, outbound data such as synthetic air traffic from NASA's Virtual Airspace Modeling System (VAMS) is packaged and shared with external partners through encrypted links, ensuring data integrity and confidentiality.

Options for federation include direct connection through NASA's simulation network for high-bandwidth scenarios or remote simulation bridging for geographically distributed partners, allowing flexibility in how external assets like the FAA Technical Center or industry partners'

tools are integrated. These configurations are adjusted based on factors such as the scale of the simulation, latency requirements, and the sensitivity of the data being exchanged, ensuring the integrity and reliability of all LVC activities.

4.2. LVC Interoperability Security Constraints

NASA's security policies for interfacing tools and systems within the LVC framework are governed by agency-wide controls to ensure data confidentiality, integrity, and availability, as well as compliance with interoperability requirements. All connections between internal tools, such as MACS, AOL, and HITL simulators, and external systems, including FAA assets and industry tools, are subject to NASA's IT Security Handbook (ITS-HBK-2810) and Federal Information Security Management Act (FISMA) requirements.

Data exchanges occur through secure gateways that enforce strict access controls. Each gateway is configured with multi-factor authentication (MFA), role-based access controls (RBAC), and encrypted communication protocols, typically using TLS 1.2 or higher. These gateways also perform real-time intrusion detection and logging to monitor for anomalies or unauthorized access attempts. NASA's internal networks employ segmentation to isolate simulation environments from other operational and administrative networks, reducing the risk of cross-system vulnerabilities.

Any external partner system interfacing with NASA tools must undergo a Security Assessment and Authorization (SA&A) process to evaluate compliance with NASA and federal cybersecurity policies. This may include vulnerability scans, penetration testing, and the verification of encryption standards.

Policy mandates require that all external systems exchanging data with NASA comply with NASA Procedural Requirements, which governs IT security, and which outline integration and testing protocols. For example, systems providing ADS-B or radar data are subject to pre-approved data exchange agreements that define acceptable use, data retention, and audit responsibilities. Additionally, any simulation federated with external partners must support NASA's requirements, and event traceability to maintain test fidelity and reproducibility.

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5. Proposed Phased Approach to Augment NASA's Simulation Capabilities

Here, we propose a phased approach to augment NASA's testing and validation capabilities within the context of the HollSafe Ecosystem.

Each phase builds on prior accomplishments, introducing incremental improvements and new architecture patterns to enhance testing fidelity, scalability, and interoperability. This phased approach enables systematic growth in simulation capabilities, allowing the framework to adapt to emerging standards and operational requirements.

To establish these phases, we must:

1. Review current capabilities
    a. This is substantially accomplished in the previous section, however additional non-NASA capabilities are discussed here
2. Roughly sketch the grand vision for an LVC enable ecosystem
3. Seek convenient groupings of capabilities that provide efficient incremental progress towards the final system from the current system

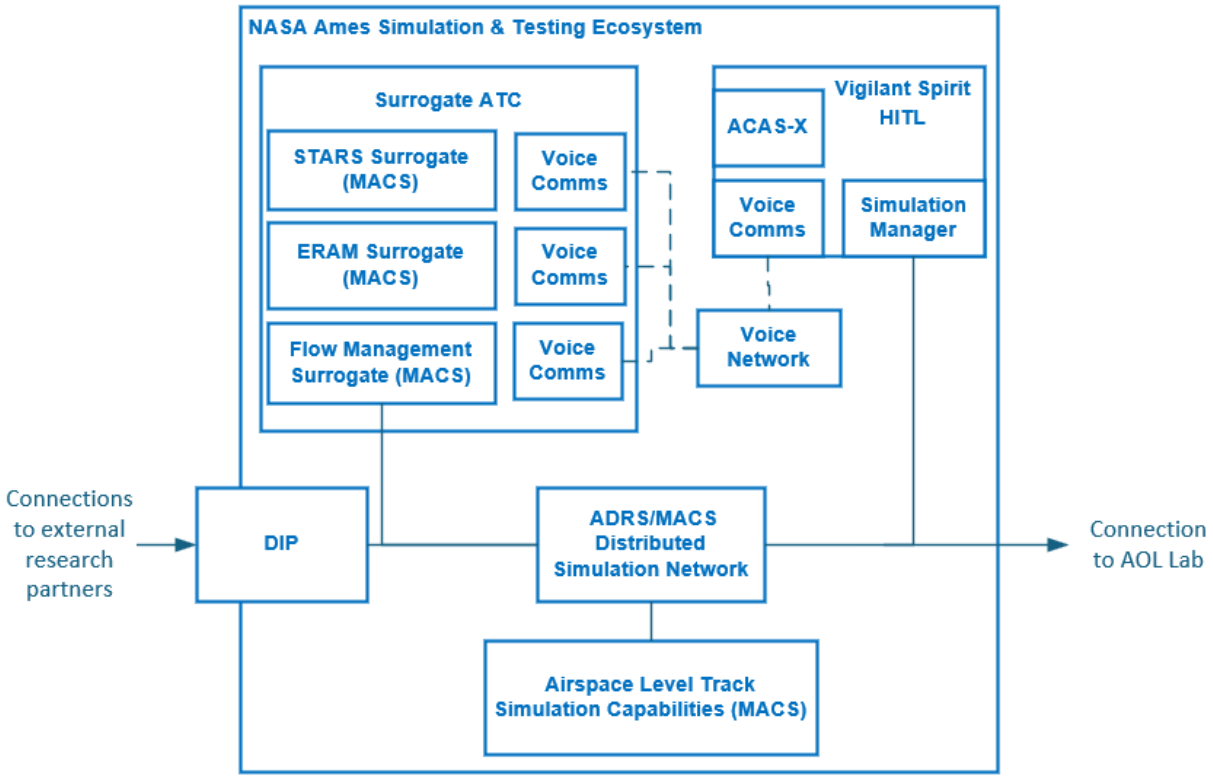
Once we have done this, we can provide detailed use-case by use-case vignettes into the proposed system (contained in Section 7 of this document).

5.1. Review of Current HollSafe Environment

The HollSafe AAM & UAS Testing & Validation Ecosystem is an ongoing effort to leverage NASA and industry simulation and validation capabilities to provide a sandbox environment suitable for evaluating various challenges relating to integrating AAM operational use cases into the NAS.

For the purposes of this discussion, the HollSafe ecosystem can be thought of as logically composed of 3 major groupings of components. Here, we describe each in isolation before providing a merged system overview.

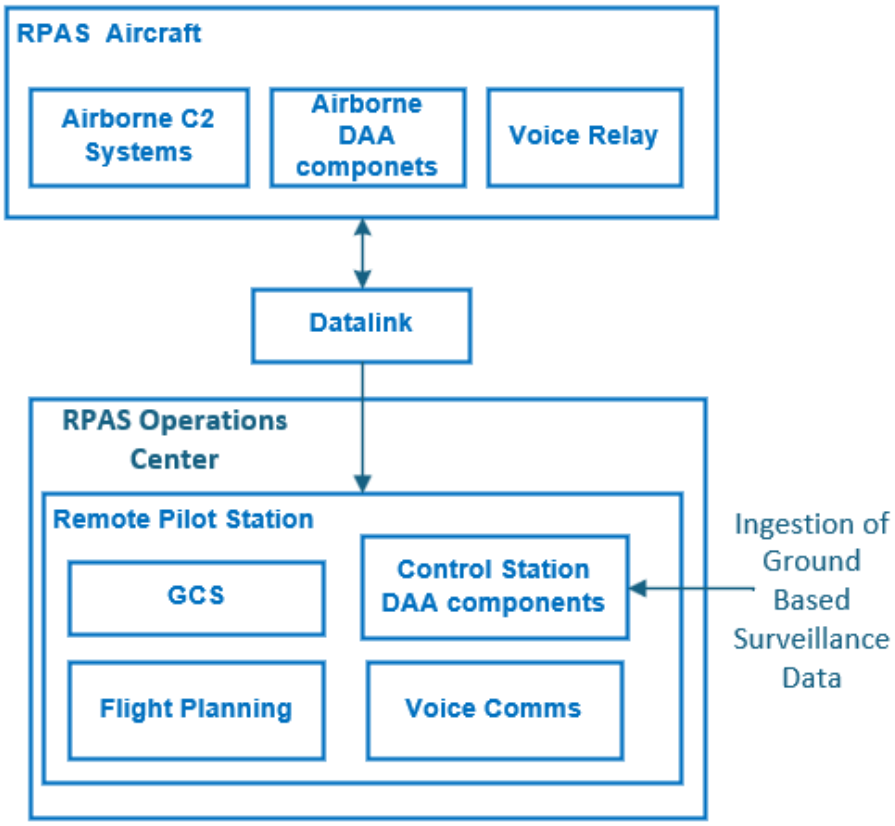
5.1.1. NASA COMPONENTS



Simplified view of NASA Ames AAM Simulation & Testing Ecosystem

The NASA hosted components of the HollSafe ecosystem are a subset of NASA's simulation capabilities relevant to the identified use cases including airspace level distributed simulation capabilities provided by MACS/ADRS, human-in-the-loop "virtual" simulation components representative of AAM vehicles and other platforms, surrogate ATC functionality (tower, TRACON, and enroute), a local voice network and other related support functions. More details on these capabilities can be found in the previous section.

5.1.2. PARTNER AAM VEHICLES

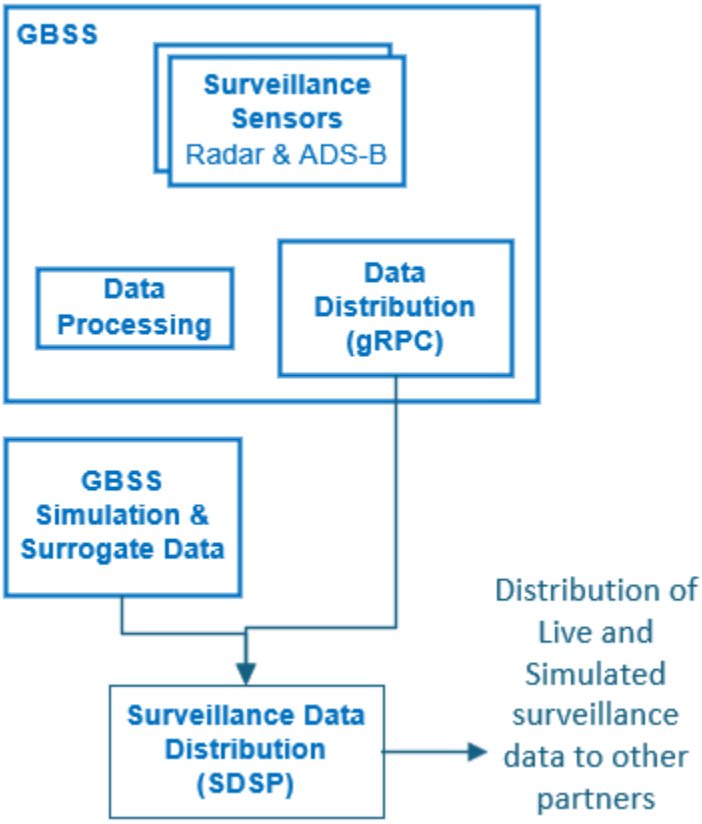


Simplified View of Reference External AAM Vehicle Operator Environment

Within PAAV and other related efforts, NASA has engaged with industry partners focused on brining various AAM operational use cases to market. The above diagram provides a generic example of such a system. Several sub-components most relevant to this discussion are highlighted. In this system, one or more RPAS aircraft are controlled remotely via a datalink connection to an “operations center.” This operations center contains one or more remote pilot stations, where pilots use a Ground Control Station to operate their aircraft within the NAS. In this particular example, voice comms connectivity is provided via a “voice relay” concept, in which the aircraft serves as a relay for voice connectivity between the remote pilot and other airspace users (aircraft and ATC).

In addition to live aircraft, it is common for platform partners of this type to have some level of existing Human-In-The-Loop (HITL) simulation, surrogate aircraft, and fully constructive simulation capability.

5.1.3. SURVEILLANCE INFRASTRUCTURE

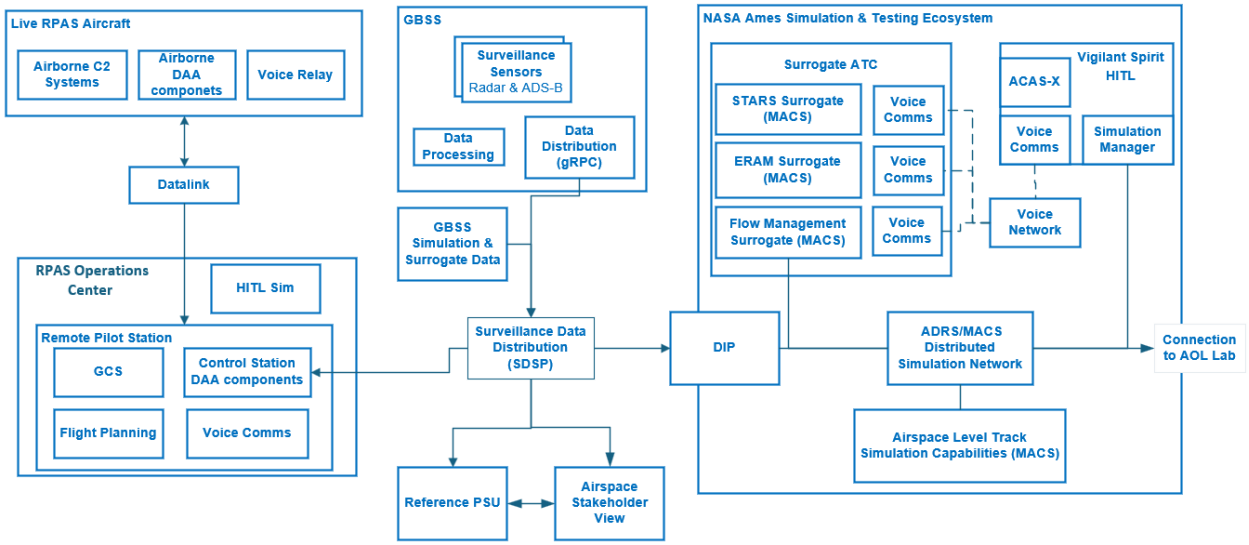


HollSafe Ground-Based Surveillance System Components

The current HollSafe system includes a representative Ground Based Surveillance System (GBSS) aligned to the RTCA MOPS for GBSS systems. The “live” demonstration system consists of a co-located radar and ADS-B receiver. These data are processed and distributed via a gRPC based “Supplemental Data Service Provider” (SDSP) mechanism. In addition to the “live” sensor system, constructive simulated and historical playback capabilities allow additional capabilities to supplement the capabilities of the live sensors for testing purposes.

Note that a reference PSU, data lake, and accompanying Airspace Stakeholder Situational Awareness view components (not pictured) are co-located with the GBSS capability. These capabilities supplement existing research test cases.

5.1.4. HOLLSAFE SYSTEM LEVEL VIEW



High level view of the HollSafe Environment

Together, these components represent a substantial baseline for research and validation activities. In this current iteration, initial lightweight and unidirectional aircraft position information is distributed via the Surveillance Data Distribution SDSP to what are otherwise not significantly integrated partner ecosystems.

5.1.5. KEY CHALLENGES OF THE EXISTING SYSTEM

- Limited synchronization of aircraft traffic and state data across the system
- Voice system fidelity to operational system and ability to access outside of NASA lab environment
- Test activity coordination mechanisms
- Data collection and management
- Representation identified technology solutions of interest for addressing identified AAM integration challenge areas
- Fidelity to the NAS

5.2. Vision for a Future LVC Enabled Testing Ecosystem

The vision for the future the LVC system expands on existing capabilities to address key challenge areas. The system attempts to provide a comprehensive NAS-level simulation environment, with a high degree of configurability to efficiently realize the appropriate level of fidelity

Major components:

Co-Simulation Infrastructure Elements

- Aircraft Simulations

    - Live – Representative AAM platforms, surrogate platforms, and additional conventional aircraft as needed
    - Virtual – A variety of human-in-the-loop simulators
    - Constructive – Airspace level traffic simulation of varying types
- ATM System
    - Live
        - Live “real” ATC is not part of the LVC system directly, but are involved to the extent required to facilitate testing activities
    - Virtual
        - “ATC” surrogate systems representing each ATC domain (Tower, terminal, enroute, etc.)
    - Constructive
        - Simple ATC interaction mechanisms using standard interfaces available in cases where the ATC function is not of core focus for the particular test
            - Example: Simple flight plan approval/disapproval, automation of airspace constraints, etc.
- Voice Infrastructure
    - VoIP Infrastructure – Core infrastructure to allow
    - VHF & UHF Radio Network Simulation
    - Voice injection
- C2 and Datalink Infrastructure
    - Live C2 link systems: Air, ground, and dynamic frequency allocation function
    - Lab based radio in the loop simulation
- Surveillance Infrastructure
- Aircraft Operations Centers
- Airport and vertiport infrastructure
- Weather systems

System-Wide Data Distribution

- **Aircraft Traffic and State Distribution**
- **Voice Communications**
- **Test Event Distribution**
- Weather data distribution
- Aircraft intent - flight plans, and approvals
- Airspace definition and constraints

5.2.1. AIRCRAFT TRAFFIC AND STATE DISTRIBUTION

Aircraft traffic and state distribution form a core component of enabling the distributed simulation environment and harmonizing between LVC elements. While current capabilities already substantially employ these techniques internal to the NASA environment, primarily thorough the MACS/ADRS system, the envisioned expansion of this system extends these capabilities to more easily include external data producers and consumers. While the current system focuses on the ability to ingest surveillance data (or simulated surveillance data) into the NASA system, establishing ubiquitous distribution of all entities within the LVC synthetic environment is a crucial building block to expanding testing capabilities.

5.2.2. VOICE COMMUNICATIONS

Due to the continued heavy reliance on voice communications at the core of most airspace-level interactions, realistic voice communications constitute a key capability of systems intending to simulate the NAS at a broad level. While the current environment provides some limited voice capability available within NASA labs, there exists significant room to achieve fidelity to the eventual operational system as well as a need to extend the system to research partner facilities.

The foundation of this approach is centered on an ED-137 compliance VoIP backbone, made available across the LVC testing ecosystem. Remote Point-of-presence (R-POP) units are employed to bridge remote sites, such as partner operations centers, into the system. Voice consoles at operator locations, Controller Working Position (CWP) units at surrogate controller positions, and handheld units where needed allow direct communications as needed throughout the system. The VoIP core network is expanded via use of radio gateway units to bridge RF environments with the VoIP network.

Additionally, when characteristics specific to RF communications are needed, L, V, and C elements can be interconnected via lab-based radio-in-the-loop communications paths, with antennation configured via an RF propagation co-simulation.

[See LVC for Voice Comms Discussion Primer for additional dialogue]

5.2.3. TEST EVENT DISTRIBUTION

Current testing activities rely significantly on manual/human led coordination of test events, especially across co-simulation environments. As testing grows in complexity and as tighter coordination across environments is required, formalization of test event coordination can yield significant benefits.

At its simplest, this could involve systems to distribute signals to start/pause/stop reset events across the various co-simulations, signals to kick off key test events such as the takeoff of a particular aircraft, or introduction of a particular simulated failure event. In many LVC enabled distributed simulation contexts, this is accomplished via the use of the underlying simulation environment/coordination mechanism such as the “Simulation Management” family of capabilities within DIS. Similar mechanisms could be employed within this ecosystem, or more rudimentary API based mechanisms could be used.

5.2.4. WEATHER DISTRIBUTION

Many test scenarios are expected to include weather elements as the catalyst of certain operator or system behaviors. To coordinate these events, a weather distribution system is envisioned. This system can allow a common shared weather picture across the system. The test director can utilize this system to introduce simulated weather events (purely artificial or replayed and re-located real data), via standardized weather data interfaces, thus allowing the various Live, Virtual, and Constructive elements to receive the data.

5.2.5. A NOTE ON NEXT GENERATION DIGITAL ATC COMMUNICATIONS

This initial version of the LVC strategy focuses on integration of novel AAM use cases into an airspace management system that substantially operates "as is." While there is certainly much research interest in evaluating next generation digital communications with ATC including those associated with TBO, data comms more generally, and collaborative separation and flow management concepts such as "UTM," the current iteration of this strategy limits the inclusion of such elements in the LVC architecture for now. Thus, system functions such as flight planning, approval, separation functions provided by ATC, etc. are conducted in a way that reflects the airspace as it is today, with some limited interfaces for submission of IFR flight plans and some uses of data comms, but still primarily reliant on voice communications between aircraft pilots and ATC controllers.

5.3. Efficient Incrementations

Based on the stated goals for efficient incrementation, a consideration of current capabilities, the rough vision for an eventual future system, and a desire to align to external timing requirements relating to standards development, certification timelines, etc. the following phases are proposed:

- Phase 1: Enabling "core" use case testing, maximizing use of existing components with the addition of more robust distribution of position/track information and voice communications throughout the network. This phase unlocks significant additional testing capabilities with a minimal amount of additional investment.
- Phase 2: Additions required to enable testing to inform certification efforts for the automated regional cargo use case. Highlights include improved capabilities for test scenario coordination, C2 related components, airspace definition distribution, and weather components.
- Phase 3: Enabling the first portion of "PAAV Next" objectives, expanding the supported use cases into AAM more broadly, facilitating introduction of an m:N coordinator concept, and components related to data comm, and initial vertiport integration concepts
- Phase 4: All remaining elements to allow full testing and research objectives of the PAAV next initiative.

A detailed breakdown of each proposed phase follows.

5.3.1. PHASE 1: ENABLING CORE LVC USE CASE TESTING

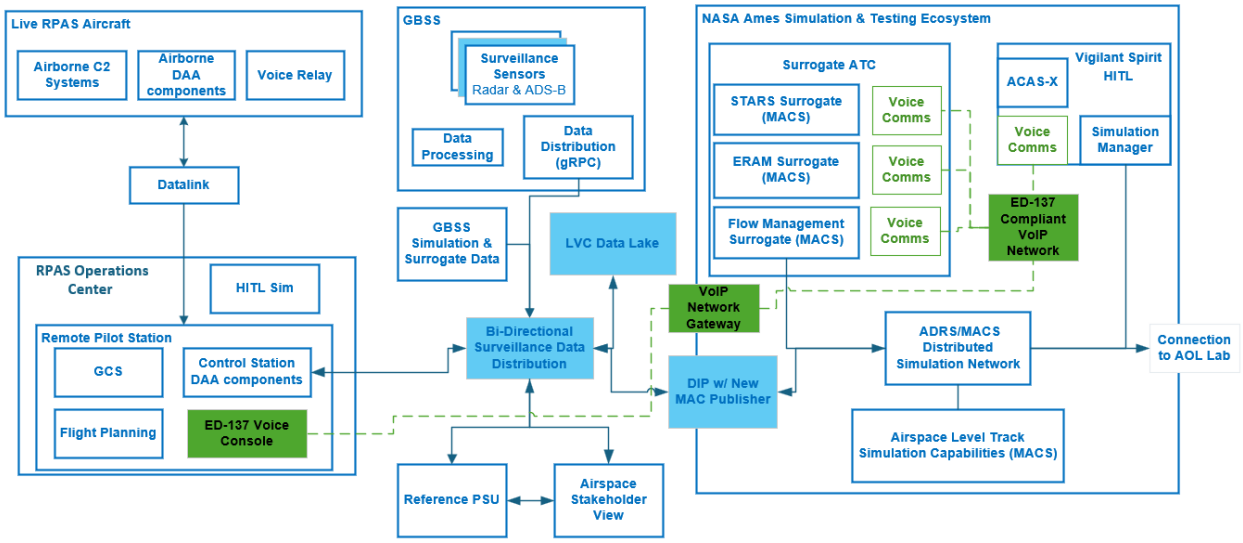
The initial deployment of the LVC framework in Phase 1 establishes a foundational capability for system testing and standards validation. The incrementations for this phase focus on "low hanging fruit" that unlock significant additional LVC testing functionality with a limited amount of additional investment. Primarily, this consists of extension of foundational data in the forms of aircraft position information, in the form of surveillance system track data, and voice data, across the system. These changes allow the core environment needed to form a single shared operational picture and establish basic communications across the full system, allowing the system as a whole to be used for a wide variety of foundational use cases.

New Elements

- **Track distribution network** - Bidirectional flow of track data (L, V, or C) throughout system. This is initially achieved via an expansion of the existing surveillance SDSP capability, in addition to the creation of MACS/ADRS adapters to bridge NASA internal systems to partner environments.
- **Core of Voice distribution network** – ED137 complaint VoIP network including voice gateways, console positions for surrogate ATC positions, operator consoles for platform GCS locations and HITL simulation locations
- Data Lake improvements – Collection of track and voice data
- Higher Fidelity ("Live") Terminal Area ATC System – N210 STARS lab
- Multi-Sensor GBSS - Additional Live Surveillance Systems and associated simulated surveillance capabilities

Use Cases Enabled

- ATC Procedures – Coordinate virtual (human in the loop surrogate) ATC with live and virtual vehicle systems
- GBSS Testing – DAA alerting based on live, virtual, or constructive elements from across the system (including DO-381 and DO-365 MOPS standard evaluation).
- Surveillance SDSP Standard
- ACAS-X MOPS



Phase 1 System Diagram with New Components Highlighted

5.3.2. PHASE 2: REALIZING AUTOMATED REGIONAL CARGO

The proposed phase 2 definition extends the phase 1 system with a focus on realizing the full validation requirements of the automated regional cargo use cases, which has been selected as the focus use case of the PAAV program. This primarily consists of the missing foundational LVC components (infrastructure and integration) that constitute the full automated regional

cargo use case. These being C2, weather systems, and test scenario event coordination and distribution.

New elements

- Networked C2 (Live) - C2 radios + C2CSP
- C2 Hardware in the loop simulation (Virtual)
- RCF CNPC attenuation from simulator – Connects to positions distribution service to allow realistic radio performance for any track source
- Scenario event coordinator & distribution – Allows signaling key system failure events such as loss of GNSS,
- WXR Distribution network – Inputs from live WXR sources
- WXR scenario generator – Allows simulated WXR data to be used in scenarios, distributed through the same source as live data
- Additional Live Surveillance Systems

Use Cases

- C2 lost link
- Spectrum deconfliction between multiple aircraft
- Emergency procedure validation: Simulation of different failure cases through scenario coordinator
- GBSS to ATAR to GBSS Handoffs
- WXR impacts on airspace system (vehicles, flight plans) - Including WIPs MOPS validation

5.3.3. PHASE 3: INITIAL PAAV NEXT OBJECTIVES FOR ENABLING AAM

Phase 3 constitutes the first portion of the envisioned “PAAV Next” process, or more generically, a representative extension of the initial capabilities into broader AAM/UAS use cases. This phase focused on the next set of capabilities that enable the most significant expansion of research capability. Key focusses include expansion of the NAS representation to include a flight plan submission mechanism as well as distribution of that data, as well as initial representations of broader AAM concepts including representative vertiport components, AAM corridor concepts, and vehicle platforms representing other operational use-cases.

New Capabilities

- Initial Autonomous Passenger Vehicle Representative System
- Vertiport domain: AMAN/DMAN
- m:N Coordinator Role
- Initial AAM Routes + Procedures
- Flight Plan distribution

Use Cases

- m:N control for automated regional cargo CONOPS development
- AAM Autonomous passenger CONOPS development

- Advanced collision avoidance MOPS development
- Cooperative surveillance MOPS development
- DAA for Uncrewed Air CONOPS development
- Autonomous taxi operations maturation
- Autonomous tower CONOPS development
- Landing system with approach radar conops development

5.3.4. PHASE 4: COMPLETION OF PAAV NEXT OBJECTIVES

This phase represents the inclusion of the more future looking AAM use cases, as well as the components needed to represent an even broader emulation of the NAS. Capabilities include those related to enabling autonomous tower operations, surrogate systems representing next generation ATC concepts/rules, and a data comm capability.

New Capabilities

- Autonomous tower operations
- Next gen ATC system surrogates – AAM ATC/Rules
- Multi-Modal C2
- Data Comm Distribution

Use Cases

- Standard maturation for
- Enhanced Collision Avoidance MOPS
- Cooperative surveillance MOPS
- DAA for Unmanned air CONOPS validation
- Autonomous Taxi
- Autonomous tower operations CONOPS development
- Landing system with approach radar CONOPS development

6. Standards and Corresponding LVC Validation Approaches

The LVC framework supports multiple validation approaches tailored to the specific requirements of the identified AAM/UAS standards of interest. These approaches—real-time operational validation, scenario-based testing, stress testing, and iterative refinement—combine live, virtual, and constructive systems to comprehensively assess UAS performance, safety, and interoperability. Each approach replicates operational conditions relevant to the standards, ensuring scalability, repeatability, and reliability. Below, the standards are cross-referenced with the validation approaches in a table, followed by detailed examples of how the approaches address specific standards.

Table 3 Cross-Referencing Standards and Validation Approaches

Standard	Real-Time Operational Validation	Scenario-Based Testing	Stress Testing	Iterative Refinement
RTCA DO-362	C2 link resilience under real-world conditions	Simulated signal loss and latency	Network congestion and interference	Feedback-based improvement of recovery
RTCA DO-365	Live DAA interaction with ATC and intruders	Simulated air traffic encounters	High-density airspace scenarios	Fine-tuning conflict resolution models
RTCA DO-366	Real world radar surveillance and tracking	Simulated terrain and interference	Large-scale UAS detection scenarios	Refining tracking accuracy algorithms
RTCA DO-377	Live communication with ground-based systems	Complex airspace conditions	Degraded communication environment	Enhancements to multi-path handling
RTCA DO-381	Real-world radar and ADS-B tracking	Simulated terrain and interference	Large-scale UAS detection scenarios	Refining tracking accuracy algorithms
RTCA DO-386	ACAS Xu tests in mixed airspace	Simulated near-collision events	High-speed conflicts	Refinement of resolution advisories
RTCA DO-400	Lost-link recovery in live tests	Simulated urban and remote recovery	Multi-UAS lost-link stress scenarios	Iterative protocol improvement

Standard	Real-Time Operational Validation	Scenario-Based Testing	Stress Testing	Iterative Refinement
RTCA DO-406	Live remote ID broadcasts	Simulated dense airspace operations	Overlapping ID signals	Enhancement of broadcast protocols
ASTM F3623-23	Real-world flight tests.	Simulated air traffic scenarios	Interference testing	Refining tracking accuracy algorithms
ASTM F3673-23	Real-world weather measurements.	Simulated weather data sets.	Adverse weather scenarios.	Expansion to higher altitudes.
RTCA DO-387	EO/IR system performance in live conditions	Simulated visibility and weather	Adverse lighting and terrain scenarios	Sensor algorithm improvements

6.1. Real-Time Operational Validation

Real-time operational validation involves live systems, such as UAS platforms, ATC workstations, and ground-based surveillance systems, to evaluate standards in actual operational settings.

Scenario-Based Testing

Scenario-based testing uses virtual and constructive systems to replicate specific operational conditions.

Stress Testing

Stress testing evaluates systems under extreme or adverse conditions.

Iterative Refinement

Iterative refinement uses insights from testing to improve systems and standards continuously.

7. Testing and Validation Use Case Vignettes

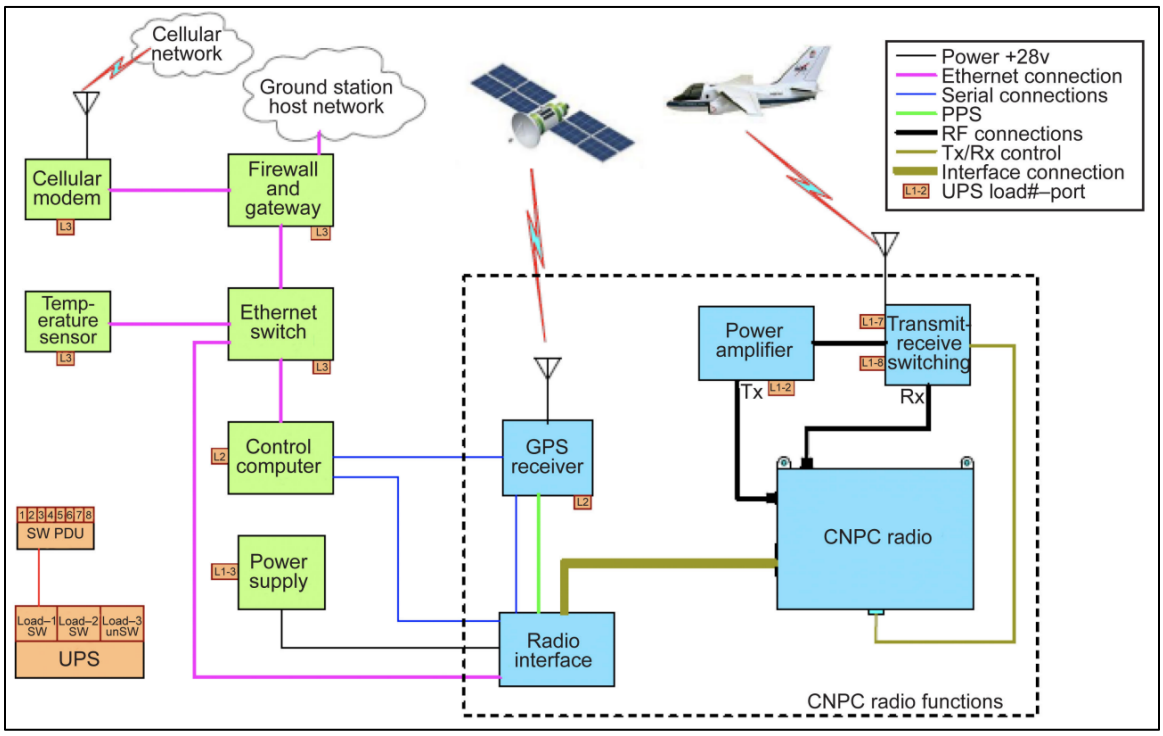
Validation of the selected AAM enabling use cases and UAS standards requires a comprehensive and structured approach to provide robustness, interoperability, and reliability in real-world operations. The Live, Virtual, and Constructive (LVC) framework offers an adaptable testing environment capable of addressing the diverse challenges posed by each standard. By combining live systems for realism, virtual simulations for controlled variability, and constructive scenarios for scalability, the LVC framework supports a wide range of validation objectives. The prioritization of tests is based on operational criticality, regulatory requirements, and the complexity of the scenarios being addressed.

The sections below provide a detailed description of how the LVC framework will be applied for each selected use or standard validation activity, including the context of its operational requirements, the LVC systems and capabilities involved, and the tests, scenarios, and outcomes associated with its validation.

7.1. RTCA DO-362: Command and Control (C2) Data Link MOPS

Context and Objectives

RTCA DO-362 defines the minimum operational standards for C2 data links, which are critical for maintaining reliable communication between UAS and ground control stations. The objective is for C2 links that consistently perform under a variety of conditions, including urban and rural airspaces, degraded connectivity, and interference. Prioritization focuses on scenarios involving multi-path effects, latency, and network congestion, as these are key challenges in real-world operations.



Control and Non-Payload Communications (CNPC) Block Diagram[2]

LVC Systems and Capabilities

- **Live Systems:** Live UAS flights near Moffett Field interacting with physical communication networks for real-world performance data.
- **Virtual Systems:** High-fidelity simulations of urban and rural airspace with emulated communication delays and interference.
- **Constructive Systems:** Large-scale synthetic traffic scenarios to stress-test network congestion and simultaneous link usage.

Types of Tests

- Evaluate C2 link performance under multi-path interference and latency.
- Assess link recovery times after temporary disruptions.

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[2] Frantz, B., Cauley, M., Bretmersky, S., Iannicca, D., Chevalier, C., Stewart, D., Dimond, R., Hanau, E., Shalkhauser, K., & Ishac, J. (2023). *Control and Non-Payload Communications Generation 7 Radio Flight Test Report* (NASA/TM-20205011515/REV1). National Aeronautics and Space Administration Glenn Research Center. Retrieved from https://ntrs.nasa.gov/api/citations/20220014741/downloads/TM-20205011515-REV1_03.2023.pdf

- Measure packet integrity and data throughput under network congestion.

Scenarios Conducted

- Urban canyon communication with multi-path signal reflection.
- Remote low-connectivity airspace with SATCOM reliance.
- High-density airspace with multiple UAS transmitting simultaneously.

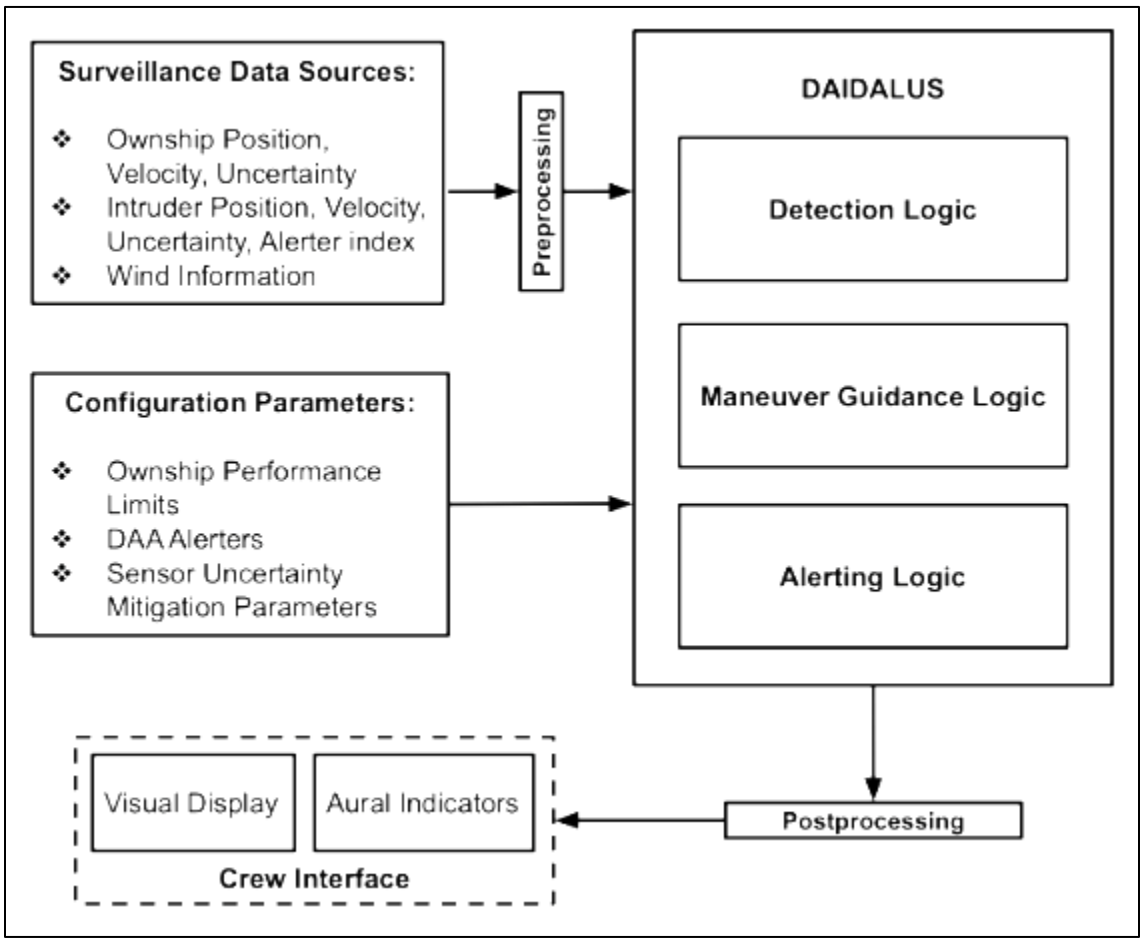
Value

These tests verify that C2 links meet the minimum performance standards necessary for BVLOS and complex airspace operations, reducing risks of communication loss.

7.2. RTCA DO-365: Detect and Avoid (DAA) MOPS

Context and Objectives

DAA systems are essential for UAS safety, enabling them to detect and avoid conflicts with other airspace users. The standards prioritize accurate trajectory prediction, conflict resolution advisories, and reliable performance under varying speeds and altitudes. The objective is to validate these capabilities in both cooperative and non-cooperative traffic environments.



High-level architecture of the DAIDALUS library[3]

LVC Systems and Capabilities

- **Live Systems:** UAS flights interacting with intruder aircraft in controlled airspace at Moffett Field.
- **Virtual Systems:** Simulated airspace environments with dynamic intruder behaviors and cooperative traffic.
- **Constructive Systems:** High-density airspace models generating variable intruder trajectories.

[3] Daidalus Team. (n.d.). *DAIDALUS (Detect and AvoID Alerting Logic for Unmanned Systems)*. Retrieved December 13, 2024, from https://nasa.github.io/daidalus/

Types of Tests

- Detection range and trajectory prediction accuracy.
- Resolution advisory timing and effectiveness.
- Performance under rapid intruder speed changes.

Scenarios Conducted

- Head-on conflicts in mixed-traffic environments.
- High-altitude intrusions involving high-speed aircraft.
- Urban navigation with erratic intruder behavior.

Value

DAA validation improves UAS safety, ensuring reliable conflict avoidance in controlled and uncontrolled airspace environments.

7.3. RTCA DO-366: Air-To-Air Radar (ATAR) MOPS

Context and Objectives

RTCA DO-366 defines the minimum operational standards for air-to-air radar traffic surveillance radars supporting DAA operations. The systems described by this standard reside on UAS and consist of both the physical radar antenna(s), as well as the processing components required to generate and geolocate tracks (through ingestion of navigation and C2 data provided by the platform) as well as associated health and status information. The objective of this use case is to validate candidate radar systems against performance standards laid out by the DO-366 MOPS to ensure the specified radar system is capable of establishing tracks for non-cooperative traffic with suitable range and accuracy to inform the broader DAA objective of remaining “well clear” of other aircraft.

LVC Systems and Capabilities

- **Live Systems:** Airborne radar systems interacting with cooperative and non-cooperative intruders.
- **Virtual Systems:** Simulated terrain and weather effects impacting sensor performance as well as Hardware in the Loop (HITL) testing of radar processing components.
- **Constructive Systems:** Synthetic high-density airspace for stress-testing tracking capabilities.

Types of Tests

- Measure system performance under a variety of environmental conditions.
- Evaluate tracking performance for different intruder categories and maneuvers.

- Assess resilience to environmental interference such as rain and fog.

Scenarios Conducted

- Multiple intruder scenarios in complex airspace.
- Remote airspace transitions between ground and satellite links.
- Dense multi-UAS airspace communication testing.

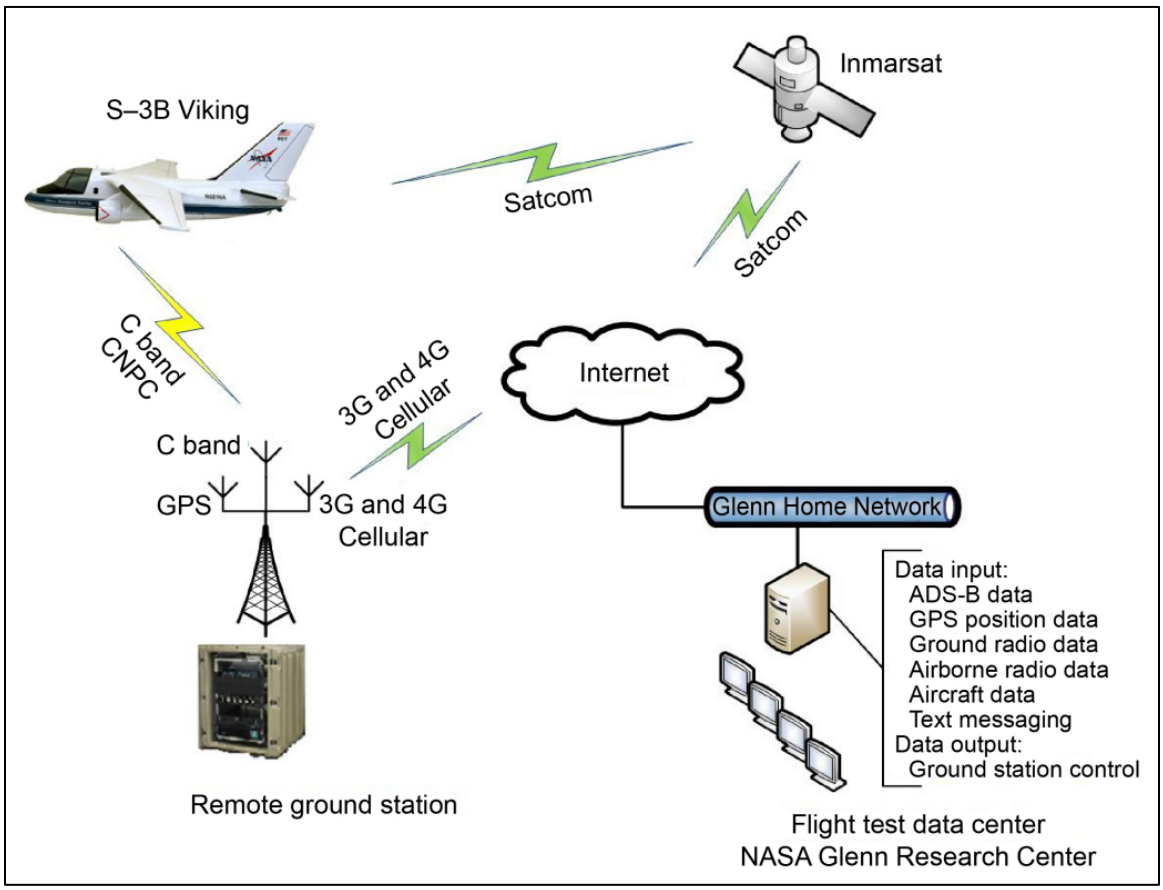
Value

Accurate and reliable air-to-air surveillance is necessary to support airborne collision avoidance.

7.4. RTCA DO-377: Command and Control (C2) Link Systems Supporting UAS Operations

Context and Objectives

This standard focuses on ensuring robust C2 link systems for UAS, including reliable communication recovery and performance in remote and urban airspaces. The objective is to validate the systems' ability to handle degraded signals, obstacles, and multi-UAS traffic.



Control and Non-Payload Communications (CNPC) Operational Concept[4]

LVC Systems and Capabilities

- **Live Systems:** Testing physical C2 equipment with live UAS under varying conditions.
- **Virtual Systems:** Simulations of degraded airspace conditions such as terrain-induced interference.
- **Constructive Systems:** Scenarios with simultaneous communication from multiple UAS.

[4] Frantz, B., Cauley, M., Bretmersky, S., Iannicca, D., Chevalier, C., Stewart, D., Dimond, R., Hanau, E., Shalkhauser, K., & Ishac, J. (2023). *Control and Non-Payload Communications Generation 7 Radio Flight Test Report* (NASA/TM-20205011515/REV1). National Aeronautics and Space Administration Glenn Research Center. Retrieved from https://ntrs.nasa.gov/api/citations/20220014741/downloads/TM-20205011515-REV1_03.2023.pdf

Types of Tests

- Evaluate signal stability during transitions between SATCOM and LOS links.
- Assess system recovery from link loss.
- Measure interference effects from physical and synthetic obstacles.

Scenarios Conducted

- Urban operations with overlapping signals.
- Remote airspace transitions between ground and satellite links.
- Dense multi-UAS airspace communication testing.

Value

Reliable C2 link performance reduces operational risks, ensuring safe UAS integration into shared airspace.

7.5. RTCA DO-381: MOPS for Ground-Based Surveillance Systems (GBSS)

Context and Objectives

The RTCA DO-381 standards provide Minimum Operational Performance Standards (MOPS) for ground-based surveillance systems (GBSS). GBSS standards are designed to validate the performance of ground-based surveillance technologies such as radar and ADS-B for safely integrating UAS into the airspace. This use case involves utilizing the LVC enabled testing environment for validating systems against the DO-381 MOPS which is especially useful for providing test coverage for scenarios with challenging terrain, overlapping sensor coverage, and environmental interference, as well as for reducing the overall cost of effectively validating systems.

LVC Systems and Capabilities

- **Live Systems:** Real ground-based surveillance sensors including radar and ADS-B installations near Moffett Field as well as associated processing and data delivery serving as the systems under test.
- **Virtual Systems:** Simulated terrain and weather effects impacting sensor performance.
- **Constructive Systems:** Synthetic high-density airspace for stress-testing tracking capabilities.

Types of Tests

- Measure detection accuracy under various conditions.

- Evaluate tracking performance in overlapping sensor zones.
- Assess resilience to environmental interference such as rain and fog.

Scenarios Conducted

- Urban airspace with dense overlapping radar zones.
- Rural areas with terrain occlusion.
- Weather-induced interference testing.

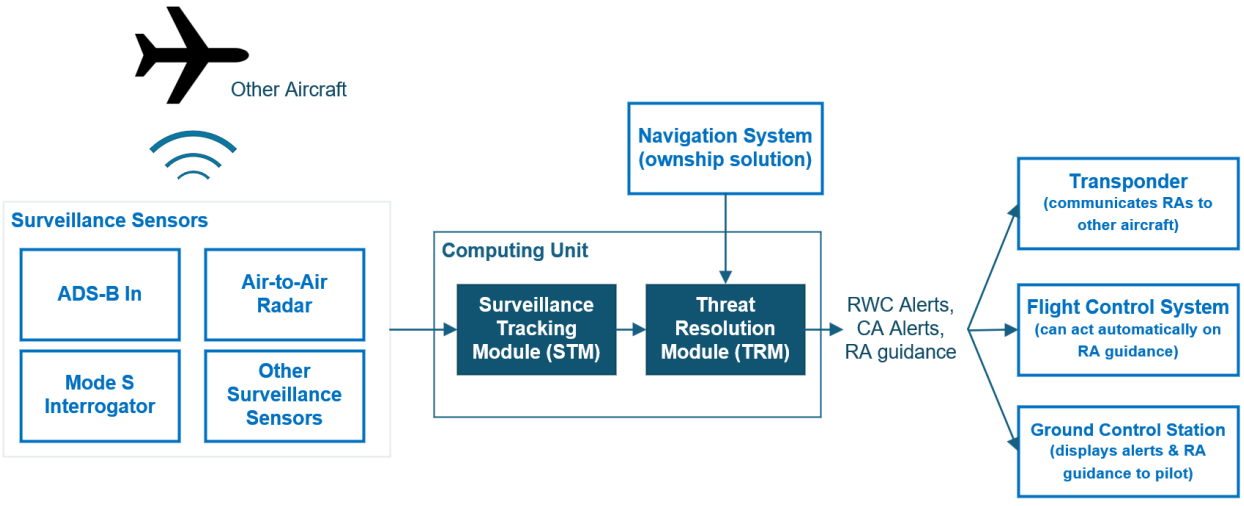
Value

Accurate ground-based surveillance allows reliable UAS tracking and situational awareness across diverse airspaces.

7.6. RTCA DO-386: Airborne Collision Avoidance System (ACAS Xu)

Context and Objectives

RTCA DO-386 establishes minimum operational performance standards (MOPS) for Airborne Collision Avoidance (ACAS) Xu systems, providing for collision avoidance (CA) and remain well clear (RWC) functionality between UAS and other airspace users. The objective of this use case is to validate conflict detection and resolution capabilities against the DO-386 MOPS using complex, high-speed, and multi-intruder scenarios.



ACAS-Xu Block Diagram

LVC Systems and Capabilities

- **Live Systems:** UAS flights interacting with manned and uncrewed intruders.

- **Virtual Systems:** Human-in-the-loop UAS and manned simulators to simulate high-speed conflicts and evasive maneuvers.
- **Constructive Systems:** Scripted simulators for multi-intruder scenarios in high-density airspace.

Types of Tests

- Assess conflict resolution advisories' timing and accuracy.
- Evaluate maneuver execution in response to advisories.
- Measure performance in mixed-traffic airspace.

Scenarios Conducted

- Head-on conflicts at cruise altitudes.
- Multi-intruder encounters in dense corridors.
- Rapid-evasion scenarios near controlled airspace.

Value

Improved collision avoidance capabilities provide operational safety in increasingly congested airspace.

7.7. RTCA DO-387: EO/IR Systems for Traffic Surveillance

Context and Objectives

Electro-Optical/Infrared (EO/IR) sensor systems enhance situational awareness by detecting and tracking other aircraft and obstacles, aiding in the detect and avoid process. The DO-387 standards lay out minimum operational performance standards (MOPS) for systems consisting of onboard EO&IR sensors with onboard processing of raw sensor data into track information in order to reduce the required bandwidth between the aircraft and ground systems. The objective of this use case is to validate candidate systems' ability to operate effectively under varying visibility and environmental conditions, ensuring reliable detection and tracking in accordance with the performance standards laid out in the DO-387 standard.

LVC Systems and Capabilities

- **Live Systems:** Real UAS flights using EO/IR systems in operational airspace near Moffett Field.
- **Virtual Systems:** Simulated environmental conditions such as heavy rain, fog, or low-light scenarios.
- **Constructive Systems:** Synthetic intruder and obstacle models with varying trajectories, sizes, and speeds.

Types of Tests

- Validate EO/IR detection ranges under different visibility levels.
- Assess tracking persistence in dynamic scenarios.
- Measure accuracy in object classification and recognition.

Scenarios Conducted

- Nighttime urban operations with artificial lighting.
- Adverse weather tests, such as fog or heavy rain.
- Rural surveillance with natural terrain and vegetation obstructions.

Value

EO/IR validates the systems, provides accurate and reliable detection capabilities, and improves safety and operational awareness in all environmental conditions.

7.8. RTCA DO-400: Lost Command and Control (C2) Link Procedures

Context and Objectives

Lost link standards provide safe UAS operations during communication failures. The objective of this use case is to validate protocols for automatic recovery, safe termination, and adherence to airspace management rules under lost-link conditions as well as to evaluate candidate systems against those procedures.

LVC Systems and Capabilities

- **Live Systems:** UAS flights simulating C2 link loss and recovery near Moffett Field.
- **Virtual Systems:** Simulated airspace with real-time failure triggers and interference models.
- **Constructive Systems:** Scenarios involving multiple simultaneous UAS with lost links.

Types of Tests

- Evaluate recovery protocol compliance and response times.
- Test automatic failover mechanisms, such as return-to-home or auto-landing.
- Validate UAS behavior under prolonged lost-link scenarios.

Scenarios Conducted

- Urban link loss with multiple nearby aircraft.
- Remote area failsafe landings.

- Multi-UAS lost-link recovery in high-density airspace.

Value

Tests UAS respond predictably and safely to lost-link events, maintaining compliance with airspace management rules.

7.9. RTCA DO-406: UHF Airborne Radio Systems MOPS

Context and Objectives

RTCA DO-406 establishes performance requirements for UHF airborne radio systems used to support UAS command-and-control (C2) link systems. These standards verify reliable communication between UAS and ground control stations, particularly in environments with significant signal interference or operational challenges. The objective is to validate the ability of UHF systems to maintain stable, low-latency, and interference-resistant communication in both controlled and uncontrolled airspaces. This capability is critical for enabling safe and effective beyond-visual-line-of-sight (BVLOS) operations.

LVC Systems and Capabilities

To validate UHF airborne radio systems under DO-406, the LVC framework will leverage live, virtual, and constructive components to evaluate performance across a range of operational scenarios.

- Live Systems: UAS equipped with UHF airborne radios will conduct flights near Moffett Field, interacting with ground control stations and other operational systems. Real-world tests will assess signal reliability under dynamic conditions, such as terrain obstructions and multi-path interference.
- Virtual Systems: Simulated environments will emulate variable airspace configurations, including urban canyons, remote operations, and high-density traffic areas. These tests will introduce controlled interference and environmental challenges to evaluate system resilience.
- Constructive Systems: Large-scale synthetic scenarios will simulate high-volume communication environments, stressing the capacity and interoperability of UHF systems.

Types of Tests

Testing will focus on the key performance attributes of UHF airborne radio systems:

- **Signal Stability**: Measure performance under varying operational conditions, including interference from other UHF users and physical obstructions.
- **Latency and Throughput**: Assess the system's ability to support low-latency data transfer required for real-time UAS command and control.
- **Interference Resilience**: Test the system's ability to maintain communication integrity in congested airspace and high-RF interference scenarios.

- **Range and Coverage**: Validate the effective range of UHF systems in rural, urban, and high-altitude operations.

Scenarios Conducted

To provide comprehensive validation of UHF airborne radio systems, a variety of scenarios will be conducted:

- **Urban Canyon Operations**: Simulate operations in dense urban environments with high levels of signal reflection and interference.
- **Rural BVLOS Operations**: Test long-range communication capabilities in remote airspace, where ground-based relays may be limited.
- **High-Density Airspace**: Evaluate system performance in congested airspace with multiple UAS and manned aircraft operating on similar frequencies.
- **Adverse Environmental Conditions**: Introduce heavy rain, wind, or electromagnetic interference to test system resilience under extreme conditions.

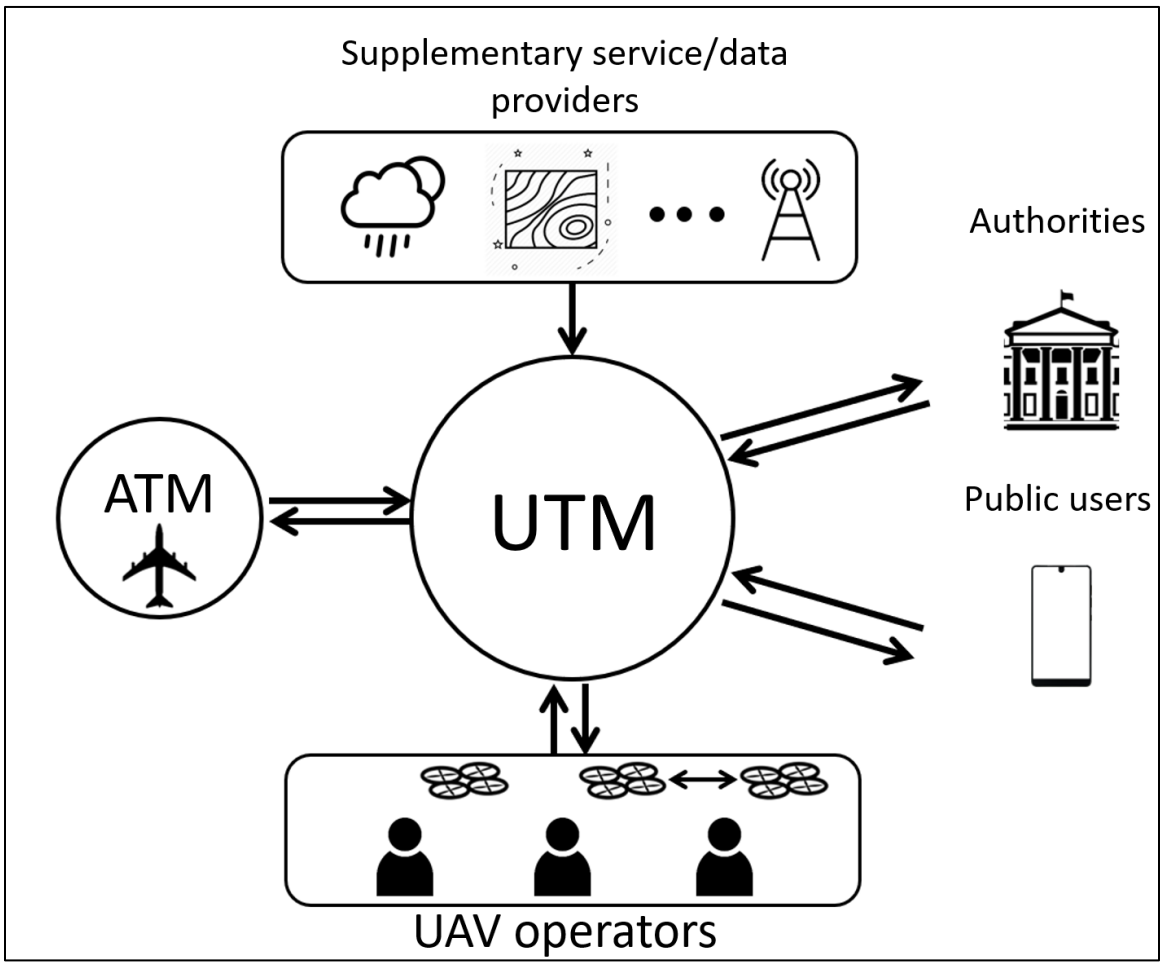
Value

The validation of UHF airborne radio systems under DO-406 is critical for ensuring the reliability and resilience of UAS command-and-control links. These systems enable safe BVLOS operations by maintaining stable and interference-resistant communication in a variety of environments. By rigorously testing UHF systems against performance benchmarks, the LVC framework provides for UAS communication capabilities that meet the demands of modern airspace operations, reducing risks and supporting regulatory approval for advanced UAS applications.

7.10.ASTM F3623-23: Surveillance Supplementary Data Service Providers (SDSP)

Context and Objectives

The ASTM F3626-23 standard defines performance requirements for Surveillance Supplementary Data Service Providers (SDSP), which supply critical surveillance data to support UAS operations. This standard provides the accuracy, reliability, and timeliness of supplementary surveillance data provided by SDSPs, such as ADS-B, TIS-B, or other cooperative and non-cooperative data feeds. The objective is to validate the integration of SDSP systems into UAS operations, particularly in environments with mixed traffic or complex airspace management needs.



Supplemental Data interface to UTM Systems[5]

LVC Systems and Capabilities

To validate SDSP performance under F3626-23, the LVC framework will integrate live, virtual, and constructive systems, enabling a comprehensive evaluation of surveillance data services.

- Live Systems: Live UAS flights and real-time surveillance data feeds will provide operational realism. Ground-based surveillance systems, such as radar and ADS-B, will integrate with SDSPs to supply real-world data.
- Virtual Systems: Simulated SDSP data services will replicate scenarios with high-density traffic, environmental interference, and varying signal conditions. This allows controlled testing of data accuracy, latency, and service reliability.
- Constructive Systems: Large-scale airspace simulations will generate synthetic surveillance data for cooperative and non-cooperative aircraft. These scenarios will test

[5] By Ego VI - Own work, CC BY 4.0, https://commons.wikimedia.org/w/index.php?curid=143017514

SDSP performance under extreme conditions, such as network congestion or data degradation.

Types of Tests

Validation activities for F3626-23 will focus on key performance metrics for SDSP systems:

- Accuracy: Test the precision of supplementary data, including aircraft position, velocity, and trajectory information.
- Latency: Evaluate data timeliness under varying network conditions, ensuring that SDSP services provide real-time or near-real-time updates.
- Reliability: Assess the resilience of SDSP systems to failures, data corruption, or loss of primary surveillance inputs.
- Interoperability: Validate integration with ground-based and airborne surveillance systems, ensuring seamless data exchange and compatibility.

Scenarios Conducted

To fully validate SDSP systems, a range of diverse scenarios will be conducted:

- High-Density Urban Airspace: Simulate environments with numerous cooperative and non-cooperative aircraft, testing SDSP data accuracy and reliability in congested areas.
- Sparse Rural Airspace: Evaluate SDSP effectiveness in low-surveillance areas where supplementary data may be critical for situational awareness.
- Environmental Interference: Test data accuracy and service continuity in conditions with heavy rain, terrain interference, or GPS denial.
- Network Congestion: Simulate high traffic volumes with multiple simultaneous requests for surveillance data, testing SDSP latency and reliability.

7.11. ASTM F3673-23: Weather Information Reports, Data Interfaces, and Weather Information Providers (WIPs)

Context and Objectives

ASTM F3673-23 defines the performance requirements for Weather Information Providers (WIPs), including the generation of weather information reports, data interfaces, and dissemination systems. This standard verifies that UAS operations have access to accurate, timely, and reliable weather data, which is critical for maintaining safety and operational efficiency in diverse environments. The objective of validation is to assess the ability of WIPs to meet these standards under varying operational conditions and to verify the seamless integration of weather information into UAS command-and-control systems.

LVC Systems and Capabilities

To validate compliance with ASTM F3673-23, the LVC framework integrates live, virtual, and constructive components to evaluate the performance of WIPs and their interfaces.

- **Live Systems**: Real-time integration of weather sensors, ground-based weather stations, and airborne weather collection systems with UAS flights operating near Moffett Field. This setup evaluates the accuracy and latency of live weather data transmission to UAS operators and ground control stations.
- **Virtual Systems**: Simulated weather models replicating diverse scenarios, including extreme weather conditions such as heavy rain, wind, turbulence, and icing. These virtual systems provide controlled conditions to assess data accuracy and system responsiveness.
- **Constructive Systems**: Large-scale airspace simulations incorporating synthetic weather patterns and their impact on UAS operations. These scenarios stress-test the scalability and interoperability of WIP data dissemination.

Types of Tests

Validation activities will focus on key aspects of WIP performance, including:

- **Accuracy**: Assessing the precision of weather information provided by WIPs, including temperature, wind speed, turbulence, and precipitation data.
- **Latency**: Measuring the time taken for weather data to be transmitted from sensors or providers to UAS operators, ensuring real-time or near-real-time availability.
- **Reliability**: Testing system resilience under conditions of sensor failure, network congestion, or incomplete data.
- **Interoperability**: Validating the seamless integration of weather data with UAS C2 systems and air traffic management tools.

Scenarios Conducted

To comprehensively evaluate WIP performance, a variety of scenarios will be conducted:

- **Dynamic Weather Transitions**: Simulating rapid changes in weather conditions, such as the onset of thunderstorms or wind shear, to assess system responsiveness.
- **Adverse Weather Conditions**: Testing the accuracy of weather reports in extreme environments, including high altitudes, heavy rain, and icing conditions.
- **High-Density Airspace**: Evaluating the ability of WIPs to support multiple UAS simultaneously, ensuring consistent and accurate weather data dissemination in congested airspace.
- **Data Loss or Degradation**: Simulating scenarios of incomplete weather data or temporary loss of connection to test system fallback mechanisms.

Collins Aerospace- Copyright- See Title Page.

Value

Validating the performance of Weather Information Providers under ASTM F3673-23 is essential for enhancing UAS operational safety and efficiency. Reliable and timely weather data enables better decision-making for route planning, collision avoidance, and risk management, particularly in adverse conditions. By ensuring that WIPs meet stringent performance standards, the LVC framework supports the safe integration of UAS into complex airspace environments while mitigating risks associated with weather-related disruptions.

7.12.RTCA DO-XXX (ACAS-Xr): Enhanced Collision Avoidance

Context and Objectives

The RTCA DO-XXX standard for Airborne Collision Avoidance System Xr (ACAS-Xr) will establish performance requirements for enhanced collision avoidance systems tailored for high-density, dynamic traffic environments. Unlike its predecessor, ACAS Xu, which focuses on unmanned aircraft systems (UAS), ACAS-Xr is designed to integrate seamlessly into environments with a mix of manned and unmanned aircraft, including rotorcraft and other complex platforms. The objective of this use case is to inform the development of a set of Minimum Operation Performance Standards (MOPS) for ACAS-Xr implementations as well as to validate those implementations' ability to reliably detect and resolve potential conflicts in scenarios involving high-speed maneuvers, dense traffic patterns, and diverse aircraft types, ensuring interoperability and safety across shared airspace.

LVC Systems and Capabilities

- **Live Systems:** Real-world conflict resolution with live rotorcraft and UAS flights serving as the system under test.
- **Virtual Systems:** Human-in-the-loop high-fidelity simulator capabilities, with use of hardware-in-the-loop components where necessary to allow for high-fidelity conflict dynamics either to supplement live testing, or as the system under test when fully live testing is not required.
- **Constructive Systems:** Multi-intruder, high-density conflict scenarios to increase test coverage.

Types of Tests

- Validate resolution advisories for simultaneous conflicts.
- Measure system response time under high-speed conditions.
- Assess interoperability with manned aircraft.

Scenarios Conducted

- Near-collision events with multiple intruders.

- High-speed conflicts in dense urban corridors.
- Low-altitude evasive maneuvers near controlled airspace.

Value

Provides robust validation for enhanced collision avoidance systems, ensuring safety in congested airspace.

7.13.RTCA DO-XXX (Surv.): Cooperative Surveillance MOPS

Context and Objectives

This standard will test interoperability between cooperative surveillance systems like ADS-B and TIS-B. The objective is to validate accurate data exchange and integration into UAS operations.

<<insert graphic>>

LVC Systems and Capabilities

- **Live Systems:** Real ADS-B and radar interactions with live UAS.
- **Virtual Systems:** Simulations of cooperative surveillance in mixed airspace.
- **Constructive Systems:** Scenarios with high-density cooperative and non-cooperative traffic.

Types of Tests

- Validate surveillance data exchange accuracy and timeliness.
- Assess tracking persistence in overlapping surveillance zones.
- Measure system reliability under network congestion.

Scenarios Conducted

- Mixed airspace with cooperative and non-cooperative traffic.
- High-density ADS-B operations in urban corridors.
- Remote area surveillance with sparse sensor coverage.

Value

Enhances situational awareness and airspace safety through reliable cooperative surveillance.

7.14.RTCA DO-XXX (DAA Taxi): Detect and Avoid for Taxi Operations MASPS

Context and Objectives

This standard will define DAA requirements for ground operations in controlled airport environments. The objective is to validate UAS can safely navigate busy taxiways and avoid ground collisions.

LVC Systems and Capabilities

- **Live Systems:** Ground-based collision avoidance sensors and UAS with real-time navigation.
- **Virtual Systems:** Taxiway models with dynamic vehicle and aircraft interactions.
- **Constructive Systems:** Simulations of dense airport environments with variable ground conditions.

Types of Tests

- Evaluate obstacle detection algorithms during low-speed maneuvers.
- Test response accuracy to ground conflict advisories.
- Assess UAS integration into mixed ground traffic.

Scenarios Conducted

- Taxiway operations during peak airport congestion.
- Obstacle avoidance under poor visibility.
- Real-time decision-making with unexpected ground conflicts.

Value

Validate safe ground navigation and collision avoidance in controlled airport environments.

7.15.RTCA DO-XXX (Auto Taxi): Autonomous Taxi Operations MASPS

Context and Objectives

This standard will establish requirements for fully autonomous taxi operations. The objective is to validate precise navigation, obstacle detection, and path planning capabilities.

LVC Systems and Capabilities

- **Live Systems:** Autonomous UAS taxi tests on controlled taxiways at Moffett Field.
- **Virtual Systems:** Airport layout simulations with dynamic traffic conditions.

- **Constructive Systems:** Large-scale synthetic environments with diverse obstacles.

Types of Tests

- Validate real-time path planning algorithms.
- Assess navigation accuracy under varying ground conditions.
- Test obstacle detection and avoidance during autonomous operations.

Scenarios Conducted

- Complex taxiway navigation with multiple obstacles.
- Path planning during rapid traffic changes.
- Operations on uneven or obstructed ground surfaces.

Value

Supports reliable and safe autonomous ground operations, paving the way for efficient UAS integration in airport environments.

8. Coordination, Integration, Engagement, and Communications for LVC Validation Activities

The success of LVC activities relies on the coordination and active engagement of organizations, individuals, and stakeholders. At its core, the effort is about aligning the roles and contributions of various entities—from NASA and FAA test organizations to local stakeholders and the UAS industry—to conduct meaningful validation activities. Clear governance, open communication, and effective collaboration are essential to achieving the objectives of standards validation and ensuring impactful outcomes.

8.1. LVC Test Organization and Governance

The LVC Test Organization is the hub for managing validation activities, overseeing the planning, execution, and evolution of the LVC environment. Its responsibility is to verify the integration of live, virtual, and constructive systems into testing processes while aligning them with regulatory requirements and operational priorities. Governance structures are implemented to maintain consistency, safety, and accountability. These include formalized processes for defining test plans, setting performance benchmarks, and reviewing outcomes.

The Test Organization must adapt the LVC Strategy in response to changing operational challenges and emerging UAS standards. This involves iterative refinement of testing protocols, ensuring that activities remain relevant and impactful. Additionally, the organization manages a centralized data repository, safeguarding the integrity of test results and enabling their dissemination to stakeholders for validation and certification purposes. The governance approach emphasizes transparency and inclusivity, inviting input from key stakeholders to advise decision-making.

8.2. Role of NASA AMES and FAA Test Organizations

NASA AMES at Moffett Field provides the physical and technical foundation for many LVC validation activities. Its controlled airspace, state-of-the-art simulation facilities, and long-standing expertise in air traffic management research position it as a critical enabler of live and virtual testing. NASA supports the design and execution of complex scenarios, integrating live UAS flights with high-fidelity virtual simulations. This includes replicating challenging environments, such as urban canyons and adverse weather conditions, to test UAS systems under diverse operational contexts.

The FAA complements these efforts by offering regulatory oversight and operational guidance. FAA test organizations, such as the FAA Technical Center, perform validation activities that align with airspace management protocols and certification processes. The FAA also facilitates coordination with adjacent air traffic operations, integrating UAS testing into broader airspace activities. Together, NASA AMES and the FAA create a cohesive operational structure that blends technical innovation with regulatory compliance.

8.3. Engagement with External Stakeholders

Effective engagement with external stakeholders is essential for the success of LVC validation efforts. Local entities around Moffett Field, including municipal governments, environmental organizations, and community groups, play an important role in shaping the parameters of live testing activities. These stakeholders provide feedback on the potential impacts of tests and help activities respect local regulations and community concerns. Regular public outreach meetings and clear communication about the purpose and scope of tests foster trust and transparency.

Pilots and adjacent FAA operations are also integral to the process. Their participation in mixed-traffic scenarios adds realism to validation activities, providing critical data on UAS integration into shared airspace. Similarly, collaboration with industry partners, including UAS manufacturers and technology providers, enables access to cutting-edge systems and insights. These partnerships create a feedback loop where LVC results inform product improvements, and industry advancements enhance the realism and utility of tests.

8.4. Mechanisms for Engagement and Communication

To maximize the impact of LVC activities, a structured approach to engagement and communication is implemented. Centralized coordination enables stakeholders to remain informed and involved throughout the testing process. Regular stakeholder forums and workshops provide venues for sharing progress, discussing challenges, and aligning priorities. Industry conferences and standards-development meetings offer additional opportunities to disseminate findings and influence broader UAS initiatives.

8.5. Participation in Standards Development

Active participation in standards development is a foundation of the LVC approach. By contributing test data and operational insights to bodies like RTCA and ASTM, the LVC Test Organization enables validation activities that directly inform the evolution of UAS standards. Representatives from NASA, FAA, and industry partners regularly engage in working groups, proposing updates to existing standards and advocating for the inclusion of real-world testing scenarios.

This participation also facilitates alignment between validation activities and regulatory objectives. By remaining closely involved in the standards-development process, the LVC Test Organization ensures that its activities are not only relevant but also forward-looking, addressing emerging challenges and opportunities in UAS operations.

8.6. Fostering Industry Collaboration

Engagement with industry peers, research institutions, and academic partners enhances the capabilities and impact of LVC validation activities. Collaborative testing initiatives with other organizations provide opportunities to benchmark performance, share best practices, and explore innovative approaches. These partnerships amplify the influence of LVC efforts, ensuring that their outcomes resonate across the UAS ecosystem.

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For example, joint efforts with technology providers enable the integration of novel systems, such as advanced sensors and AI-driven analytics, into the LVC environment. Collaboration with universities fosters innovation in areas like human-machine interaction and autonomous decision-making. These activities position the LVC framework not only as a validation tool but as a driver of progress in UAS technology and operations.

9. Monitoring and Evaluation

A monitoring and evaluation process within the LVC framework must provide for continuous safety and adherence to operational performance standards. This includes real-time monitoring of system behavior during testing, post-evaluation assessments to identify areas for improvement, and iterative refinement of validation methodologies. Tests are designed to track and assess metrics that directly influence UAS safety and operational efficiency, aligning with specific standards such as RTCA DO-362, DO-365, and DO-406.

9.1. Real-Time Monitoring and Performance Data Construction in the LVC Framework

Real-time monitoring and performance data construction are required for compliance with safety and operational standards. Real-time monitoring captures performance data across live flights, virtual simulations, and constructive scenarios, allowing insights into system behaviors. Performance data construction integrates these streams to provide actionable information, aligning with test objectives and the standards being validated.

9.1.1. DATA SOURCES AND INTEGRATION

Performance data comes from:

- **Live Systems**: Real-time telemetry from UAS flights, including position, velocity, and battery levels; ground control logs; and environmental inputs such as terrain and weather impacts.
- **Virtual Systems**: Simulated scenarios providing controlled variability, such as modeled traffic conflicts or GPS-denied environments.
- **Constructive Systems**: Large-scale synthetic environments producing aggregate metrics like network congestion, high-density airspace interactions, and systemic performance under stress.

Real-time monitoring captures and integrates test data during test events. Live systems provide immediate feedback on anomalies; virtual and constructive systems contribute scalability and reproducibility. Integration of data from differing sources involves:

- **Temporal Correlation**: Aligning events across systems to analyze data in the correct sequence.
- **Spatial Correlation**: Mapping performance data to specific airspace regions or operational zones.
- **Contextual Correlation**: Linking metrics to environmental factors such as traffic density or weather conditions.

9.1.2. BALANCING DATA SCOPE

A significant challenge is balancing the breadth and depth of data collection:

- Capturing **too much data** risks overwhelming analytical capabilities, while **too little data** can miss critical insights.
- Data relevance is achieved by focusing on metrics aligned with specific test objectives, such as latency thresholds for DO-362 or accuracy benchmarks for ACAS-Xr.
- Automated tools filter and prioritize data streams, ensuring usability and efficiency in analysis.
- Clear and consistent labeling of collected data, along with proper documentation of how the data were collected reduces the chances of misinterpretation,

Table: Example Data Sources and Metrics by Standard

Table 4 Example Data Sources and Metrics

Standard	Data Source	Metrics Captured	Use Case
RTCA DO-362	Live telemetry, C2 logs	Granular signal latency, packet integrity, data throughput, SNR, channel quality, transmission queue length, retry counts, base station handoff events, normalized useability metric (per flow), range, tx/rx geometry, recovery time	Validates reliable UAS C2 links across environments.
RTCA DO-406	Live UHF radios, constructive traffic	Signal range, interference resilience	Validates UHF airborne radios for complex airspace.
RTCA DO-400	Live telemetry, scenario logs	Link loss recovery rate, automatic behavior compliance	Validates safety during C2 failures.
ASTM F3673-23	Live weather stations, virtual models	Weather data accuracy, latency	Enables safe UAS operations with precise weather inputs.
ACAS-Xr	Virtual intruder models, telemetry	Conflict detection accuracy, advisory latency	Prevents mid-air collisions in high-speed scenarios.

9.1.3. FROM DATA TO ACTIONABLE INSIGHTS

Real-time monitoring tools collect and process raw data that is processed to inform decisions:

1. **Raw Data Capture**: Systems provide telemetry, sensor data, and performance metrics.

2. **Data Processing**: Automated tools correlate and align data across live, virtual, and constructive streams.
3. **Insight Generation**: Metrics are analyzed against performance thresholds, and anomalies are flagged for investigation.

For example, if a latency spike is detected in a UHF system during high-density traffic, the root cause can be traced through correlated data, such as signal interference from a constructive simulation.

9.1.4. REAL-TIME VS. POST-TEST ANALYSIS

While real-time monitoring enables immediate detection of performance issues, post-test analysis aggregates and evaluates data to inform system improvements. Both processes work in tandem:

- Real-time monitoring identifies operational deviations or anomalies during tests.
- Post-test evaluations consolidate and compare results, identifying trends and informing refinements.

9.2. Post-Test Evaluation

Following each test, an evaluation consolidates live, virtual, and constructive test results into a single performance review. This evaluation focuses on:

- **Standards Compliance**: Validating whether test outcomes meet the specific requirements of the standards under review.
- **Safety Metrics**: Assessing risk mitigation effectiveness, such as loss-of-link recovery rates (DO-400) or conflict resolution success (ACAS-Xr).
- **System Reliability**: Measuring long-term performance stability, such as the resilience of UHF C2 systems (DO-406) or the accuracy of weather reporting (ASTM F3673-23).

Evaluation reports are shared across stakeholders to provide transparency and foster collaborative improvement.

9.3. Continuous Safety Evaluation Framework

The table below outlines key standards, associated monitoring metrics, evaluation criteria, and continuous safety goals:

Standard	Monitoring Metric	Evaluation Criteria	Continuous Safety Goal
RTCA DO-362	Signal latency, packet loss, recovery time	Latency below X ms; packet integrity > Y%; recovery in Z seconds	Validate uninterrupted UAS command-and-control link stability.

Standard	Monitoring Metric	Evaluation Criteria	Continuous Safety Goal
RTCA DO-365	Conflict detection, resolution timing	Detection success > 98%; resolution advisories issued within 3s	Prevent loss of separation in dense, mixed airspace.
RTCA DO-406	UHF signal stability, range, interference	Signal coverage > 95%; interference impact < 2%	Maintain reliable C2 communications in complex environments.
RTCA DO-400	Loss-of-link recovery, automatic behavior	Recovery success > 90%; compliance with safety protocols	Enable safe UAS behavior during and after C2 failures.
ASTM F3673-23	Weather data accuracy, update latency	Accuracy within ±5%; updates < 10s latency	Provide timely, precise weather data for safe UAS operations.
ACAS-Xr	Conflict resolution accuracy, latency	Resolution success > 98%; advisories within 2s	Prevent collisions in high-speed or dense airspace scenarios.

9.4. Iterative Refinement

The results from post-test evaluations feed directly into the iterative refinement of test methodologies, LVC systems, and operational protocols. Regular stakeholder reviews provide lessons learned that are incorporated into future tests, and emerging challenges are addressed proactively. For instance:

- Scenarios flagged as high-risk are re-tested under controlled conditions with adjusted parameters.
- New technologies, such as improved sensors or algorithms, are integrated into the LVC framework for expanded validation.

10. LVC Risks and Mitigations

Validating UAS requirements through an LVC framework introduces challenges that must be addressed to ensure accurate, reliable, and scalable testing. The integration of live flights, virtual simulations, and constructive scenarios creates complexities in data synchronization, communication reliability, scenario alignment, and system scalability. These risks can impact the fidelity of results and the ability to validate operational and safety standards effectively. Identifying and mitigating these risks is critical to maintaining the integrity of the validation process and achieving comprehensive evaluation outcomes. The table below outlines key risks associated with the LVC framework, their impacts, and strategies for mitigation.

Risk	Mitigation Approach
If data integration fails **due to** poor synchronization across live, virtual, and constructive systems during testing, **then** UAS requirements validation will lack fidelity, leading to incomplete or invalid outcomes.	Develop a centralized data integration and synchronization system tailored to NASA Ames LVC operations, ensuring temporal, spatial, and contextual alignment.
If live and virtual systems experience communication latency **due to** network congestion or insufficient bandwidth **then** real-time monitoring of UAS test scenarios will be compromised, reducing the reliability of results.	Deploy redundant communication networks (where needed) and optimize bandwidth allocation for LVC systems during UAS testing.
If scenario complexity is misaligned to the capabilities of LVC components **due to** insufficient planning or incompatible systems, **then** NASA Ames tests will fail to accurately replicate UAS operational requirements, limiting validation effectiveness.	Establish detailed pre-test scenario alignment protocols and conduct integration tests to ensure compatibility across live, virtual, and constructive systems.
If virtual and constructive data are not validated against live UAS system results **due to** inadequate verification protocols, **then** simulated outcomes will misrepresent real-world performance, undermining NASA Ames' confidence in UAS validation.	Use live flight data as the baseline for validating simulation models, ensuring alignment with real-world conditions.
If scalability of the LVC environment is not achieved **due to** resource constraints or technical limitations, **then** large-scale stress testing for UAS operational scenarios will be incomplete, reducing confidence in system robustness.	Prioritize modular, scalable LVC designs, and secure additional computing resources to support high-density airspace simulations.
If stakeholder coordination breaks down **due to** misaligned objectives between NASA Ames, FAA, and industry partners, **then** UAS standards validation	Establish governance frameworks with clearly defined roles, conduct regular coordination meetings, and use a

Risk	Mitigation Approach
activities will face delays, impacting overall program objectives.	centralized reporting system to align stakeholder efforts.
If test execution is interrupted **due to** unforeseen technical failures or environmental conditions, **then** UAS validation results will be incomplete, delaying progress toward meeting operational standards.	Develop robust contingency plans, including backup systems for live tests and adaptive scenarios in virtual and constructive environments.

Appendix A – History of LVC

LVC grew out of the concept of Advanced Distributed Simulation, which refers to the use of multiple, interconnected simulation systems to create a larger, collaborative virtual environment. The development has been driven primarily by the needs of the military, large-scale engineering projects, and increasingly complex systems that require coordinated operations in real-time across various locations. An overview of its development follows.

The roots of distributed simulation can be traced back to the early days of computer simulation in the 1960s, when simulation models were used to study complex systems like aerospace and defense. However, these simulations were typically isolated and ran on individual computers.

In the 1980s, networking technology made it possible to link multiple systems together. During the 1990s, the military's need for joint training operations across various branches led to increased investment in ADS. The U.S. Department of Defense spearheaded the development of several distributed simulation standards.

- **SIMNET (Simulator Networking)**: Early military initiatives developed by DARPA were among the first implementations of distributed simulation. SIMNET allowed multiple training systems (such as tank simulators) to be networked so that they could interact in real-time, laying the foundation for more advanced architectures and protocols.
- **Distributed Interactive Simulation (DIS)**: Developed in the early 1990s, DIS was one of the first major frameworks designed to allow various simulation systems to operate together. It set the groundwork for real-time interactions between simulations over networks.
- **High-Level Architecture (HLA)**: As the complexity and scale of simulations grew, DIS had limitations. In response, the U.S. DoD developed HLA in the mid-1990s to provide a more scalable and flexible architecture. HLA defined a general framework for simulation interoperability, allowing different simulation systems to work together regardless of their individual designs.

Although these techniques were originally developed for military applications, their utility in other industries soon became apparent. With advancements in computing power, networking, and software, they are increasingly common techniques used in:

- **Transportation**: For testing and optimizing traffic systems, airports, and logistics.
- **Healthcare**: Simulations for medical training, large-scale public health preparedness exercises.
- **Engineering and Manufacturing**: Design, testing, and validation of systems like automotive assembly lines, power grids, and aerospace systems.
- **Entertainment and Gaming**: Multiplayer video games and virtual reality (VR) experiences, which rely on similar networking and simulation concepts.

Several technologies have fueled this development:

- **Networking**: The evolution of high-speed networks and the internet made it feasible to connect simulations across large distances, enabling broader collaboration.
- **Interoperability Standards**: Standards like HLA, DIS, and the Test and Training Enabling Architecture (TENA) ensure that different systems can work together smoothly.
- **AI and Machine Learning**: Incorporation of AI has allowed simulations to include more sophisticated behaviors, enhancing their realism and making them more dynamic.

While distributed simulation has seen significant advancements, several challenges remain. These are particularly relevant in simulation architectures supporting test and evaluation activities. They include:

- **Synchronization**: Ensuring that distributed simulations remain in sync across geographically dispersed locations is a major technical hurdle.

- **Scalability**: Simulating very large or complex systems (e.g. smart cities or global logistics networks) continues to push the limits of current computing and networking capabilities.
- **Cybersecurity**: Distributed systems are vulnerable to attacks, and securing these networks is crucial for maintaining the integrity of simulations.

The development of advanced distributed simulation has transformed how large, complex systems are analyzed and tested. From its early military roots in the 1980s with SIMNET, to its broad application across industries today, advanced, interactive simulation architectures continue to evolve with technological advances in networking, AI, and computing. The growth of distributed simulation has paved the way for the creation of powerful, real-time collaborative environments for experimentation and analysis.

Roots of LVC-enabled Test

The concept of LVC-enabled flight testing has evolved in the last few decades due to the increasing complexity and cost of testing modern aircraft systems and combat scenarios. Significant phases of its development include:

Origins in Distributed Simulation and Training (1970s-1990s)

- **Simulation technology**: In the 1970s and 1980s, advances in digital computing allowed military and civil aviation to integrate simulators into their training regimens. Early flight simulators were primarily used for pilot training, reducing the need for expensive live flying hours.
- **Distributed simulation**: In the 1990s, the concept of distributed simulation emerged, enabling multiple simulators to be networked together. This allowed for more complex scenarios that included not just a single pilot, but also multiple airframes, ground forces, and other systems operating in a coordinated manner.

Rise of Virtual and Constructive Elements (2000s)

- **Integration of virtual pilots**: With advances in networking and computational power in the early 2000s, it became feasible to integrate virtual pilots (those in simulators) with live test scenarios. This enabled mixed environments where real aircraft and pilots interacted with those in simulators, enhancing testing without requiring large fleets.
- **Constructive simulations**: At the same time, algorithms and computer models advanced to the point where constructive simulations, entirely computer-generated entities, could be used to simulate additional aircraft, ground-based threats, and weather conditions. These concepts are easily applied to non-military scenarios to add complexity in civilian airspace.

Adoption for Flight Test and Mission Training (2010s)

- **Blended environments**: By the mid-2010s, LVC-enabled flight tests started to be adopted more widely for mission training and testing of advanced systems like sensor fusion, electronic warfare, and network-centric operations. These scenarios allowed for the integration of real-world (live) aircraft with computer-generated forces (constructive) and simulators (virtual), simulating highly complex operational environments that would be cost-prohibitive or impractical to recreate with live assets alone.
- **Advancements in datalinks and communication**: LVC-enabled environments require robust, secure, and high-bandwidth communications between the live and virtual/constructive components. Technologies like advanced datalinks and communication protocols matured during this period, enabling LVC environments to scale up. It became common to incorporate specific test datalink functions to provide LVC input to aircraft that did not interfere with other systems functions

Modern Day Use and Future Trends (2020s)

- **Complex test environments**: Today, LVC environments are used to test a variety of systems, from fighter jets and bombers to UAVs and autonomous systems. These environments allow for testing in highly contested or classified scenarios that would be difficult or impossible to test in live environments. For example, stealth aircraft like the F-35 benefit greatly from LVC-enabled testing, as it allows for simulated threats that can be tailored to specific testing needs. Unmanned aircraft control systems are routinely tested with simulated aircraft, allowing operators to develop skills and new operating concepts without the need for flight.
- **Artificial Intelligence and Machine Learning**: LVC systems are increasingly leveraging AI and ML to create more dynamic and unpredictable scenarios. This allows for better training and testing, as the virtual and constructive elements can adapt to pilot or system actions in real time.

Current Applications

LVC-enabled flight tests are now widely used around the world. They allow for:

- **Cost-effective testing**: Reducing the need for large fleets of aircraft or extensive live-flying hours.
- **Enhanced safety**: Testing scenarios that would be too dangerous to conduct in real life.
- **Advanced warfare testing**: Simulating complex, multi-domain operations involving air, land, sea, space, and cyber components.

The future of LVC-enabled flight testing looks to incorporate even more sophisticated AI-driven constructive simulations. The increased importance of testing unmanned or autonomous air vehicles, integrating complex features into test environments, motivates an even more comprehensive and realistic testing ecosystem.