NASA/TM–20210011098

Report: X3 Simulation with National Campaign-Developmental Test (NC-DT) Airspace Partners

Nicholas Craven
Millennium Engineering & Integration Co.

Savita Verma, Spencer Monheim
NASA Ames Research Center

Annie Cheng
Millennium Engineering & Integration Co.

Robert Wood
Flight Research Associates

Victoria Dulchinos
San Jose State University Research Foundation

Chin Seah, Fritz Renema
KBR Wyle Services

Amir Farrahi
Universities Space Research Association

David Zahn
Flight Research Associates

Dan Liddell
KBR Wyle Services

Jenessa Lin, Mohana Gurram
NASA Ames Research Center

Qiang (Shawn) Li
KBR Wyle Services

Mark Snycerski, Michele Cencetti
San Jose State University Research Foundation

April **2021**

NASA STI Program ... in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

- E-mail your question to help@sti.nasa.gov

- Phone the NASA STI Information Desk at 757-864-9658

- Write to:
  NASA STI Information Desk
  Mail Stop 148
  NASA Langley Research Center
  Hampton, VA 23681-2199

NASA/TM–20210011098

Report: X3 Simulation with National Campaign-Developmental Test (NC-DT) Airspace Partners

Nicholas Craven
Millennium Engineering & Integration Co.

Savita Verma, Spencer Monheim
NASA Ames Research Center

Annie Cheng
Millennium Engineering & Integration Co.

Robert Wood
Flight Research Associates

Victoria Dulchinos
San Jose State University Research Foundation

Chin Seah, Fritz Renema
KBR Wyle Services

Amir Farrahi
Universities Space Research Association

David Zahn
Flight Research Associates

Dan Liddell
KBR Wyle Services

Jenessa Lin, Mohana Gurram
NASA Ames Research Center

Qiang (Shawn) Li
KBR Wyle Services

Mark Snycerski, Michele Cencetti
San Jose State University Research Foundation

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, CA 94035

April **2021**

Acknowledgments

We would like to acknowledge Jillian Keeler, Richard Mogford, and Rania Ghatas for helping us with the report writing and editing, and Doug Isaacson for communicating and being an awesome liaison with X3 industry partners. We would also like to extend our gratitude and acknowledge our colleagues from the National Campaign Airspace Test Infrastructure (ATI) - John Sprague, Tim Bagnall, Jerry Wilwerding, Latha Madhavi, Faisal Omar, Irene Smith, and David Smith for designing and building the X3 data collection system that was foundational to the scenario testing and data collection with industry partners.

This report is available in electronic form at

https://ntrs.nasa.gov/

Introduction

NASA's vision for Advanced Air Mobility (AAM) is to help emerging aviation markets develop a safe air transportation system that would allow moving people and cargo between places previously not served or underserved by aviation [1]. Advanced Air Mobility (AAM) encompasses a range of innovative aviation technologies (small drones, electric aircraft, automated air traffic management, etc.) that are transforming aviation's role in everyday life, including the movement of goods and people. Urban Air Mobility (UAM) represents one of the AAM concepts with highly automated aircraft, providing commercial services to the public over densely populated cities to improve mobility. The improvement of UAM envisages a future in which advanced technologies and new operational procedures enable practical, cost-effective air travel as an integral mode of transportation in metropolitan areas. This includes flying to local, regional, intra-regional, and urban locations using revolutionary new electric Vertical TakeOff and Landing (eVTOL) aircraft that are only just now becoming possible.

The previous research (X1) investigated the operational capabilities in the current day ATC environment. The results of X1 showed that ATC communication and workload are bottlenecks for scalability of the UAM operations [3]. The objective of X2 was to utilize the UTM's Technical Capability Level-4 (TCL-4) capabilities for UAM operations with one industry partner. It unraveled the challenges for using operational volumes for UAM operations that are not standardized across the industry [4].

Both NASA and the FAA have been collaborating to describe the innovative UAM operations through a Concept of Operations (Conops) document. The document also describes the challenges to these operations, which range from integration of UAM operations in the National Airspace (NAS), safety, noise impacts, public acceptance, and many more. The FAA's Conops v1.0 on UAM operations [2] describes near term to mid-term UAM operations that define airspace structures, such as corridors, that would allow UAM operations without Air Traffic Control (ATC) services. These corridors could be defined in any class of airspace as well as defined from vertiport to vertiport. The UAM operations would require minimum performance requirements to operate within the corridors and to traverse them. The Conops also defines an architecture where Providers of Services for UAM (PSUs) would provide the relevant services for UAM operations that would utilize eVTOL vehicles. NASA's Vision Conops [1] focuses on the mature UAM operations and describes a different set of airspace structures –a UAM Operational Environment (UOE) that would be utilized for more complex and higher density UAM operations.

In support of the AAM mission to accelerate the integration of UAM operations in the NAS, a series of test activities that are focused on flight and simulation are planned by the National Campaign Sub Project (NC SP). The NC flight test series will guide the collective community and stakeholders through a series of scenario-based test activities that involve vehicles and airspace management services operating in a live test environment. NC SP plans to conduct flight tests over the next several years. The first flight test, referred to as National Campaign – Development Test (DT), focuses on testing with helicopters in March 2021. The airspace partners with NC are referred to in this document as NC-DT airspace partners or just airspace partners.

The UAM Sub-Project (SP) conducted initial lab simulations with NC developmental testing (NC-DT) airspace partners to evaluate and demonstrate their capabilities and components prior to NC flight activities. The X3 series of simulations focuses on the development of technologies, capabilities, and procedures with the objective of integrating the UAM operations in the NAS via simulation test activities. It does not utilize the airspace structures defined by FAA Conops or the NASA Vision Conops. The goal of these tests was to provide insight into the evolving regulatory, operational, and safety environment. The insights generated by these tests are necessary to gather crucial data about the UAM concept while promoting public confidence in safety. This document defines the process leading up to the X3 simulation test events, the execution of the X3 simulation tests, and their results.

Scope

These simulation activities, referred to as X3, were conducted during the second half of 2020 and completed in December 2020. X3 was an initial opportunity to assess the UAM airspace system developed by the Air Traffic Management – eXploration (ATM-X) Project's UAM Sub-Project (SP) in collaboration with National Campaign Sub Project's Airspace Test Infrastructure (ATI) team. The capabilities provided by the airspace partners were tested during these simulation activities. In X3, the UAM SP executed initial lab simulations with NC-DT airspace partners to test and demonstrate their capabilities and components prior to flight activities. The NC SP's ATI team was responsible for providing data collection capabilities for X3. In addition, the ATM-X UAM SP facilitated the connection of NC-DT airspace partners to the UAM airspace system and simulation platform.

The X3 simulation started with eleven NC-DT airspace partners. None of the 11 airspace partners completed all the available testing with UAM Airspace Simulation Platform. More details are provided about the number of completed tests in the Results section.

Requirement Process

The UAM SP and NC SP's ATI teams collaborated to gather initial internal (NC, NASA) and external (FAA, Airspace Partners) requirements and capabilities based on the NC goals, objectives, success criteria, and scenarios, which served as the foundation of the X3 simulation activities. Figure 1 shows the system architecture used to meet these requirements.

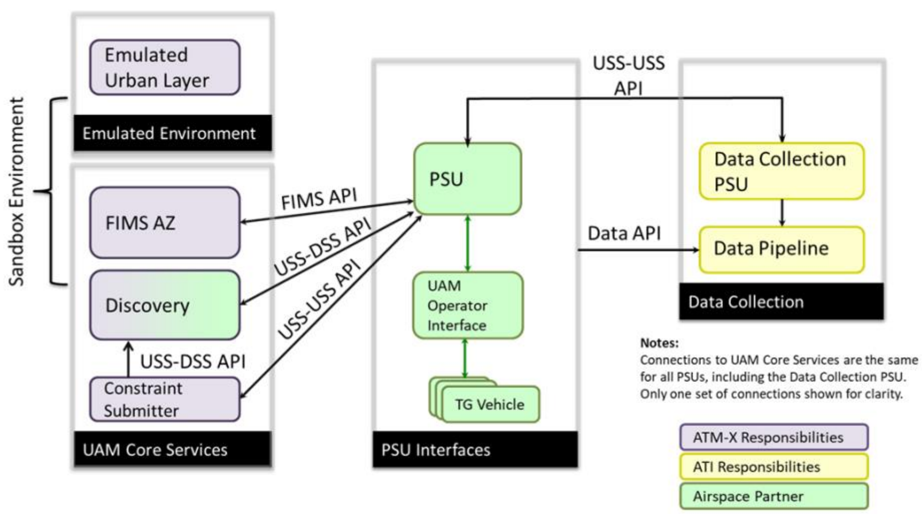

Figure 1 X3 System Architecture Diagram

Components in the Emulated Environment and UAM Core Services comprised the UAM Airspace Simulation Platform. Each component in the Figure 1 architecture is defined in Table 1.

Table 1 Components in the Emulated Environment

Component	**Description**
Emulated Urban Layer	Provides adaptation data (e.g. routes and airspace constructs) to the Airspace Partners.
Flight Information Management System – Authorization (FIMS AZ)	Authorizes and authenticates PSU to ensure access is provisioned to those permitted to use the system.
Discovery and Synchronization Service (DSS)	Enables a PSU to identify other PSUs with active operations or subscriptions in the area of interest.
Constraint Submitter	Generates an airspace constraint with defined spatial and temporal boundaries and distributes it to the PSU Network.
Provider of Services for UAM (PSU)	A PSU is an entity that supports UAM operators with meeting UAM operational requirements that enable safe, efficient, and secure use of the airspace [2]. A PSU: 1. Provides a communication bridge between federated UAM actors, PSU to PSU via the PSU Network, to support the UAM operator's ability to meet the regulatory and operational requirements for UAM operations 2. Provides the UAM operator with information gathered from the PSU Network, about planned UAM operations so that UAM operators can ascertain the ability to conduct safe and efficient missions 3. Provides the confirmed flight intent to the PSU network 4. Distributes notifications (e.g., constraints, restrictions) for the intended area of operation
UAM Operator Interface	Represents an entity that manages UAM operations. Meets regulatory responsibilities, plans operations, and safely conducts operations using all available information.
Target Generator (TG) Vehicle	Simulated UAM vehicle.
Data Collection PSU	NASA developed system component leveraging PSU API to collect data during NC simulation and flight test. A PSU that collects data but does not submit operations.
Data Pipeline	NASA developed system to collect real-time and post-flight data during simulation and flight test.

The Application Programming Interfaces (API) for each interface identified in the system architecture were defined in a GitHub repository which was available to all airspace partners. Links to all applicable API are included in
Table 2 GitHub links for the different interfaces in X3 simulation environment.

Table 2 GitHub links for the different interfaces in X3 simulation environment

Data Pipeline	https://github.com/nasa/uam-apis/blob/master/datacollection/openapi/X3/uam-data-collection-X3.yaml
FIMS	https://github.com/nasa/utm-apis/blob/master/fimsauthz-api/fims-authz.yaml
USS-to-DSS and USS-to-USS (Based on ASTM API)	https://github.com/nasa/uam-apis/blob/master/datacollection/nasa-astm-utm.yaml
Vehicle Telemetry	https://github.com/nasa/uam-apis/blob/master/datacollection/openapi/X3/utm-telemetry.yaml

The ASTM API [6] was originally written for Unmanned Aircraft System (UAS) Traffic Management (UTM) [5] and the UAS Service Supplier (USS) in that architecture. For X3, the same API was used, and 'USS' and 'PSU' were used interchangeably. In future, ‘USS’ and ‘PSU’ will not be interchangeable in actual applications and operations.

System Requirements

To support the System Architecture, there were two categories of System Requirements; UAM Airspace Simulation Platform Requirements and Airspace Partner Requirements. The first category consisted of requirements to provide the UAM Airspace Simulation Platform with the services necessary to execute and collect data for the scenarios to meet the minimum success criteria. These included requirements for providing airspace definitions (such as airspace classes and nominal/off-nominal routes); providing authorization, discovery, and constraint submission services; and receiving and storing data. As depicted in the System Architecture (Figure 1), these systems were primarily developed by the ATM-X / UAM SP, and the NC Sub-Project / ATI teams. The DSS was developed by industry and hosted by one of the airspace partners.

The second category of requirements were capabilities the NC-DT airspace partners needed in order to connect to the simulated airspace services and exercise the capabilities necessary for the scenarios. This included a PSU that interfaced with the UAM Airspace Simulation Platform so that operations could be planned and re-planned and enabled simulated vehicles to fly the planned operations. These capabilities, while not strictly necessary to meet the success criteria of X3, were beneficial because they supported data collection, and could be used for the development and refinement of the requirements for future NC simulations and flights tests.

Scenarios

Three simulated scenarios were tested in X3 as part of a joint effort between NASA, the FAA, and airspace partners. All industry partners in X3 were encouraged to execute any or all of the NC Scenarios 1 through 3 out of the 7 total NC Scenarios. The UAM SP maintained flexibility to enable data collection and validation of NC scenarios for partners that were ready to test.

General assumptions which apply to all scenarios are described in Table 3.

Table 3 General Assumptions for X3

Element	Assumption
UAM Airspace Management System Authorization	Pre-authorization to submit operations; does not include airspace and/or performance authorization. Letter of Authorization (LOA) authorizes flight to enter Class D.
Weather Conditions	Daytime Visual Meteorological Conditions (VMC).
UAM Routes Interaction with Instrument Flight Rules (IFR) and Visual Flight Rules (VFR)	UAM airspace/routes are designed to be de-conflicted with Instrument Flight Rules (IFR) and Visual Flight Rules (VFR) routes using current day separation requirements. UAM airspace/routes are expected to be high density routes that are notified to the rest of the VFR traffic in Class G for awareness. No interaction is assumed between UAM and IFR/VFR flights.
Background Traffic	None.
UAM Routes Sharing	Each UAM operator manages its own set of UAM routes (i.e., UAM routes are not shared among multiple UAM operators at the same time).
Vertiport Sharing	Each UAM operator manages its own set of Vertiports (i.e., Vertiports are not shared among multiple UAM operators at the same time).
Small Unmanned Aircraft Systems (sUAS) and Non-Transponder Flights	Not included in the traffic.
Simulation Environment	Only one airspace partner will run the scenario at any given time in X3.

Scenarios were designed such that complexity increased in each scenario. Adaptation files in KML format were provided to the airspace partners for each scenario and included details such as airspace classes, nominal routes, and off-nominal routes.

Scenario 1 Description

Scenario 1 included flight and operation planning for nominal operations. Additional assumptions specific to Scenario 1 are included in Table 4.

Table 4 Scenario 1 Assumptions for X3

Element	Assumption
Airspace	Class E/G, Day VMC.
Air traffic control (ATC) Communications	Current day (verbal) communications not required.
Adaptation	UAM airspace/routes are pre-defined and shared with partners as adaptation (files), including terrain elevation data along the route.

The airspace objectives for Scenario 1 were to demonstrate a PSU's ability to perform pre-departure flight planning for UAM aircraft, including scheduled departure and arrival times and strategic deconfliction. In Scenario 1, the PSUs planned an operation using the provided routes and interfaced with the UAM Airspace Simulation Platform to announce the operation. This was followed by a simulation of vehicle(s) which conformed to that plan. A generic representation of this scenario is shown in Figure 2. The line indicates the route, and the arrows indicate the intended direction of the aircraft.

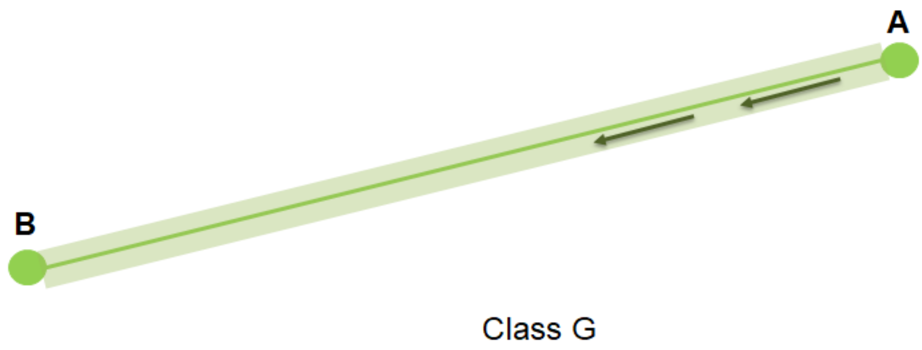

Figure 2 Scenario 1 Generic Representation

Scenario 2 Description

Scenario 2 included en-route operation re-planning in response to an announced airspace constraint. Additional assumptions specific to Scenario 2 are included in Table 5.

Table 5 Scenario 2 Assumptions for X3

Element	Assumption
Airspace	Class D/E/G, Day VMC.
Adaptation	UAM airspace/routes are pre-defined and shared with partners as adaptation static files. Generic airspace with terrain data along the route and locations of Class D, E/G airspace boundaries.
ATC Communications	Current day (verbal) communications are not required. Exit of the UAM route will normally prompt UAM vehicle and ATC interaction in Class D airspace. Presume that ATC has communicated to and pre-authorized the UAM aircraft regarding the re-route around the Constraint and re-joining the corridor.
Constraint Creation	Will be announced by a NASA service using the USS-USS and USS-DSS APIs.
UAM Re-route	The UAM re-route flight path is pre-authorized by ATC and provided as updated waypoints to the PSU.

In addition to the airspace objectives listed in Scenario 1, the objectives of this scenario are to demonstrate:

- Interfaces for generating, and announcing airspace constraints to operations that may be impacted by the constraints both pre-departure and in flight
- PSU's ability to receive airspace constraints and re-plan operations accordingly

In Scenario 2, the PSUs planned the operation(s) using the provided routes, interfaced with the UAM Airspace Simulation Platform to announce the operation(s), and then simulated vehicle(s), which were expected to conform to that plan. While the operation(s) were in-flight, an airspace constraint (a UAS Volume Reservation, or UVR) was announced by the UAM Airspace Simulation Platform using the defined APIs. The PSU:

1. Updated the operation plan(s) using the waypoints around the constraint which were provided in the adaptation files,
2. Announced the updated plan(s) to the UAM Airspace Simulation Platform,

3. Simulated the vehicle(s) that were expected to conform to the updated operation plan(s).

A generic representation of this scenario is shown in Figure 3.

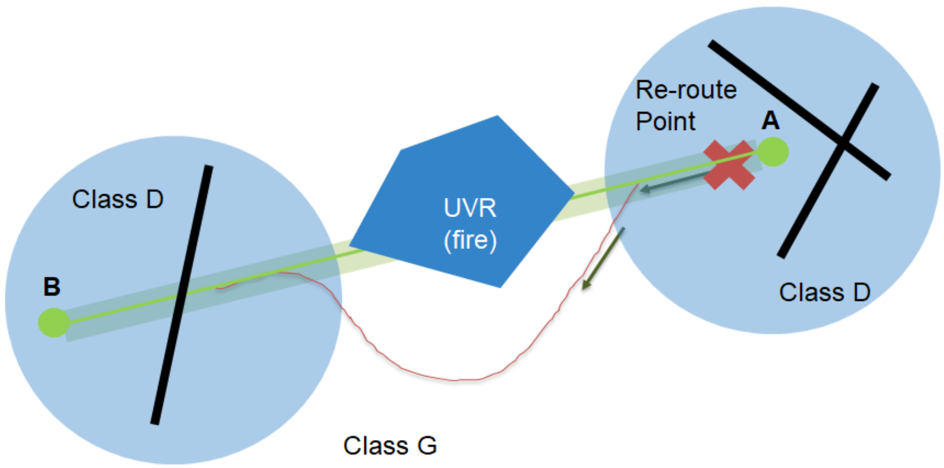

Figure 3 Scenario 2 Generic Representation

Scenario 3 Description

In order to develop a scalable Vertiport design and procedures, and explore influencing factors, Scenario 3 was split into three test cases: Scenarios 3A, 3B, and 3C. The influencing factors that were explored included the impacts of go-arounds and landing on an unplanned vertipad or location on the surface of the airport

The overarching airspace objectives for this scenario were to demonstrate:

- Vertiport operations including density of landing/takeoffs, traffic flow management, and operations at closely spaced UAM vertipads
- A PSU's ability to safely and efficiently support UAM aircraft that perform a go-around with another approach/landing attempt
- A PSU's ability to safely and efficiently support UAM aircraft with emergency states that require changing landing locations

Scenario 3A

Scenario 3A included en-route operation re-planning in response to an occupied or obstructed vertipad. Additional assumptions specific to Scenario 3A are included in Table 6.

Table 6 Scenario 3A Assumptions for X3

Element	**Assumption**
Airspace	Class D/E/G, Day VMC/ VFR.
Adaptation	UAM airspace/routes are pre-defined and shared with partners as adaptation (files). Generic airspace with terrain data along the route and locations of Class D, E/G airspace boundaries.
ATC Communications	Current day (verbal) communications not required. Go-Around is a published procedure that does not require ATC communication.

Element	Assumption
Go-Around trigger	PSU detects that the landing pad is unavailable and triggers the go-around
UAM Go-Around Route	The UAM go-around route is a pre-defined contingency plan (similar to the loiter path) and is taken by the flight.

In Scenario 3A, the PSUs planned operation(s) using the provided routes, interfaced with the UAM Airspace Simulation Platform to announce the operation(s), and then simulated vehicle(s) that were expected to conform to that plan. Prior to arrival of the operation, the PSU was alerted that the intended landing location was unavailable. As a result, the PSU:

1. Generated an updated operation plan to perform a go-around using the provided route,
2. Announced the updated operation plan to the UAM Airspace Simulation Platform,
3. Simulated vehicle(s) that were expected to conform to the updated operation plan.

Following the go-around, the operation was expected to be re-sequenced with the other operations planned to land at the same vertiport. A generic representation of this scenario is shown in Figure 4.

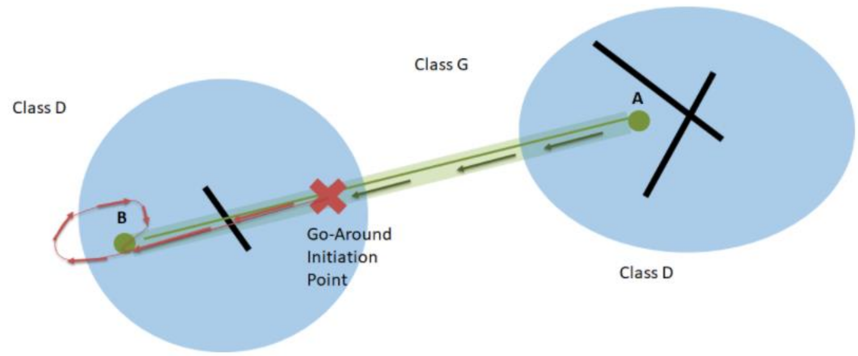

Figure 4 Scenario 3A Generic Representation

Scenario 3B

Scenario 3B included en-route operation re-planning in response to an occupied or obstructed vertipad similar to Scenario 3A. Additional assumptions specific to Scenario 3B are included in Table 7.

Table 7 Scenario 3B Assumptions for X3

Element	Assumption
Airspace	Class D/E/G, Day VMC/ VFR.
Adaptation	UAM airspace/routes are pre-defined and shared with partners as adaptation (files). Generic airspace with terrain data along the route and locations of Class D and E/G airspace boundaries.
ATC Communications	Current day (verbal) communications not required. Landing on the same vertiport but to a different vertipad is assumed to be managed by the operators
Alternate Landing Trigger	PSU detects the landing pad is unavailable and the aircraft is unable to do a go-around, requiring landing on a different pad.

Element	Assumption
Alternate Landing Location	The PSU will update its operation volume and land at the new location. The alternate vertipad is a pre-defined contingency plan

In Scenario 3B, the PSUs planned operation(s) using the provided routes, interfaced with the UAM Airspace Simulation Platform to announce the operation(s) plan, followed by simulation of the vehicle(s) that were expected to conform to that plan. Prior to the arrival of the operation at the intended vertipad, the PSU was alerted that the intended landing location was unavailable. The vehicle was not be able to perform a go-around (like in Scenario 3A) due to the vehicle status and needed to land at an alternate vertipad on the same vertiport. As a result, the PSU:

1. Generated an updated operation plan to land at the provided alternate vertipad,
2. Announced the updated operation plan to the UAM Airspace Simulation Platform,
3. Simulated the vehicle, which was expected to conform to the updated operation plan.

A generic representation of this scenario is shown in Figure 5.

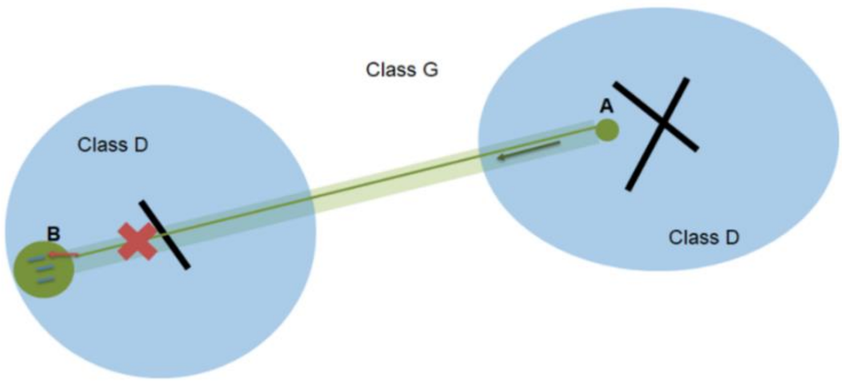

Figure 5 Scenario 3AB Generic Representation

Scenario 3C

Scenario 3C included en-route operation re-planning in response to an emergency landing request made by the UAM aircraft. Additional assumptions specific to Scenario 3C are included in Table 8.

Table 8 Scenario 3C Assumptions for X3

Element	Assumption
Airspace	Class D/E/G, Day VMC/ VFR.
Adaptation	UAM airspace/routes are pre-defined and shared with partners as adaptation (files). Generic airspace includes terrain data along the route and locations of Class D, E/G airspace boundaries.
ATC Communications	Current day (verbal) communications are not required. Emergency landing will normally prompt UAM vehicle and ATC interaction in Class D. Presume that ATC has communicated to and pre-authorized the landing and location.
Emergency Landing	UAM flight is unable to use the vertiports and the operator triggers the emergency landing on the airport surface (not a vertipad). Assumes that landing location was authorized by the ATC.

Element	Assumption
Landing to Runway	The PSU will update its operation volume and land at the new location.

In Scenario 3C, the PSUs planned operation(s) using the provided routes, interfaced with the UAM Airspace Simulation Platform to announce the operation(s), and then simulated vehicle(s) that were expected to conform to that plan. Prior to arrival of the operation at the planned landing location, the PSU was alerted that the operation needed to perform an emergency landing which required a contingency state and diversion to a runway landing location. As a result, the PSU:

1. Generated an updated operation plan to land at the provided runway landing location,
2. Announced the updated operation plan to the UAM Airspace Simulation Platform,
3. Simulated the vehicle that was expected to conform to the updated operation plan.

The PSU also indicated the contingency state of the operation to the UAM Airspace Simulation Platform. A generic representation of this scenario is shown in Figure 6.

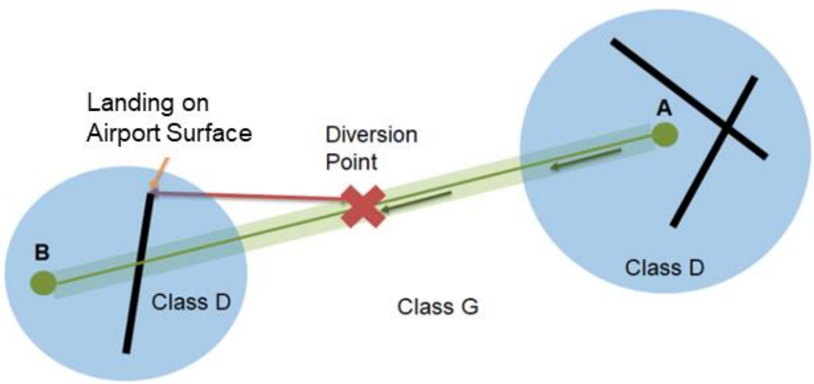

Figure 6 Scenario 3C Generic Representation

Method

Airspace Definition

For each scenario described in the Scenarios section of this document, adaptation files were used to define a common airspace for all the airspace partners. Included in the files were applicable airspace definitions, available landing / takeoff vertipads, nominal routes between the vertipads, and off-nominal routes. Airspace definitions included the applicable Class D airspace, and a portion of the Class D airspace referred to as 'UAM Airspace' in which UAM operations were allowed to occur under an assumed predefined agreement with ATC. The airspace partners were not required to plan their operation at a specific cruise altitude while in Class G airspace. Points along the routes were provided and included the World Geodetic System (WGS) 84 altitude of the terrain at that location. All adaptation data was provided to the airspace partners in Keyhole Markup Language (KML) format.

For each scenario test, one route was identified in the test procedure as the primary route. Operations identified as part of the test procedure were required to use this primary/nominal route as shown in Figure 8. Similarly, if there was a scripted off-nominal event, that off-nominal route was also identified in the procedure. Both the nominal and off-nominal routes were provided to exercise control over the scenarios and allow comparisons where possible among different airspace partners.

The adaptation for the routes and classes of airspace created a generic airspace based on Class D airports in Dallas area. The two class D airspaces that were emulated included Arlington and Alliance airspaces. These airspaces were then transposed to Edwards Airforce Base (EDW) for terrain because the NC flight test was planned at that location. The emulation of the route planned for NC flight test was referred to as the nominal route that all airspace partners were required to fly as shown in Figure 7.

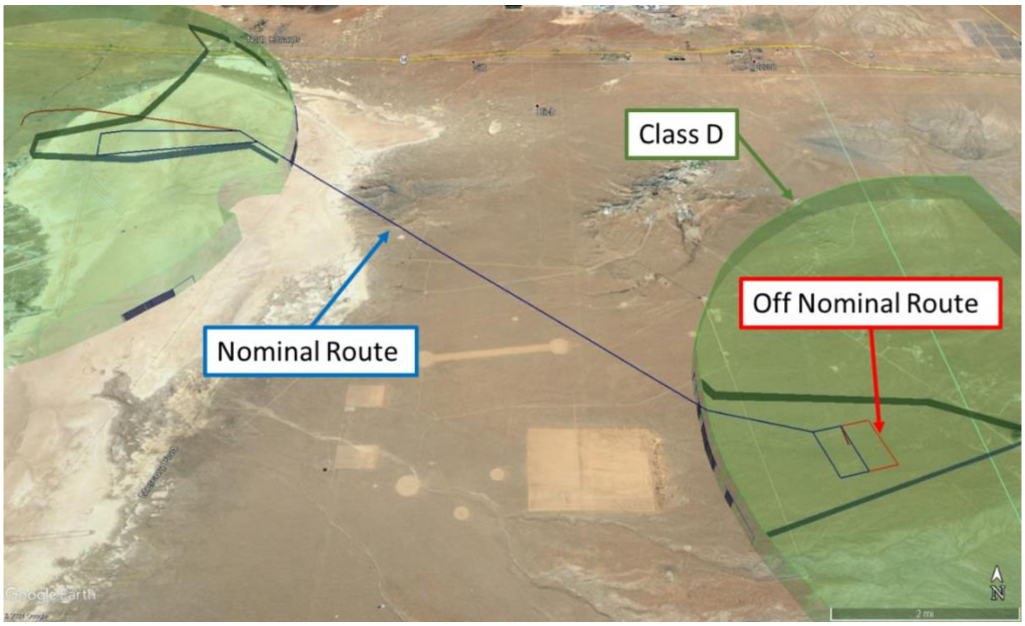

Figure 7 Airspace Adaptation used for X3

Test Approach

The general sequence of test events for a scenario is shown in Figure 8. This sequence was used for each scenario, based on that scenario's test plan. Connectivity and validation tests were followed by functional tests that focused on required functionality for the scenarios. Lastly scenario tests were used for data collection with every partner who was ready and available to test.

Figure 8 X3 Testing Sequence Per Scenario

Validation tests were performed on individual subsystems to exercise the applicable API endpoints without connecting to other subsystems. This approach was based on the testing performed in UTM TCL-4 [8]. The primary focus of the validation test was verifying the expected HTTP response that was returned when the validation criteria identified in the API failed. Only endpoints exercised by a simulated PSU were tested. The FIMS Authorization Server (FIMS-

AZ) Validation Test was developed by NASA. The DSS-USS and USS-USS validation tests were developed jointly by NASA and the airspace partners. These tests included two categories: tests which required an airspace partner operation, and tests which did not. The test that could be run without an airspace partner operation were run routinely. Tests which required an active operation from the airspace partner were run during the connectivity tests at the beginning of a test session.

Connectivity Tests were performed with multiple connected subsystems at the beginning of each test session to ensure that the exchanged data were as expected. In general, this was limited to posting an operation and/or constraint, and not necessarily flying a route. Once the operation/constraint was active, the additional Validation Tests were performed. If the expected data were exchanged successfully during the connectivity test, the functional tests and/or the scenario tests were performed.

Functional tests were intended to be run before the scenario tests as a preliminary assessment of the capabilities needed by the scenario tests. This provided additional confidence that the scenario test would be successful and collected data would be of good quality. The functional tests also exercised capabilities that may not be specifically identified in a scenario test but may be encountered. One example of this was correctly reporting a non-conforming state, which is when an operation goes out of its planned operation volume.

Following completion of the applicable functional tests, the scenario tests were performed. In some cases, all functional tests were not performed leading up to the scenario test. The reasons for not performing functional tests were resource constraints, time constraints or lack of capability. In the event of time constraints, priority was given to the scenario tests. An example of the impact of not performing a functional test prior to the scenario test is provided in the NonConforming Announcement Section of this document.

Schedule

The X3 simulation tests started on July 30, 2020 and completed on December 11, 2020. X3 testing was intended to be as flexible as possible to allow partners with different levels of maturity and capabilities to be able to test at their own pace. To support this, partners were able to test any procedure or capability that was available up until the scheduled end date of the simulation.

Test Configurations

Each test scenario built on the functionality tested in the previous scenario. As a result, the configuration of the system under test evolved with the added functionality. The test configuration was documented for every test procedure that was conducted with the airspace partners. The Scenario 1 configuration included testing with the FIMS-AZ server, Discovery System, Data Collection PSU, and the Data Pipeline. The Scenario 2 configuration included the Scenario 1 configuration, and the Constraint Submitter used for submitting the temporary flight restriction. These capabilities were not included prior to the start of Scenario 1 testing, resulting in the need for additional validation, connectivity, and functional testing for Scenario 2. The Scenario 3 configuration did not add any additional subsystems.

Test Sessions

All airspace partners were allowed to reserve a test session for up to 2 hours, where they would have full access to the designated test area and could run any procedure available to them at that time. Generally, each test session began by running the Connectivity test, followed by the applicable Functional or Scenario test. Results and notes from each test were recorded for the test procedures.

Data Collection Approach

Data were collected throughout the testing and stored in the Data Pipeline Database. All collected data were per the USS-USS API or the Data Collection API referenced in the Requirement Process section. For each of the functional and scenario tests, the Data Collection PSU collected all PSU-to-PSU data models identified in the ASTM API. Data received by the Data Collection PSU were then provided to the Data Pipeline where they were processed for preliminary data validation checks and organized into a database structure before being added to a PostgreSQL database for storage.

Airspace partners also provided additional data models which were not included as part of the USS-USS API. These data models were directly added to the Data Pipeline using the Data API. The Data Pipeline processed the data by performing preliminary data validation checks and organizing those data into a database structure and stored the data in the same PostgreSQL database.

Table 9 includes definitions of data models that were used during X3 and the API used to submit them.

Table 9 X3 Data Model Definitions and applicable APIs

Model	**Applicable API**	**Description**
AuxiliaryOperation	Data API	Operation data which are not specifically included in the operation model, such as actual takeoff / landing times.
ConPreRunOp	Data API	Data regarding planned takeoff and landing locations, including alternate / contingency landing locations.
Constraint	USS-USS API	Details of the airspace constraint. Includes the volume, start time, and end time of the constraint.
ConstraintOccurrence	Data API	Data regarding the enactment of a constraint from the perspective of PSU to operator interaction. Includes the time the PSU is alerted to the constraint, the time the operator is alerted to the constraint by the PSU, and the time the operator responds to the PSU about the constraint.
FlightRunMetadata	Data API	Provides context for the corresponding operation. Includes metadata such as scenario ID, run number, and PSU name.
OffNominalResponse	Data API	Data regarding messages between an operator and a PSU when an off nominal event occurs. Includes the time the operator alerts the PSU to the off nominal event, and the planned response (such as go-around, use alternate landing location, or announce contingent state), and the revised landing location as a result of the event.
Operation	USS-USS API	The information of a planned or active operation. Includes the owning PSU, the state of the operation (e.g. Activated, NonConforming, etc.), the applicable operation volumes, and the version of the operation (used to track updates to the operation volumes/states,etc).
PSUExchange	Data API	Performance and interoperability data for a PSU. Includes the type of request (e.g. operation, constraint, etc.) and method (e.g. Get, Post, etc.), time the request was initiated, time the request was completed, who initiated the request, and the HTTP response. This model was correlated to the operation data received to identify the times at which operations were submitted and/or modified.
VehicleTelemetry	USS-USS API	Vehicle telemetry data at a given timestamp. Includes the position and velocity of the vehicle.

Model	Applicable API	Description
Waypoint	Data API	A single waypoint. When these waypoints are grouped by operation ID, they provide the planned route which will be flown by the operation. Includes the phase of flight (e.g., takeoff, cruise, landing, etc.), target time, and target speed associated with the waypoint.

Metrics

The system requirements, as described in the Requirement Process section, were used in conjunction with the planned scenario test events, as described in the Scenarios section, to identify metrics. Metrics served two main purposes during X3:

1. To assess the success of a given test procedure by identifying if the events expected in the procedure occurred, and if the expected data were received.
2. To analyze the Airspace Partner's ability to perform the capabilities needed by the scenarios.

To support these purposes, 38 metrics were identified, and corresponding SQL queries were developed to access the data stored in the PostgreSQL database, and perform the necessary associations / transformations. Observations from a partial set of these metrics are discussed in the Results section.

Results

The X3 simulation started with eleven NC-DT airspace partners. Out of the 11 airspace partners, nine were able to perform testing with UAM Airspace Simulation Platform. Of those nine airspace partners, seven were able to complete Scenario 1, four of those seven partners were able to complete Scenario 2, and only two were able to complete Scenario 3, as shown in Table 10. The total number of times the scenario test was performed, and the total number of UAM operations flown in that scenario irrespective of their origin and destination was counted along with the Number of airspace partner who participated and is included in Table 10.

Table 10 X3 Airspace Partner Participation

Scenario	Number of Airspace Partners Participated	Total Number of Test Runs	Total Number of Operations Flown
1	9	13	70
2	4	8	39
3	2	4	14

For all the runs of the three scenario tests, metrics were calculated to help understand how the test unfolded, and how the airspace partners interpreted and interacted with the UAM Airspace Simulation Platform. The following sections describe a subset of the metrics. The metrics relied heavily on the PSUExchange data model to provide timestamps for message exchanges / events. If this model was not populated by the airspace partner, or was inaccurate, not all metrics could be calculated.

To maintain anonymity, the names of the airspace partners have been removed in the following sections. For each metric, a result range observed or calculated across all test runs for all airspace partners who participated in the identified test is provided.

Airspace Conformance

Conforming to airspace is an important consideration for UAM. Airspace conformance means that the operations are expected to stay within the boundaries of authorized airspace as well as operational volume. The factors that contribute to airspace conformance include the size of the operational volume and the awareness of the authorized airspace, this will have an effect on how future airspace structures like corridors are defined and disseminated. For X3, every airspace partner received the definition of the airspace via a set of adaptation files for each scenario as described in the Airspace Definition section. With this information, the airspace partners planned their own operations to conform to this airspace.

Size of Operation Volumes

Operation volumes were used in UTM and continued to be used for UAM operations in X3. Design of UAM volumes is not standardized, and the airspace partners were allowed to design them based on the simulated or intended vehicle performance. The size of the volume has an impact on conformance monitoring and performance requirements for the vehicle. Generally, conformance to a larger volume is easier than conformance to a smaller volume but may impose constraints on surrounding airspace availability.

Figure 9 shows three operations from three different airspace partners. The sizes for the volumes shown in Figure 9 (separated by horizontal size, vertical size, and volume duration) are shown in Table 11.

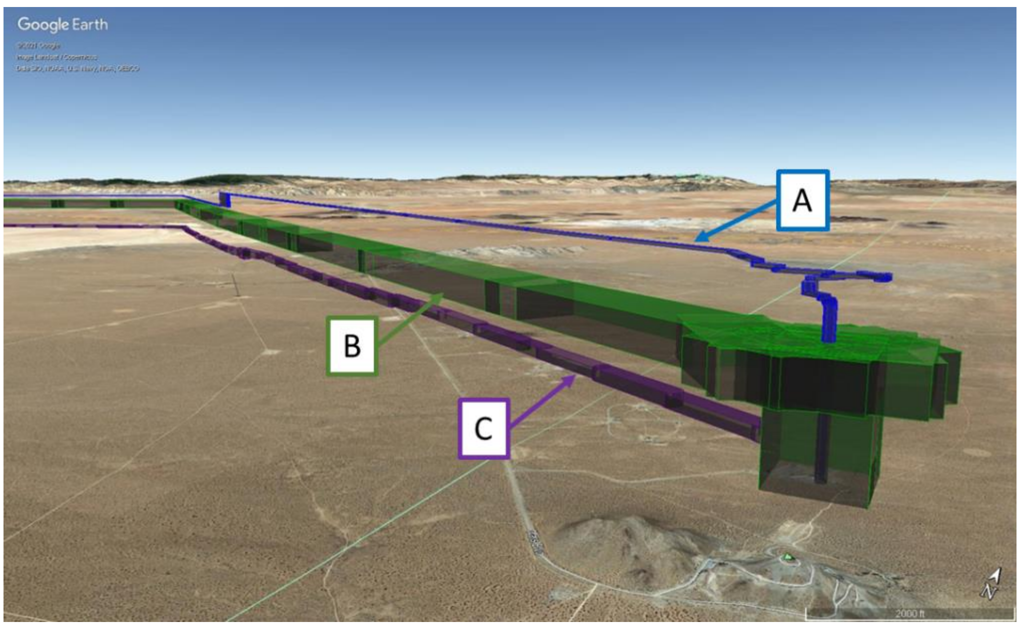

Figure 9 Operation Volumes for different airspace partners

Table 11 Operation Volume Sizes

Operation (Color)	Min Horizontal Size (ft^2)	Max Horizontal Size (ft^2)	Min Vertical Size (ft)	Max Vertical Size (ft)	Min Duration (s)	Max Duration (s)
A (Blue)	6,384	172,188	49	2411	45	142
B (Green)	525,269	3,794,084	656	2755	20	83
C (Purple)	54,770	269,120	200	557	7,200	7,200

Despite the differences in sizes between A (blue) and B (green) operation volumes, the corresponding PSUs supported five concurrent operations with no volume intersections with other operations along the route. This was primarily a result of the short volume durations. The C (purple) operation may have similarly been able to support multiple operations. However, the duration of C's operation volumes was 2 hours, which caused time overlaps of the volumes between operations.

Figure 10 shows the size of the volumes of new operations near a vertiport location. It was observed that the size of operation volumes in some cases were large enough to encompass multiple vertipads. As seen in Figure 10, the last volumes of the operation were large enough to encompass both the 'KGKY-a' and 'KGKY-b' landing pads, which were separated by approximately 230 feet.

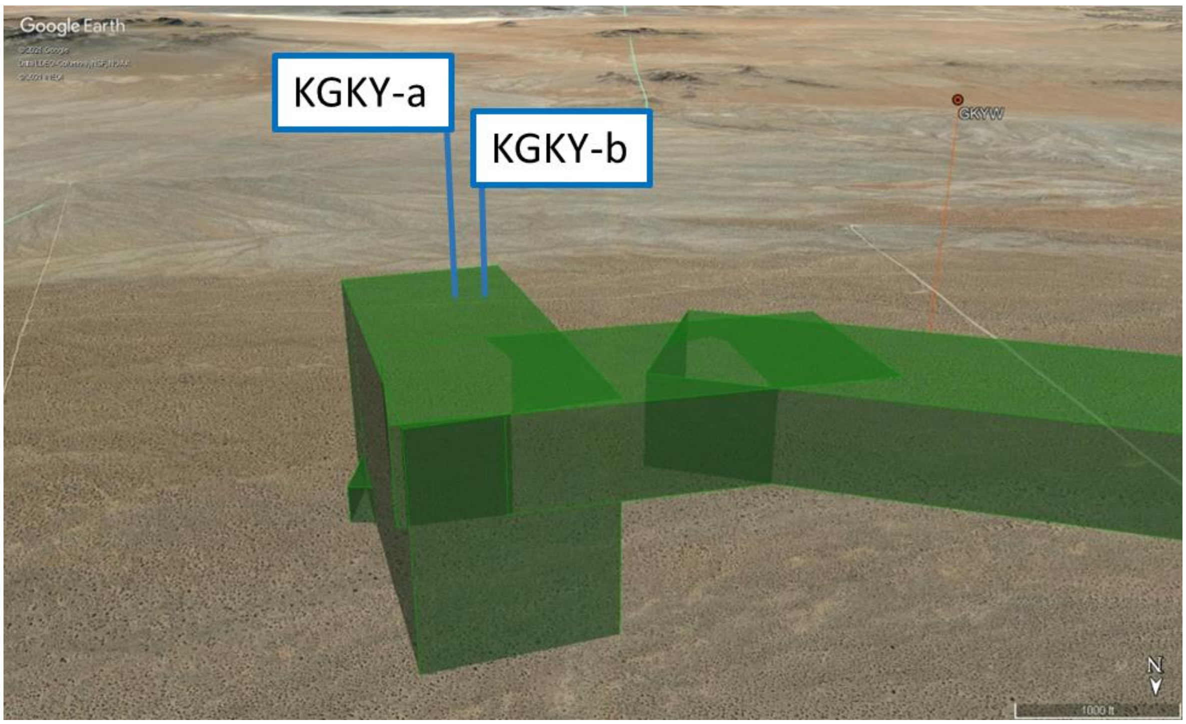

Figure 10 Operation Volumes Near Vertipad

Additional requirements regarding volume sizes and use of the volumes by multiple vehicles operating concurrently in the same airspace is required. Additional requirements are also be needed to further define the size of an operation volume over a vertipad or an increase the spacing between vertipads.

Operations Near Class D Airspace

Metrics used to assess airspace conformance relative to the defined UAM and Class D airspace are included in Table 12. These metrics evaluated the operation volumes provided by the airspace partner via the PSU-PSU API and compared them to the airspace definitions in the adaptation files. In cases where multiple operations are compared to each other, only pairs or operations with versions that had overlapping active time ranges were used. The active time ranges were determined using the PSUExchange data, where the start of the range was the time the version was announced, and the end time was the time the next sequential version was announced.

Table 12 Airspace Conformance Metrics

#	Description	Result Range among partners
1	Percent of operations in a test run with active volumes per UAM Airspace concurrently.	Scenario 1: Not Applicable Scenario 2: 0% to 100% Scenario 3: 0% to 40%
2	Percent of operations in a test run with active volumes per UAM Route concurrently.	Scenario 1: 50% to 100% Scenario 2: 60% to 100% Scenario 3: 100%
3	Percent of operations in a test run where all waypoints for a route are contained within operation volumes.	Scenario 1: 50% to 100% Scenario 2: 80% to 100% Scenario 3: 100%
4	Percent of operations in a test run that submit updated operation volumes which contain updated route waypoints.	Scenario 1: Not Applicable Scenario 2: 60% to 100% Scenario 3: 20% to 100%
5	Percent of operations in a test run with active volumes outside of UAM Airspace and within Class D airspace.	Scenario 1: Not Applicable Scenario 2: 0% to 100% Scenario 3: 0% to 100%

For each run of Scenario 1 and 2, a total of five operations were required on the route concurrently. Scenario 3 required a minimum of two concurrent operations. Scenario 2 and Scenario 3 required the partners to re-plan their operations and utilize the provided reroute. In general, the airspace partners were able to meet these requirements, as seen by the frequent upper range of 100% in the metric results in Table 12.

It was observed that some airspace partners did not conform to the UAM airspace inside Class D as shown by lower range of 0% for metric #5 in Table 12. These operations entered the Class D airspace above the UAM airspace as shown in Figure 11.

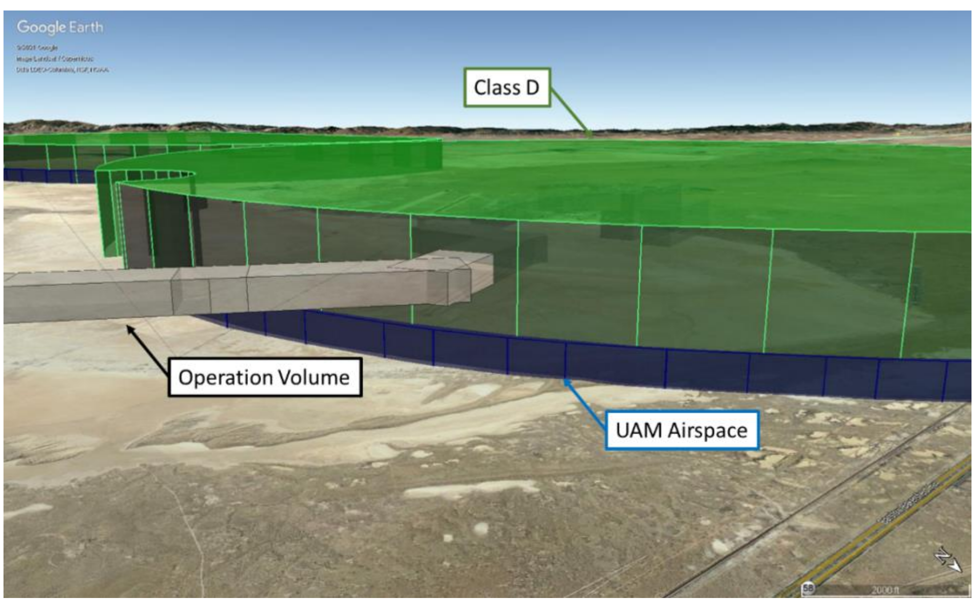

Figure 11 Operation Volumes in Class D Airspace

The operation volume in Figure 12 is entering the Class D airspace (green area) instead of the expected UAM Airspace (blue area). Several factors potentially contributed to this, including difficulty parsing the KML files, and not considering the separate airspace definition files that were provided in their entirety. In the future, a service that provides adaptation data to PSUs could be designed so that the operators have access to all the information in one place and updates to the adaptation are well managed.

Operations submitted by airspace partners conformed to the UAM Airspace horizontally, as this conformance was factored into the design of the routes that were provided by NASA as shown by Figure 13. In this case, the route was designed to have adequate separation from the edge of the UAM Airspace to allow the operation volumes to be well separated. Separation from the edge of the UAM Airspace also needs to be considered when planning contingency operations within the UAM Airspace, such as a go-around. While the exact route into and through the UAM Airspace was provided for X3, if this is not provided in future tests, additional requirements for operation volumes within the UAM Airspace may be needed. Additional requirements for how to manage operations in UAM airspace may also be needed to ensure that they do not enter other classes of airspace. Exploration of 4D trajectories instead of volumes is also suggested especially if pre-defined routes are not designed in UAM airspace.

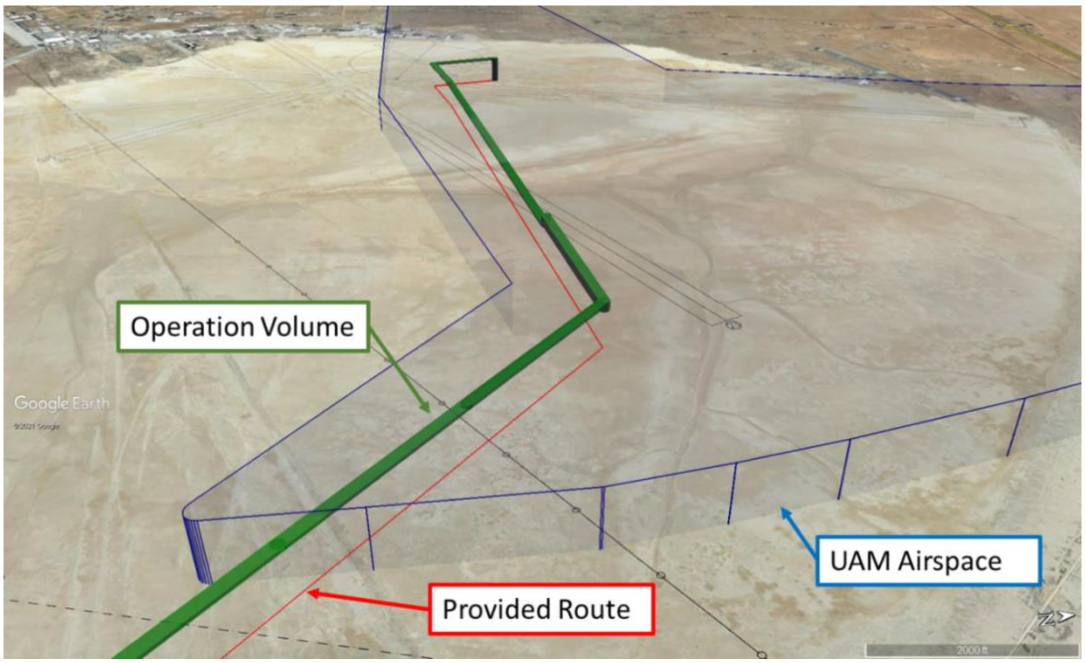

Figure 12 Operation Volumes in UAM Airspace inside Class D

Submissions to DSS

The DSS enables a PSU to identify other PSUs with active operations or subscriptions in an area of interest. In order for an operation to be accepted by the DSS, the submitting PSU must prove that it is aware of the other operations in the airspace at the time the operation is submitted. This is done using an Opaque Version Number (OVN) which is assigned to the operation version when it is accepted by the DSS. Figure 13 shows a general depiction of the events around the initial submission of an operation, relative to the OVN, as they were understood for X3. This figure assumes that the PSU has no knowledge of the airspace prior to submitting the operation.

Prior to submitting an operation, the PSU would query the DSS for all operations in the area (indicated by the 'POST operation_references' line), then contact the owning PSU of the returned operations (indicated by the 'GET operations' line) to obtain the applicable details, such as operation volumes and OVN. With those details, the PSU could then submit its operation to the DSS with the list of received OVNs (indicated by the 'PUT operation_references' line). If the list of OVNs matched the list held by the DSS at that time, then the DSS accepted the operation. DSS played an important role in identifying potential operational conflicts.

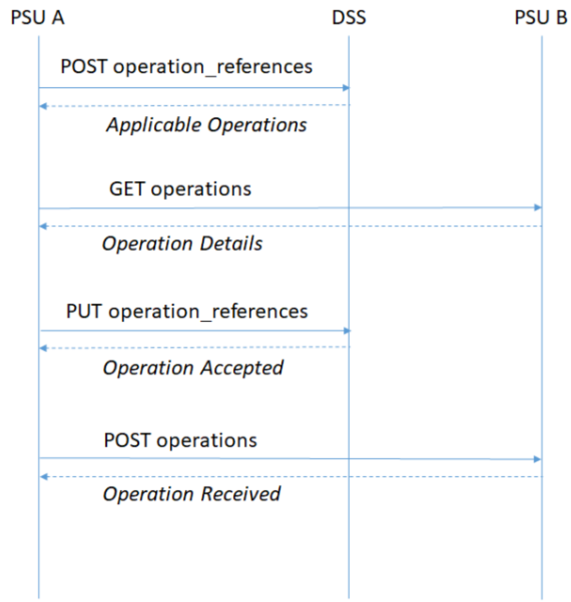

Figure 13 Steps in Operation Submission to DSS

Overlapping Operation Volumes

Metrics used to identify operation intersections are included in Table 13. These metrics compared the operation volumes provided by the airspace partner via the USS-USS API to other operations in the airspace. For X3, all operations in the airspace belonged to a single PSU in a given test run. Only operation pairs with versions that had overlapping active time ranges were compared. In these metrics, ‘intersect’ means that the volumes shared a portion of the same horizontal and/or vertical space at the same time.

Table 13 Operation Intersection Metrics

#	Description	Result Range
1	Percent of operations in a test run, at the time of submission, with 4D volumes that intersect the 4D volumes of another UAM operation that is already active.	Scenario 1: 0% to 100% Scenario 2: 0% to 80% Scenario 3: 0%
2	Percent of operations in a test run whose 4D volumes intersect the 4D volumes of another UAM operation at any time during the operation	Scenario 1: 0% to 100% Scenario 2: 0% to 100% Scenario 3: 0%

When the 'PUT operation_references' is performed, per the ASTM API [6], the operation was expected to be "deconflicted from all relevant features in the airspace." Based on that statement, NASA gave its airspace partners a requirement for operations to not intersect the 4D volumes (i.e., share the same space) of other operations. As can be seen in the results of the Table 13 metrics, some airspace partners met this requirement and had zero overlapping operation volumes. While this requirement was based on the description in the API, it was not a validation check performed by the DSS, as it was an 'expectation' that the PSU would perform this check. If an operation proved to the DSS that it was aware of the other operations in the airspace (via the provided OVN values), the operation would be accepted by this DSS implementation, regardless of the possibility that the operation intersects with other operations. This can also be seen in the results of the Table 13 metrics where some airspace partners had operations with intersecting operation volumes. These overlaps between operation volumes occurred for varying reasons.

One occurrence was during a test of Scenario 2, where the airspace constraint was announced in a way that it did not impact all operations. As a result, the impacted operations re-planned to reduce speed and join the route around the constraint. The last operation was not impacted by the constraint and continued to fly its original route at its original speed. The unimpacted operation proceeded to pass the impacted operations at the same altitude. In this example, the operation re-plans were created by the PSU, and accepted by the DSS under the expectation that they were deconflicted, even though they were not. Similar issues regarding assumed operation deconfliction and re-plans due to airspace constraints were observed during UTM TCL-4 testing [7].

Another series of occurrences was due to airspace partners having their own business logic for how to manage their operations in the systems using the defined APIs. They may have alternate means to deconflict their own operations internally, and not require non-overlapping volumes. This is allowed by the DSS, as 'deconflicted' is not fully defined, and can be interpreted multiple ways.

Additional requirements regarding the definition of 'deconflicted' and right-of-way among UAM operations is needed for future testing.

Constraint Response

Operations faced with a constraint needed to re-plan to avoid the constraint and potentially de-conflict with other operations. Metrics used to identify operation volume intersections in Scenario 2 and Scenario 3, in which a constraint was submitted, are included in Table 14. These metrics compared the operation volumes provided by the airspace partner via the USS-USS API to the announced airspace constraint. In addition to the volumes, the PSUExchange model provided by the airspace partner PSU was used to identify the time at which the operation version changes occurred as compared to the time the Constraint was announced, and the number of exchanges to both the DSS and the Data Collection PSU. If the PSUExchange model was not provided for a test run, that run was not included in the Table 14 results. Note that in Scenario 3, not all operations were expected to be impacted by the Constraint.

Table 14 Constraint Response Metrics

#	Description	Result Range
1	Percent of operations in a test run that intersect a Constraint 4D Volume and were airborne before the Constraint start time.	Scenario 1: Not Applicable Scenario 2: 60% to 100% Scenario 3: 40% to 67%
2	Percent of operations in a test run with 4D volumes that intersect the 4D volume of a Constraint.	Scenario 1: Not Applicable Scenario 2: 60% to 100% Scenario 3: 40% to 67%
3	Percent of operations in a test run with volumes that intersected the Constraint 4D Volume at the time of the Constraint announcement that re-plan to avoid that Constraint.	Scenario 1: Not Applicable Scenario 2: 60% to 100% Scenario 3: 40% to 67%

During the Scenario 2 functional test, an airspace partner initially tried to re-plan all operations at the same time when the constraint was announced. When this happened, the first operation was accepted but the other operations were rejected by the DSS. This appeared to be because the other operation exchanges submitted to the DSS did not include the OVN for the newly accepted operation re-plan. There were several possible ways to correct this behavior.

One possibility was to add a several second delay between each of the exchanges with the DSS to stagger the change to the new route. This solution will not be scalable when there are multiple PSUs operating in the airspace at the same time, as there will be less ability to coordinate the re-plans using the current architecture. When an operation is rejected due to the provided OVNs, the HTTP response from the DSS indicates that "the provided key did not prove knowledge of all current and relevant airspace Entities" [6]. Using this error response, another approach would be to re-perform the operation requests to get the updated OVNs as identified earlier in this section. This approach, however, would still lead to additional race conditions, albeit with fewer operations, until all operations were eventually able to successfully re-plan.

Additional requirements may be needed to handle events where multiple operations re-plan simultaneously or provide additional detail on when a re-plan due to a constraint should occur since constraints are generally announced by regulatory authorities with a lead time.

NonConforming Announcement

Metrics used to identify vehicle non-conformance to an operation plan are included in Table 15. These metrics compared the provided vehicle position data (including the location at a timestamp) to the corresponding volumes for that operation. The vehicle position was only compared to the volumes of the operation version that was active at that time. The PSUExchange model was used to identify the time ranges for each operation version. To be within a volume, the vehicle position data needed to be both horizontally within a volume's polygon and vertically within a volume's altitude range, as well as temporally within a volume's time range. Included in the Operation model was a State property for a PSU to indicate if its vehicle is NonConforming.

Table 15 NonConformance Metrics

#	Description	Result Range
1	Percent of operations in a test run with Vehicle Telemetry data that is outside of an operation volume (i.e., not conforming throughout the entire operation).	Scenario 1: 0% to 100% Scenario 2: 0% to 100% Scenario 3: 0%
2	Percent of operations in a test run that announce a NonConforming state.	Scenario 1: 0% to 60% Scenario 2: 0% to 20% Scenario 3: 0%

The scenarios expected all operations to remain conforming to their plans for the entire operation. The scenario tests did not specifically force a NonConforming state to occur, but conformance was monitored by NASA at all times during the tests. Per the API definitions, the NonConforming state was announced when the operation left its volume spatially or temporally. Data used in this analysis showed a small number of operations that inadvertently left their volumes; thus, these data were available from a limited number of partners and is anecdotal in nature.

For one airspace partner, vehicle telemetry was only inside the volumes briefly at the beginning of the operation, then it was ahead of the volume for the remainder of the flight. The vehicle was identified as out of its volume as shown by metric #1 in Table 15. Even though the telemetry data were outside of the volume, the operation never reported as NonConforming as calculated by metric #2 in Table 15. As part of the functional testing leading to the scenario tests, there was a procedure to test a partner's ability to announce a NonConforming state after commanding the vehicle to leave its volumes. This capability (commanding a vehicle to leave its volume) was not specifically included as part of the scenario tests and, as a result, was not implemented and/or not tested by all partners. It is recommended that future events test the NonConforming state of the operations prior to proceeding into data collection.

During a Scenario 2 test when the operation re-plan occurred, a single position message was outside of the new operation volume for several operations. In these cases, there was minimal overlap in time or volume before and after the re-plan. There was also a potential time difference between when the PSU considers its operation updated (i.e., when it was received and accepted by the DSS) to when other PSUs in the network receive / are aware of the update. Due to these factors, the position may have been within a volume from the perspective of the PSU but outside of the volume by the time the Data Collection PSU was aware of the new volumes. According to the ASTM protocols and specifications used in this test, the operation was conforming to its plan. However, there was no process available for another PSU to validate the conformance using the specification, because there were no synchronized timestamps indicating the start of a modified operation plan. Additional requirements to provide timestamps for an operation and its updates may be needed in future.

In another Scenario 2 test, an airspace partner encountered an issue when their operation re-plans were rejected by the DSS. The simulated vehicles for the operations which failed to re-plan continued to fly the expected re-plan route, even though it wasn't accepted by the DSS, resulting in the operations becoming NonConforming. If these operations continued to fly the original route, the operations would have flown through the airspace constraint. The resolution of this issue may be related to how operations re-plan as a result of a constraint injection.

Summary

NASA's UAM SP under ATM-X project has been investigating UAM operations over the last few years. The first experiment- X1 that explored DFW operations under the current day air traffic management paradigm and found that UAM operations are not scalable due to air traffic control workload. The X2 simulation researched using UTM paradigm for UAM operations and how advanced services would be utilized for UAM operations with one industry partner. As part of X3, the UAM Sub-Project (SP) conducted initial lab simulations with NC Developmental Testing (NC-DT) airspace partners to evaluate and demonstrate their capabilities and components prior to NC flight activities. As part of this effort, the UAM SP facilitated the connection for nine NC-DT airspace partners to the UAM Airspace Simulation Platform.

Out of the 11 original airspace partners, nine were able to perform testing with UAM Airspace Simulation Platform. Of those nine airspace partners, seven were able to complete Scenario 1, four of those seven were able to complete Scenario 2, and two of those four were able to complete Scenario 3. Requirements for running the three NC scenarios were provided to the airspace partners and testing spanned several months. A single airspace partner tested using the UAM Airspace Simulation Platform at any given time. All seven airspace partners were able to run at least the five concurrent operations as required by the simulations.

The testing provided insights into how the operations were able to conform to the requirements of the airspace. For instance, many operations flew within the horizontal boundaries of the UAM airspace but exited the vertical boundaries and entered controlled airspace. In the real world, this would have implications for contacting ATC since the operations were in the positively controlled environment. It was also observed that there is no standardization for operation volumes design, some airspace partners created large volumes and others made them really small. The size of the volume has an effect on the conformance of the volumes as was also found in X2 studies [4]. It is suggested that usage of 4D trajectories and standardization of volumes for the operations should be explored for future tests related to UAM operations. Another insight related to rejection of an operation re-plan by the DSS while in flight. This could lead to operations becoming 'NonConforming', especially if the re-plan was to avoid an airspace constraint. These insights have been valuable and will aid in building rigorous requirements for future tests and simulations planned for NC in pursuit of preparing the airspace partners for future flight tests. The next series of tests will focus on information exchange requirements between different UAM actors and new airspace structures like corridors for UAM operations.

References

1. UAM Vision Concept of Operations (ConOps) UAM Maturity Level (UML) 4 | *1.0.* Retrieved March 18, 2021, from https://ntrs.nasa.gov/api/citations/20205011091/downloads/UAM%20Vision%20Concept%20of%20Operations%20UML-4%20v1.0.pdf
2. Concept of operations v1.0 Urban Air Mobility (UAM). Federal Aviation Administration, Washington, D.C., 2020.
3. Verma, S.; Keeler, J.; Edwards, T. & Dulchinos, V. (2019). Exploration of Near-term Potential Routes and Procedures for Urban Air Mobility. 19th AIAA Aviation Technology, Integration, and Operations Conference. 17th June 2019, Dallas, Texas
4. Verma, S. A., Monheim, S. C., Moolchandani, K. A., Pradeep, P., Cheng, A. W., Thipphavong, D. P., … Wei, B. (2020, October 1). Lessons Learned: Using UTM Paradigm for Urban Air Mobility Operations. DASC 2020. https://doi.org/10.1109/DASC50938.2020.9256650
5. Concept of Operations v2.0 Unmanned Aircraft System (UAS) Traffic Management (UTM). Federal Aviation Administration, Washington, D.C., 2020.
6. ASTM API: https://github.com/nasa/uam-apis/blob/master/datacollection/nasa-astm-utm.yaml
7. Rios, J. et.al. (2020) Strategic Deconfliction Performance: Results and Analysis from the NASA UTM Technical Capability Level 4 Demonstration.
8. Smith, I., Rios, J., Mulfinger, D., Baskaran, V., Verma, P., "UAS Service Supplier Checkout: How UTM Confirmed Readiness of Flight Tests with UAS Service Suppliers," NASA TM–2019–220456, December 2019.

Acronyms

AAM	Advanced Air Mobility
API	Application Programming Interface
ASTM	formerly known as American Society for Testing and Materials
ATC	Air Traffic Control
ATI	Airspace Test Infrastructure
ATM-X	Air Traffic Management - eXploration
Conops	Concept of Operations
DSS	Discovery and Synchronization Service
DT	Developmental Test
eVTOL	electric Vertical takeoff and Landing
FAA	Federal Aviation Administration
FIMS AZ	Flight Information Management System – Authorization Server
HTTP	Hypertext Transfer Protocol
IFR	Instrument Flight Rules
KML	Keyhole Markup Language
LOA	Letter of Authorization
NAS	National Airspace
NC	National Campaign
OVN	Opaque Version Number
PSU	Providers of Services for UAM
SQL	Structured Query Language
SP	Sub-Project
TBD	To Be Determined
TCL-4	Technical Capability level- 4
TG	Target Generator
UAM	Urban Air Mobility
UAS	Unmanned Aircraft System
UML	UAM Maturity Level
UOE	UAM Operational Environment
USS	UAS Service Supplier
UTM	UAS Traffic Management
UVR	UAS Volume Reservation
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions
WGS	World Geodetic System