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Enabling UTM Airspace Equity Using an Agent-Based Model

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1 Executive Summary

This report describes the “Enabling UTM Airspace Equity Using an Agent-Based Model” project, which aimed to develop insights and recommendations for managing uncrewed aircraft systems (UAS) operational capacity and ensuring equitable prioritization in the future UAS airspace. We developed an integrated UAS simulation framework (iUSF) that included services for submitting flight intents, disseminating information, and resolving flight planning conflicts. We demonstrated the iUSF in a series of live flight demonstrations to address the effect of prioritization of operations, segmentation of operational volumes, airspace constraints, and conflict resolution protocol on the overall system. We also executed high-capacity simulations using scenarios with a high density of flights and a high tempo of operations. We found that using a tiered prioritization scheme for operations enabled higher priority flight intents to be more successfully scheduled than lower priority flights. The use of a lottery-based conflict resolution protocol (versus a first filed first served (FFFS) protocol) and the allowance of segmented operational volumes reduced overall system delays and conflicts, but the operational effects of these practices in other scenarios still need to be evaluated. The results from the high-capacity simulations using scenarios with a high density of flights and a high tempo of operations demonstrated an average increase in canceled intents of 15 percent and an average decrease in replanned intents of 22 percent when using FFFS with priority. However, as alternative methods were applied, further reductions in replanned and canceled intents followed. Finally, we also compiled lessons learned regarding the use of demonstrations (live and simulated) to validate and employ technologies such as the iUSF. Overall, the iUSF and similar technologies are crucial tools for the Federal Aviation Administration (FAA) and UAS Traffic Management stakeholders to forecast and plan for the complexities of a denser future UAS operational environment. The influence of this work extends to enhancing the safety, efficiency, and fairness of UAS flight planning, thereby supporting the FAA in planning for the widespread integration of UAS into the National Airspace System.

2 Introduction

To prepare for increases in demand for uncrewed aircraft systems (UAS) operations, the Federal Aviation Administration (FAA) and industry stakeholders are preparing for the future of a higher density UAS airspace. As technology matures to support a diverse range of UAS operators and applications, the challenges in regulating efficient and equitable use of a more congested operational environment become more apparent.

The UAS community is exploring new methods for managing these challenges with concepts such as UAS Traffic Management (UTM). Recent efforts, such as the UTM Field Tests [1], work in the ASTM International Committee F38 on UAS [2], and lessons from ongoing activities (e.g., the Dallas UTM Key Site [3]) seek to provide guidance, standards, and use cases to ensure a safe and equitable future UAS environment. However, guidance regarding how UAS flight intents should be prioritized and deconflicted is pending and requires further exploration.

2.1 Purpose of Work

The purpose of this project was to develop insights and recommendations into UAS operational capacity management and equitable prioritization through the maturation and demonstration of an integrated UAS simulation framework (iUSF) for UAS flight planning operations.

2.2 Project Team

This project was a collaboration between CNA, the Alaska Center for UAS Integration (ACUASI), ATA Aviation (ATAA), and the FAA. The project team members and their roles and responsibilities are summarized in Table 1.

Table 1 Project team and roles

Team Member	Roles
CNA 	Nonprofit research and analysis organization that provides project management and simulation capabilities for UAS flight planning and has experience supporting government use of UAS.
ACUASI 	FAA UAS Test Site that manages and coordinates the flight-testing facilities at the University of Alaska Fairbanks.
ATAA 	FAA Low Altitude Authorization and Notification Capability (LAANC) UAS Service Supplier (USS) and a public Supplemental Data Service Provider (SDSP) with experience integrating aviation data and field deploying systems.
FAA 	Project sponsor that provides feedback and direction and coordinates engagement with the ASTM F38 standards body committee.

2.3 Project Objective

This project consisted of four objectives:

- 1) Expand the UAS Cooperative Airspace Traffic Simulation (UCATS™) technology to include various operation types and conflict resolution protocols.
- 2) Align the technology with ASTM standards for USS operational intent data inputs.
- 3) Validate the technology through test scenarios and demonstrations using realistic data.
- 4) Develop recommendations and highlight key outcomes for the FAA to share with industry standards bodies.

To satisfy the first two objectives (“Expand and align technology”), we developed the iUSF solution, which integrates three mature components:

- 1) ATAA’s Beeline™, a UAS USS flight planning and compliance tool that provides an interface and flight planning services for UAS operators.
- 2) ATAA’s AirDEX™, a supplemental data service provider tool that supports ASTM F3548-21 Standard Specification for UTM USS Interoperability and provides three-dimensional geospatial visualization capabilities.
- 3) CNA’s UCATS, a simulation tool that provides conflict resolution capabilities.

We updated these components to support multiple operation types, different conflict resolution methods, and other key concepts that we defined. The components exchange Operational Intent and Constraint data models as defined by ASTM F3548-21 [2] using application programming interfaces. A conceptual view of the iUSF is shown in Fig. 1.

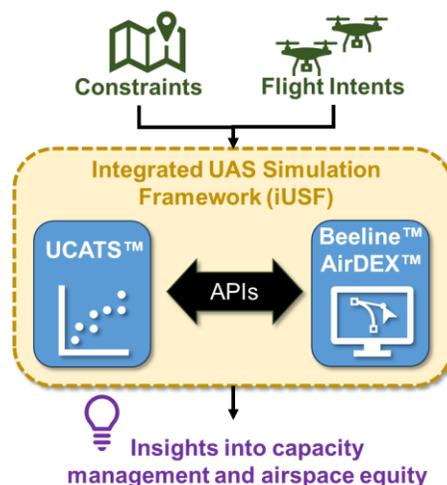


Fig. 1 iUSF conceptual view.

For the third objective (“Validate technology”), we developed a series of test scenarios to address our defined key concepts around airspace capacity management and prioritization. We evaluated these scenarios using both live flight demonstrations and fully simulated demonstrations. The live demonstrations allowed us to (1) evaluate the realized effect of flight intent conflicts and replanning on operators’ ability to complete mission objectives and (2) assess the iUSF’s system performance. The simulations allowed us to evaluate key concepts in high-capacity scenarios.

We designed the iUSF as a full-cycle framework that can assess a variety of UAS flight planning scenarios. Fig. 2 shows the roles of each iUSF component in the live flight demonstrations.



Fig. 2 Roles of each iUSF component.

We met the final objective (“Develop recommendations”) by compiling the lessons learned and findings from the live flight demonstrations and simulations. We provided insights on how systematic implementation of key concepts may affect airspace capacity management and prioritization. We also provided recommendations on the use of live flights and simulations as validation exercises for technologies such as the iUSF.

2.4 Background

Because the demand for and the variety of UAS operations are expected to increase, the FAA and industry stakeholders recognize the connected challenges of capacity management and equitable prioritization for the future UAS ecosystem. Stakeholders also understand the importance of creating viable policies and guidance that can successfully implement UTM into the current National Airspace System (NAS) to address these challenges. The FAA has already taken steps to research and demonstrate implementation methods, showing its intent to be a leading organization in the UTM community. The agency discussed plans for policy and regulation in the 2023 FAA UTM Implementation Plan [4]. The FAA intends this plan to be the blueprint to ensure the implementation of safe, secure, and operable beyond visual line of sight (BVLOS) operations.

Under UTM, the FAA will set the “rules of the road,” but operators and third-party UAS service providers will be responsible for coordinating, executing, and managing operations [5]. With the decentralization of UTM, competing operators must collaborate to ensure equitable access to the airspace for everyone. The FAA and UTM community must ensure that UTM is implemented safely and equitably, despite the varying interests and business needs among operators. Future operators will encompass both private and public entities, the latter of which include public safety agencies, first responders, and others carrying out critical operations. These missions should be prioritized above less urgent operations to ensure the timely and successful delivery of critical services to the public.

Existing literature on how UAS operations should be planned, prioritized, and deconflicted has gaps that require further exploration. In addition, UTM work to date has focused on basic exploration of systems and the operational integration among cooperative, participating traffic in a relatively low-density, low-tempo environment. Operators manually resolve conflicts in these environments for live flights on a case-by-case basis (e.g., as exhibited in the Dallas UTM Key Site). Limited work has placed the FAA’s current UTM approach under strain in the “real” world to determine what emergent behaviors could be expected.

In 2023, CNA developed the UCATS prototype to investigate UAS airspace equity and provide insight into future decision-making regarding UTM [6]. Using an agent-based modeling approach, UCATS focuses on simulating the UAS flight planning process and its effects on UAS flow and capacity management and equitable airspace access for UAS operators as they participate in the NAS. In a previous study, we used UCATS to evaluate airspace fairness for package delivery operators in a congested UAS environment [7]. As a modeling tool, UCATS can evaluate the effect of flight intent parameters (e.g., file-ahead time, departure time, and delay tolerance) on the outcome of the flight plans (e.g., canceled, replanned, accepted as-is).

To help the FAA enhance its ability to analyze UAS airspace capacity and ensure equitable airspace access, we expanded the capabilities of UCATS in this project. Our team integrated UCATS with other UAS planning systems from our partners to create a new simulation framework called the iUSF. We then demonstrated the framework in a series of live flight campaigns and simulations.

3 Methodology

3.1 Approach

We designed this project to answer five research questions related to UAS operational capacity management and equitable prioritization:

- 1) What effect will a tiered prioritization schema have on ensuring that higher-priority operators achieve mission objectives?
- 2) What effect will a tiered prioritization schema have on allowing lower-priority operators to achieve mission objectives?
- 3) What effect does partitioning an operational intent into discrete segments have on the rate of conflict and rate of nonresolvable conflict?
- 4) What effect does varying conflict resolution protocols have on the rate of conflict and rate of nonresolvable conflict?
- 5) What effect do UTM externalities represented by constraints have on the rate of conflict and the rate of nonresolvable conflict?

Our research questions addressed how conflicts in UAS flight planning are affected by four key concepts: tiered prioritization schema, operational intent segments, conflict resolution protocols, and constraints. We developed the iUSF solution to support the evaluation of these questions and designed test scenarios implementing combinations of the key concepts to evaluate the specific effects on rate of conflict and successful resolution for each key concept. These test scenarios were demonstrated in a live flight campaign and through high-capacity simulations.

3.2 Terminology

A *flight intent* refers to the UTM concept that participating operators will communicate key information about an intention to operate (e.g., operational volume, active flight times, priority). In this project, a flight intent can have three states:

- 1) *Filed*, which means that the operator has submitted an intent to the AirDEX SDSP through the Beeline USS tool, but the intent has not been scheduled (i.e., accepted without conflict or conflict resolved).

- 2) *Scheduled*, which means that any conflicts with existing intents have been successfully resolved by UCATS and the flight intent is discoverable by other USSs. After conflict resolution, a scheduled flight intent is considered:
 - a) *As planned* if the scheduled intent is identical to the filed intent.
 - b) *Replanned* if the scheduled intent is different to that of the filed intent (e.g., the flight has been delayed).
- 3) *Canceled*, which means the filed intent was not successfully scheduled (e.g., because of nonresolvable conflicts).

The term *live flight* refers to the actual flight intent that is followed by the test flights in the live demonstration. The live flights may differ from the scheduled flights because of unforeseen test site conditions and operations.

A *conflict* occurs when the operational volume of a flight intent overlaps in time and two-dimensional space with the operational volume of another flight intent (see Fig. 3). We assumed that a submitted flight intent cannot be accepted by the flight planning system if it causes a conflict. Instead, one of the flight intents in conflict must be replanned before the submitted flight intent is accepted; conflict resolution through altitude separation is not allowed. In addition, only strategic conflict resolution of flight intents is considered (i.e., adjustments made in the flight planning phase). Tactical deconfliction of live operations (i.e., adjustments made in the airborne flight phase) is out of scope.



Fig. 3 Illustration of conflict (red) between two flight intents (green rectangular boxes).

In this project, there are two types of conflicts:

- 1) *Resolvable* conflicts can be successfully resolved and all flight intents involved can be scheduled (and not canceled).
- 2) *Nonresolvable* conflicts cannot be successfully resolved, and one flight intent is canceled.

3.3 Key Concepts

3.3.1 Tiered prioritization schema

To categorize the range of future UAS operations, we defined the tiered prioritization schema shown in Table 2 in order of lowest (0) to highest (3) priority. The schema has four levels of self-declared priority and is based on discussions and experience at the Dallas UTM Key Site. If two flight intents are in conflict, the flight intent with a higher priority takes precedence, and the flight intent with a lower priority must be replanned. We assume that public and public safety operations will file flight intents before departing. In addition, emergency operations will not require existing airborne flights to exercise tactical adjustments and must not conflict with ongoing flight operations.

Table 2 Tiered prioritization schema

Priority Level	Description	Safety Impact	Scheduling Flexibility	Examples
0—Base	Nonurgent, low-risk operations	None	Maximum	<ul style="list-style-type: none"> • Package delivery • Routine data collection
1—Inspection	Routine critical infrastructure inspection operations that are important for public safety or service continuity but not time sensitive	Minimal	Moderate	<ul style="list-style-type: none"> • Bridge inspection • Power lines inspection • Pipeline inspections
2—Mission	Critical operations involving public safety that are time-sensitive responses but do not require immediate action	Moderate	Minimal	<ul style="list-style-type: none"> • Oil spill monitoring • Critical infrastructure damage assessment
3—Emergency	Critical, high-risk operations involving public safety that are emergencies and require more immediate action	Major	None	<ul style="list-style-type: none"> • Wildfire monitoring • Search and rescue

3.3.2 Operational intent segments

For this project, flight intents are defined by a set of airspace volumes, each characterized by start and end times. As described earlier, conflicts are identified when the volumes from one or more flight intents intersect in both time and space, indicating an overlap in flight intents. To improve airspace use efficiency, we tested the effect of dividing volumes into three segments to reduce the chance of conflict, as seen in Fig. 4.

- 1) Segment 1: Flight from takeoff to target site
- 2) Segment 2: Task at target site
- 3) Segment 3: Flight from target site back to landing

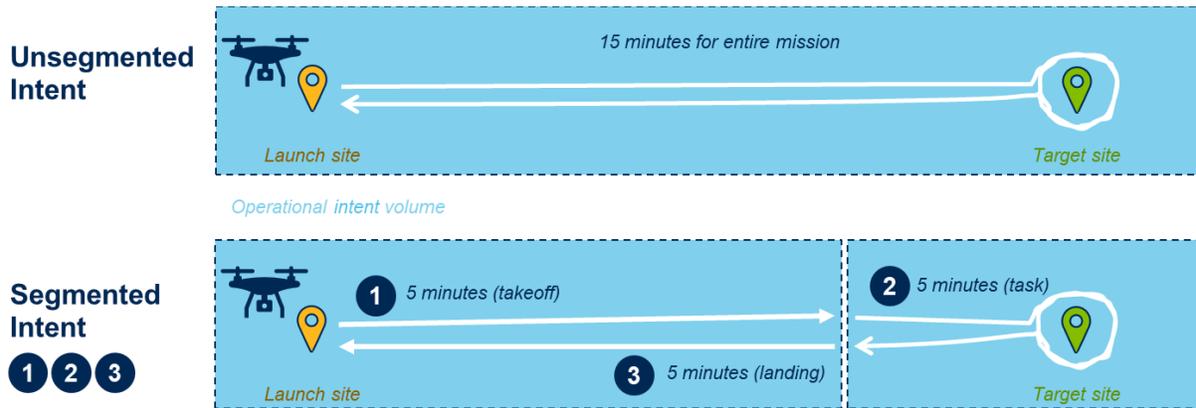


Fig. 4 Illustration of the difference between an unsegmented and segmented flight intent.

3.3.3 Conflict resolution protocols

We evaluated two protocols for conflict resolution: the default FFFS and “lottery” (LOTT). These protocols are used to resolve conflicts for flight intents within the same priority tier; conflicts for flight intents among different priority tiers are resolved based on which intents have the higher priority. The two resolution schemes for flight intents used for conflicts within the same priority tier are described in Table 3.

Table 3 Conflict resolution protocols

Deconfliction Protocol	Description
First filed first served (FFFS)	Flight intents are approved chronologically. When a proposed flight intent conflicts with an existing flight intent that was filed and approved earlier, the later proposed flight is delayed until no conflicts occur at any point in any of the flight intent’s segments.
Lottery (LOTT)	Flight intents are considered in blocks (e.g., hours). When a proposed flight intent is submitted, the flight intent is sorted based on its current departure block. If the intent was submitted in the same block as its proposed departure block, its departure time is automatically delayed to the next block. Shortly before the start of each block, all intents with departure times within the upcoming block are randomly assigned a scheduling order. The intents are then scheduled using that order, with the highest order approved first and lower order flights delayed if any conflicts occur. For any intents that cannot be scheduled during the upcoming block, their departure times are delayed to the beginning of the following block.

3.3.4 Constraints

UAS may be restricted from flying through or into a predefined area of airspace that has been scheduled in advance. In our project, any flight intents that conflict with a constraint are delayed to resolve the conflict. This rule applied to all flights, regardless of priority level. We evaluated the effect of temporary constraints with at least 30 minutes of lead time notice. Emergency constraints that require existing airborne flights to exercise tactical adjustments were out of scope (e.g., for ad hoc nonparticipating aircraft).

3.4 Test Scenarios

We designed a series of eight test scenarios that systematically incorporate the key concepts to evaluate the research questions through live and simulated demonstrations using the iUSF (see Table 4). Scenario 0A and 0B were defined as baseline scenarios that did not consider prioritization and were demonstrated only through simulations.

Table 4 Test scenario matrix

Scenario	Prioritization Tiers Included	Segmentation Applied	Conflict Resolution Protocol Used	Constraints Included
0A	No	No	FFFS	No
0B	No	Yes	FFFS	No
1	Yes	No	FFFS	No
2	Yes	Yes	FFFS	No
3	Yes	No	FFFS	Yes
4	Yes	Yes	FFFS	Yes
5	Yes	No	LOTT	Yes
6	Yes	Yes	LOTT	Yes

For the scenarios, we defined three types of flights:

- 1) *Delivery*, which is a 10-minute intent that involves flying to the target site and back, pausing briefly to drop a package; segmentation is not applicable.
- 2) *Loop*, which is a 30-minute intent that involves continuously looping within the flight intent volume; segmentation is not applicable.
- 3) *Task*, which is 30-minute intent that involves flying to a target site, completing a longer duration task at the target site, and returning to the launch site; segmentation is applicable.

For the live demonstration, we evaluated each scenario with the same flight intents between the hours of 0900 and 1500 local time. All original flight intent geometries, file times, and overall start and end times were the same for each scenario, allowing for direct comparison of scenario outcomes based on the time, segment, and external factors being

studied. Although the original flight intents were the same, some flights were replanned during the execution of the scenario and thus had different outcomes because of each scenario’s characteristics.

3.5 Data Collection

We collected the three areas of data described in Table 5 to calculate metrics for comparison across test scenarios to address the research questions, evaluate iUSF replanning effects, and assess the iUSF system’s performance. For the live demonstrations, we collected data in all three areas. For the high-capacity simulations, we collected data only from UCATS to address the research questions.

Table 5 Data collection areas for demonstrations

Area	Source	Example Data Collected	Metrics
Address the project research questions	UCATS	<ul style="list-style-type: none"> • Total number of flight intents • Number of conflicts identified • Number of resolved conflicts • Number of unresolved conflicts • Cause of the conflicts 	<ul style="list-style-type: none"> • Number of updates • Proportion of intents with conflict • Proportion of intents without conflict • Proportion of resolvable conflict • Proportion of nonresolvable conflict • Proportion of affected intents
Evaluate iUSF re-planning impacts	Aircraft, pilots	<ul style="list-style-type: none"> • Telemetry logs for each live flight • Pilot surveys 	<ul style="list-style-type: none"> • Temporal flight deviation • Spatial flight deviation
Assess iUSF system performance	Beeline, AirDEX	<ul style="list-style-type: none"> • Total system uptime • Receipt timestamp of each message • Forwarding timestamp of each message • Number of invalid messages • Number of messages exchanged 	<ul style="list-style-type: none"> • Processing time latency of messages • Latency of data exchanges • Message malformation rate • System traffic load

3.6 High-Capacity Simulations

To assess the effect of the key scenarios in complex, high-tempo, high-density operating environments (i.e., a high number of flight intents per day), we simulated 50 iterations for all scenarios at three total flight densities: 50, 100, and 250. Before each of the iterations, we sampled flight intents based on priority and mission type from a predefined set of flight paths in the distributions shown in Table 6.

Table 6 Flight intent distribution

Total Flights	0–Base (Package)	0–Base (Food)	1–Inspection	2–Mission	3–Emergency
50	36	10	1	1	2
100	74	19	2	2	3
250	185	47	5	5	8

After sampling, we set each intent’s departure time randomly using a uniform distribution for all mission types except for food delivery, which received a triangular distribution spanning the duration of the simulated day, with its peak at noon. After assigning departure times, we determined the file-ahead time (i.e., how far in advance of departure time a flight intent was submitted) based on the probability distributions in Table 7. We predefined constraints with set start times as well as a file-ahead time of one hour for all constraints.

Table 7 Flight file-ahead time distribution

File Ahead (min)	0–Base (Package)	0–Base (Food)	1–Inspection	2–Mission	3–Emergency
15	0%	50%	0%	0%	100%
30	50%	50%	50%	50%	0%
60	25%	0%	25%	25%	0%
120	25%	0%	25%	25%	0%

4 Results and Discussion

4.1 Demonstration and Verification Execution

From July 7 to 18, 2025, we conducted live demonstrations and tabletop exercises with the iUSF at Poker Flat Research Range (PFRR) in Fairbanks, Alaska. During the live demonstrations, we executed the scenarios using aircraft flown in the field and collected data from the iUSF as well as from the pilots and aircraft. In the tabletop exercises, we executed the scenarios in an office setting without aircraft and collected data from the iUSF only.

Halfway through the demonstrations, we decided to add an extra “Game” scenario on the last day of the campaign. In the Game scenario, each pilot was given a list of missions that did not have specified submission or departure times. The pilots were responsible for adjusting and submitting flight intents at their discretion. Throughout the day, the pilots also received ad hoc missions that they were required to complete. This Game scenario gave additional insight into how agents may leverage the iUSF in a more realistic context.

Scenarios 0A and 0B were simulated before the July flight campaign in UCATS as expected. Because of rain and wildfires adjacent to the range, we adjusted the live demonstrations as described in Table 8. Scenarios 1 and 3 were

cut short because of rain and smoke, and some flights throughout the campaign were manually delayed for safety reasons. Scenario 4 was executed as a tabletop exercise with the pilots because of rain. For both Scenario 1 and the Game scenario, we collected only partial data because of external interference. During the demonstration, other, non-iUSF systems unexpectedly sent messages to AirDEX, which then relayed these messages to its subscribers (as AirDEX is a national system), including UCATS. These messages caused unexpected errors when UCATS tried to process them, disrupting data collection by UCATS. The messages were filtered out after Scenario 1, but the issue returned on the last day and disrupted data collection for the Game scenario. As such, we analyzed the data and feedback collected during the demonstration with these limitations and adjustments.

Table 8 Summary of executed demonstrations

Scenario	Date	Type	Limitations
0A	July 4	Simulation	N/A
0B	July 4	Simulation	N/A
1	July 8	Live	Poor visibility and weather delayed, canceled, or shortened flights. UCATS data from the demonstration were not captured because of message interference.
2	July 10	Live	N/A
3	July 11	Live	This scenario was unintentionally repeated on July 14.
3	July 14	Live	Inclement weather canceled later flights.
4	July 15	Tabletop	Inclement weather prevented live flights.
5	July 16	Live	N/A
6	July 17	Live	N/A
Game	July 18	Live	UCATS data from the demonstration were not captured because of message interference. Pilot surveys and aircraft telemetry data were not quantitatively analyzed because different flight intents were used.

4.1.1 Test site

We carried out all live flights within the operational area shown within PFRR in Fig. 5. The operational area is approximately 1.25 miles long by 0.3 miles wide and 0.36 square miles. The terrain in this area is a valley, bordered to the south and northeast by trees and increasing elevation (i.e., hills), which limits the ability of the visual observers to observe aircraft. The Poker Flat Advanced Incoherent Scatter Radar is on the northwest border of the operational area, which is a restricted area because the radar disrupts UAS command and control links.

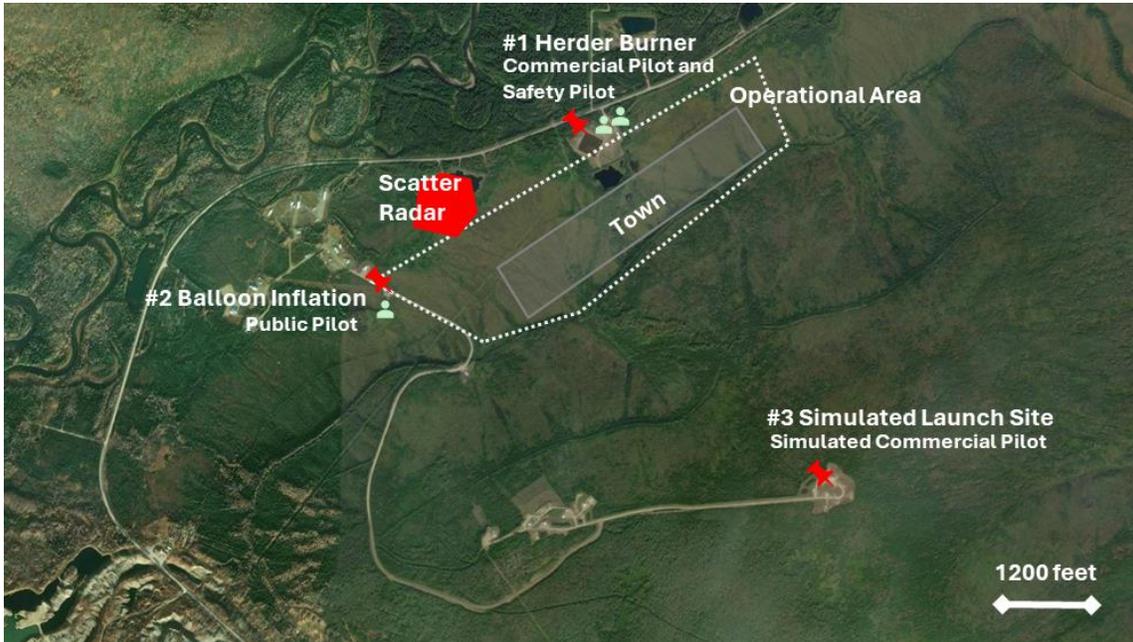


Fig. 5 Close-up aerial image of PFRR operational area.

There were two live flight launch sites: Herder Burner (#1) near the middle of the site to the north and Balloon Inflation (#2) to the west. The pilot assuming the role of a “public” pilot (i.e., priority 1) was stationed at Balloon Inflation, and two pilots with the roles of “commercial” (i.e., priority 0) and “safety” (i.e., priorities 2 and 3), respectively, were stationed at Herder Burner. A third launch site (#3) was located to the south of the operational area, where simulated commercial flights were launched.

4.1.2 Aircraft

We used the four UAS in Table 9 for the flight tests. SuperVolo, a fixed-wing aircraft, was the only aircraft flown from Balloon Inflation with an operational volume with a width of 1,500 feet because of its limited turning radius. The other aircraft were flown from Herder Burner with an operational width of 600 feet.

Table 9 UAS used for the flight tests

UAS	Type	Power Source	Endurance (min.)	Speed (mph)	Weight (lb.)
Autel EVO	Quadcopter	Electric	30	22	2
Perimeter 8	Octocopter	Gas/electric hybrid	300	44	23
S500	Quadcopter	Electric	15	22	1.5
SuperVolo	Vertical takeoff and landing	Gas/electric hybrid	240	60	55

4.1.3 Flights

Each scenario in the live demonstration was designed with 20 flights, as shown in Table 10. Fifteen live flights (1 through 15) were flown by the pilots, and five flights (91 through 95) were simulated to safely allow for more density.

Two constraints were considered for the scenarios that included restrictions (i.e., Scenarios 3, 4, 5, and 6).

Table 10 Flights defined for each scenario (where * indicates simulated flights)

ID	Title	Priority	Launch Site	Type	Start Time	File Time
1	Find Debris A	2	#1	Task	0950	0920
2	Find Wildlife	2	#1	Task	1100	0930
3	AED to Hiker	3	#1	Task	1200	0930
4	Check Noise	2	#1	Task	1245	0935
5	Find HAZMAT	2	#1	Task	1340	0955
6	Sensor Readings A	1	#2	Loop	1000	0955
7	Sensor Readings B	1	#2	Loop	1105	1030
8	Comms Network	1	#2	Task	1200	1000
9	Map Area 1	1	#2	Loop	1255	935
10	Map Area 2	1	#2	Loop	1355	1130
11	Deliver Package A	0	#1	Delivery	1000	1000
12	Deliver Package B	0	#1	Delivery	1025	1135
13	Sensor Readings C	0	#1	Loop	1100	1140
14	Deliver Package C	0	#1	Delivery	1210	0935
15	Deliver Package D	0	#1	Delivery	1245	1110
91*	Deliver Package E	0	#3	Delivery	1000	1145
92*	Deliver Package F	0	#3	Delivery	1100	1155
93*	Deliver Package G	0	#3	Delivery	1205	1310
94*	Deliver Package H	0	#3	Delivery	1235	1315
95*	Deliver Package I	0	#3	Delivery	1340	1255

Fig. 6 shows all 20 flight intent volumes and two constraints overlaid in one layer. The flights were staggered over time, but they were designed to overlap in volume to produce conflicts for the iUSF to resolve.

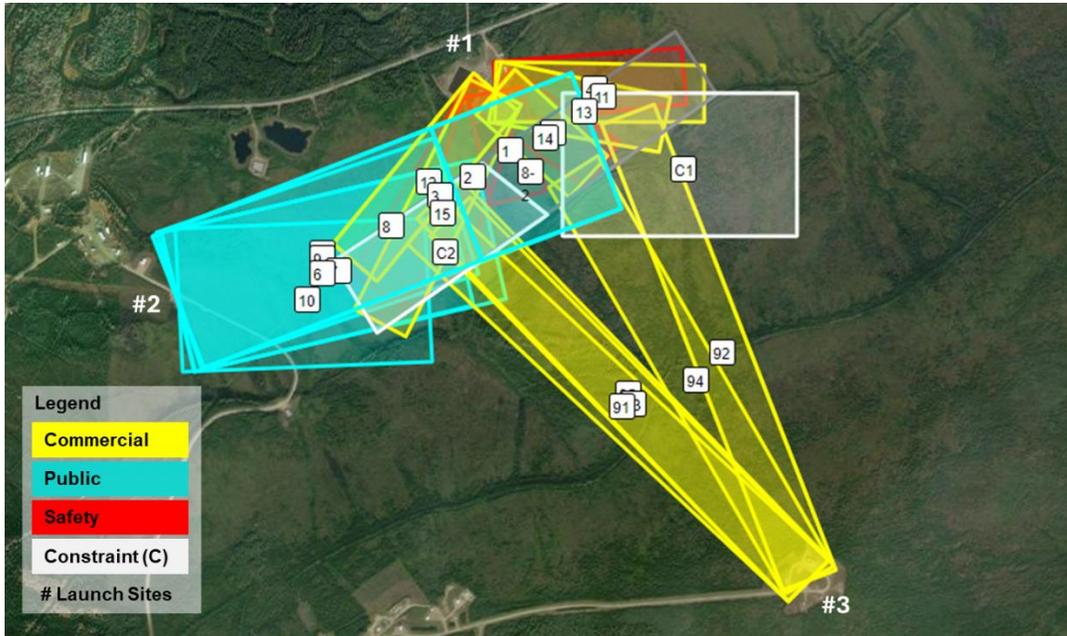


Fig. 6 Overlay of all flights and constraints.

4.1.4 Pilot interactions

Each pilot used a tablet with access to the Beeline USS web application to manage their operations (see screenshot in Fig. 7). Flight intents (i.e., operational volume, segments, altitude, start and end times) were preloaded into Beeline to ensure consistency, and pilots could see only their own flight intents.

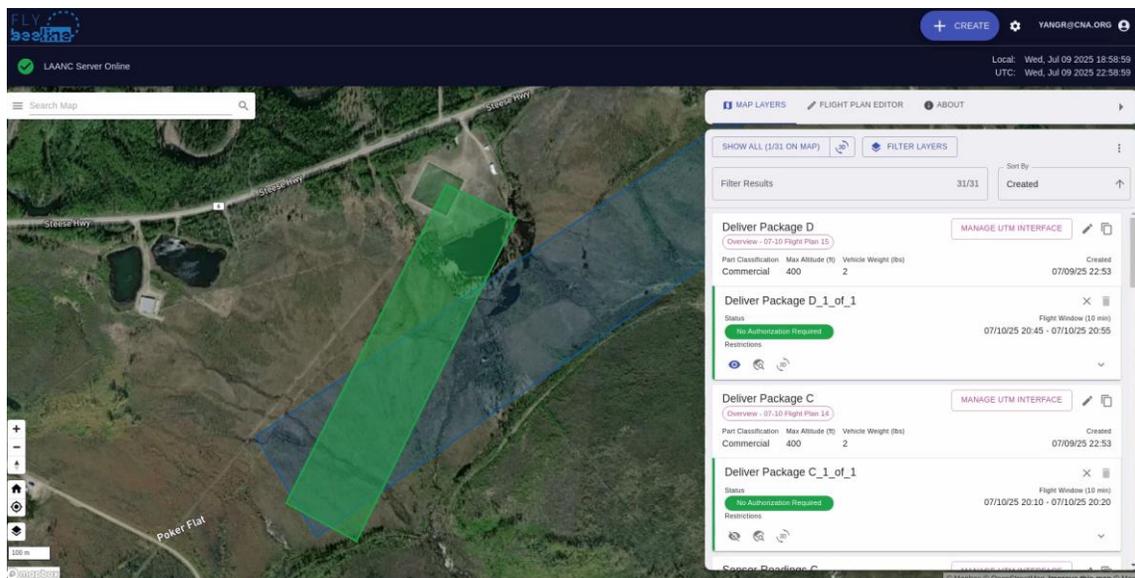


Fig. 7 Example screenshot of the Beeline interface.

Each pilot was also given a set of mission cards describing the tasks for each live flight (see the example in section A of the appendix). Test cards were completed by the pilot and/or visual observer to document each live flight (see the example in section B of the appendix). The test cards included information such as pilot role, location, crew assignments, limitations, aircraft configuration, observations, and post-operation questions.

4.2 Demonstration Results and Data Analysis

The results of the live demonstrations represent one iteration of each scenario, which was affected by imperfect field conditions. Thus, we discuss findings that represent the specific set of flights used in the demonstration. Generalized conclusions about the key concepts and scenarios will be discussed in high-capacity simulation results, which will consider many iterations of each scenario. The results and data analysis discussed in this section follow the data collection areas from Table 5.

4.2.1 Address project research questions

For each scenario, we collected data from the UCATS conflict resolution component and calculated six metrics: proportions of intents without any conflict and with conflict, proportions of resolvable conflict and nonresolvable conflict, conflict rate by cause, average number of updates, average departure delay, and average scheduling delay. In each of the metric summaries that follow, Scenario 0A and 0B results are shown as “0A(s)” and “0B(s)” to indicate that they were conducted as baseline simulations. Scenario 4 results are shown as “4(t)” to indicate that Scenario 4 was conducted as a tabletop exercise. All the other results are from live demonstrations. No results from UCATS were captured for Scenario 1 and the final Game scenario because of interference from unplanned, non-iUSF systems, preventing calculation of the metrics.

4.2.1.1 Proportion of intents with conflicts

Fig. 8 shows the proportion of flight intents with and without conflicts for each scenario. The baseline scenarios, 0A and 0B, had the highest proportion of intents with conflicts because all flights are subject to replanning without regard for their priority. Scenario 4 had the lowest proportion, and Scenarios 2 and 3 had the next lowest proportions. As such, the constraints seemed to reduce the number of intents with conflicts for Scenarios 3 and 4 by delaying the affected intents out of conflicts with other flight intents. Scenarios 5 and 6 had greater proportions of intents with conflict because of the LOTT blocking effect, which resolves intents in batched hourly intervals instead of

immediately as they are submitted (i.e., the FFFS protocol). Thus, any intent submitted in the same hour as its proposed departure time is automatically replanned to the next hour and included in the next hour’s batch.

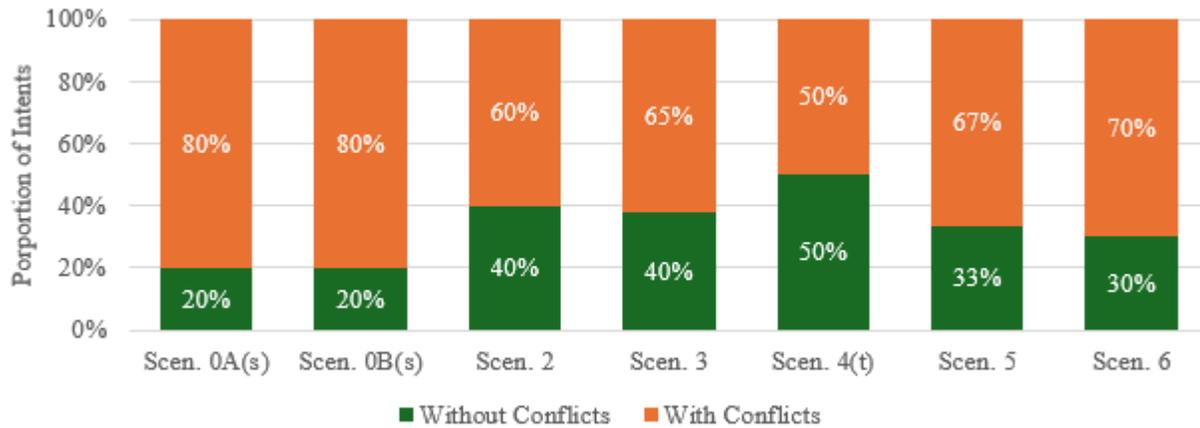


Fig. 8 Proportion of intents with and without conflicts per scenario.

4.2.1.2 Proportion of resolvable conflicts

All conflicts in the demonstrations were resolved through replanning. This trend can be attributed to scenario design decisions of using a relatively low volume of flights and scheduling all flights to depart before 2:00 p.m. local time, which was far in advance of the iUSF’s airspace cutoff time of 6:00 p.m. (after which flights would be canceled). In the future, the actual operational end time for the pilots (i.e., 3:00 p.m.) should be used for the airspace cutoff time. However, although the intents were not canceled, some of the live flights were not flown. One intent was not submitted because of software error, and multiple live flights were canceled because of weather concerns and time constraints (both before and after intents were submitted).

4.2.1.3 Conflict rate by cause

We also determined the rate of conflict by unique causes. Some flight intents were replanned multiple times because of conflicts from the same cause, but the conflict rate metric counts each unique cause only once. The causes of the conflict include other intents, constraints, or LOTT block restrictions. Conflicts due to other intents could be caused by another intent having a higher priority or being filed or chosen first based on whether the FFFS or LOTT approach was used.

Figure 9 shows that the baseline scenarios, 0A and 0B, had the greatest number of conflicts and a larger proportion of conflicts from lower priority missions because of lack of prioritization. The conflicts due to other intents are

relatively similarly proportional by priority for the other scenarios except Scenario 6, which did not have any conflicts from emergency missions (priority 3). In this scenario, the emergency flight #3 was delayed by the constraint and replanned to a new slot that did not conflict with other flights. Constraints cause 29 and 22 percent of the conflicts for Scenarios 3 and 4, respectively, but block restrictions become the dominant cause of conflicts at 36 and 47 percent for Scenarios 5 and 6, respectively.

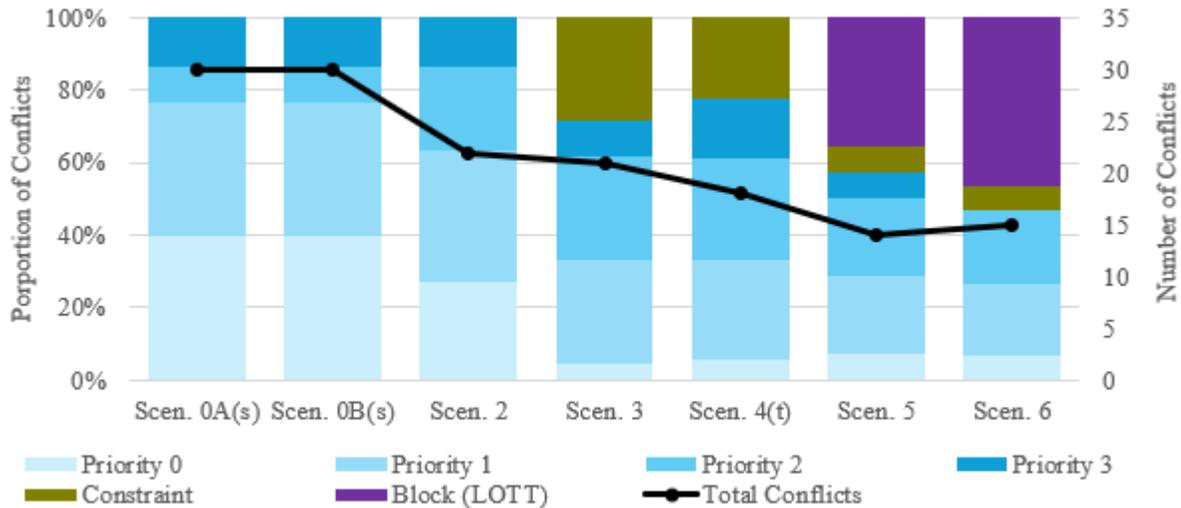


Fig. 9 Conflicts by cause per scenario.

4.2.1.4 Number of updates

The number of updates metric is defined by the number of times a flight intent was replanned, which is also the number of updated messages the pilot received through Beeline. Table 11 shows that Scenario 2 had the highest number of average and total updates. Because of the FFFS approach and lack of constraints, the intents in Scenario 2 were resolved and updated more gradually. The baseline scenarios, 0A and 0B, have lower numbers of updates than Scenario 2 because, without prioritization, replanning is distributed more evenly across all flights (rather than just lower priority flights). For Scenarios 5 and 6, the LOTT approach had an extra blocking restriction in that any intents submitted in the same block (i.e., hour) as the departure time would have automatically received an update that the departure time was moved to the top of the next hour because of batch scheduling. Despite the blocking restriction, the LOTT protocol did not significantly increase the number of updates in Scenarios 5 and 6, which implies that the LOTT approach resulted in more efficient replanning.

Table 11 Statistical summary of number of updates per scenario

Scenario	Average (num./intent)	St. Dev. (num./intent)	Max. (num./intent)	Sum (num./scenario)	Replanned Intents (num./scenario)
0A	0.9	0.5	2	17	16
0B	0.9	0.5	2	17	16
2	1.1	1.1	4	21	12
3	0.9	0.9	3	17	12
4(t)	0.7	0.7	2	13	10
5	0.7	0.6	2	13	12
6	0.7	0.5	1	14	14

4.2.1.5 Departure delay

The departure delay metric is defined by the difference between the start time of the original intent and the actual start time scheduled by the iUSF. As Table 12 shows, the baseline scenarios, 0A and 0B, had the greatest departure delays without prioritization. Out of the other scenarios, Scenario 2 had the lowest average departure delay (11.0 minutes per intent, 220 minutes total), whereas Scenario 3 had the greatest average departure delay (24.0 minutes per intent, 480 minutes total). Scenario 2 did not include constraints and avoided guaranteed delays for affected intents. Scenario 3 introduced two constraints, which led to multiple delays, including a maximum 130-minute delay by public flight #8. This flight did not receive such a large delay in subsequent scenarios because segmentation and the LOTT blocking effect arbitrarily replanned the adjacent safety flights to accommodate #8. Additional simulations can help determine whether this pattern holds true for other combinations of flight intents.

Table 12 Statistical summary of departure delay per scenario

Scenario	Average (min./intent)	St. Dev. (min./intent)	Max. (min./intent)	Sum (min./scenario)	Replanned Intents (num./scenario)
0A	31.8	27.9	85	635	16
0B	31.8	27.9	85	635	16
2	11.0	11.2	30	220	12
3	24.0	33.5	130	480	12
4(t)	13.8	16.0	45	275	10
5	15.0	12.2	30	270	12
6	13.8	12.3	35	275	14

4.2.1.6 Scheduling delay

The scheduling delay metric is defined as the time elapsed between the time the intent was first submitted (i.e., filed) and the time of its final update. The scheduling delay is zero if the intent was never replanned or if it was replanned immediately when submitted. Table 13 shows that the scheduling delay is zero for the baseline scenarios,

0A and 0B, which is expected because the baseline scenarios strictly follow a FFFS approach without prioritization. The average scheduling delay is much higher for Scenarios 5 and 6, which employed the LOTT approach. When submitted in the LOTT scenarios, all intents are entered into a batch to be scheduled five minutes before the next hour. On the other hand, intents in the FFFS scenarios are processed immediately upon submittal for replanning and thus have less scheduling delay. Scenarios 3 and 4 included constraints, which immediately replanned affected intents, whereas Scenario 2 intents were gradually resolved as new intents were submitted, increasing scheduling delay.

Table 13 Statistical summary of scheduling delay per scenario

Scenario	Average (min./intent)	St. Dev. (min./intent)	Max. (min./intent)	Sum (min./scenario)	Replanned Intents (num./scenario)
0A	0	0.0	0	0	16
0B	0	0.0	0	0	16
2	18.5	35.2	135	370	12
3	11.8	40.7	175	235	12
4(t)	8.8	28.4	115	175	10
5	36.4	23.9	115	655	12
6	38.8	23.8	115	775	14

4.2.2 Evaluate iUSF replanning impacts

For each scenario, we collected surveys from the pilots and telemetry data from the aircraft to calculate two types of metrics: temporal deviations and spatial deviations of live flight from schedule flight intent. In each of the metric summaries that follow, Scenarios 0A, 0B, and 4 are not shown because they were simulated or tabletop exercises. We captured no results from UCATS for Scenario 1 and the final Game scenario because of interference from unplanned, non-iUSF systems, preventing calculation of the metrics.

4.2.2.1 Temporal deviations

We determined temporal deviations by comparing the actual start and end times of a flight from the test cards to the times scheduled by the iUSF. Fig. 10 shows that the average absolute percentage deviation with respect to total flight duration (i.e., 10 minutes or 30 minutes) for both start and end times varies among the scenarios (0 to 60 percent) with large standard deviations.

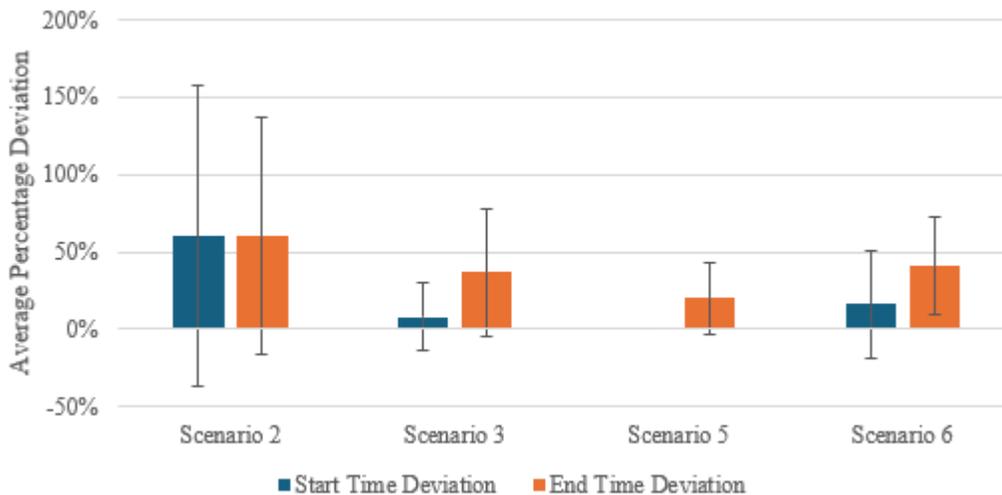


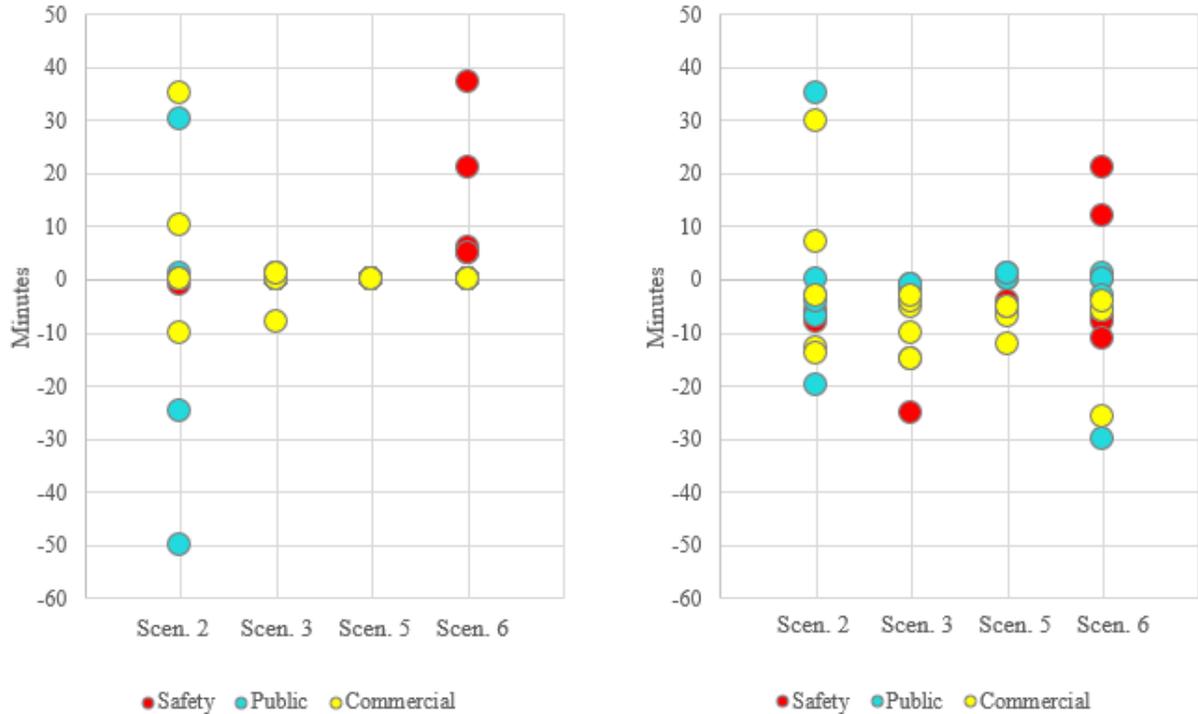
Fig. 10 Average absolute percentage start and end time deviations per scenario.

Deviations occurred because of imperfect field conditions or pilot choice. For example, in Scenario 2, two public flights overlapped, so the pilot chose to combine the flights and manually adjust the flight times to be able to fly both flights. In Scenario 6, the safety flights were combined and shortened to reduce total flight time because the Perimeter 8 (P8) aircraft was low on fuel. In many of the scenarios, the commercial flights were shorter than scheduled because the delivery missions were completed in less than the allotted 10 minutes. In addition, some of the commercial flights were shortened because of high winds, which reduced the endurance of the smaller aircraft (i.e., Autel Evo and s500).

Figure 8 shows a breakdown of the deviations by aircraft. The deviations are negative if the live flights began or ended earlier than scheduled and positive if the live flights began or ended later than scheduled. Overall, the deviations skew positive for start time (i.e., flights tended to start later than scheduled) and negative for end time (i.e., flights tended to end earlier than scheduled). This finding aligns with observations from the demonstration. Pilots waited until the designated start time to take off but landed earlier if the mission was completed or other factors (e.g., fuel) required it. This behavior complies with the concept of the flight intents and reservation of the operational volumes.

The outliers in Fig. 11 are largely due to overlapping intents that the pilots needed to manually adjust. In Scenario 2, the public flights have high temporal deviations because flights #8, #9, and #10 overlapped in time, and the pilot decided to complete multiple missions at the same time. In Scenario 6, two other factors caused the safety flights to have greater temporal deviations. First, the pilot chose to manually delay an overlapping intent, safety flight #4, by 20

minutes. Second, emergency flight #3 was delayed by 30 minutes according to UCATS logs but noted as a 60-minute delay by the pilot on the test card, implying a user error.



(a) Start Time Deviations

(b) End Time Deviations

Fig. 11 Start and end time deviations for all live flights per scenario.

4.2.2.2 Spatial deviations

We determined spatial deviations by comparing the actual telemetries against the operational intent volumes for each flight. For each flight, the spatial deviation metric is defined as the percentage of the flight path length that was outside the boundaries of the intent volume. Fig. 12 shows the average percentage spatial deviation by aircraft, with the average for all flights equal to 21 percent. SuperVolo had the lowest average metric at 15 percent, whereas P8 had the highest average metric at 30 percent. None of these averages comply with the 95 percent in-volume containment requirement in ASTM F3548-21 [2].

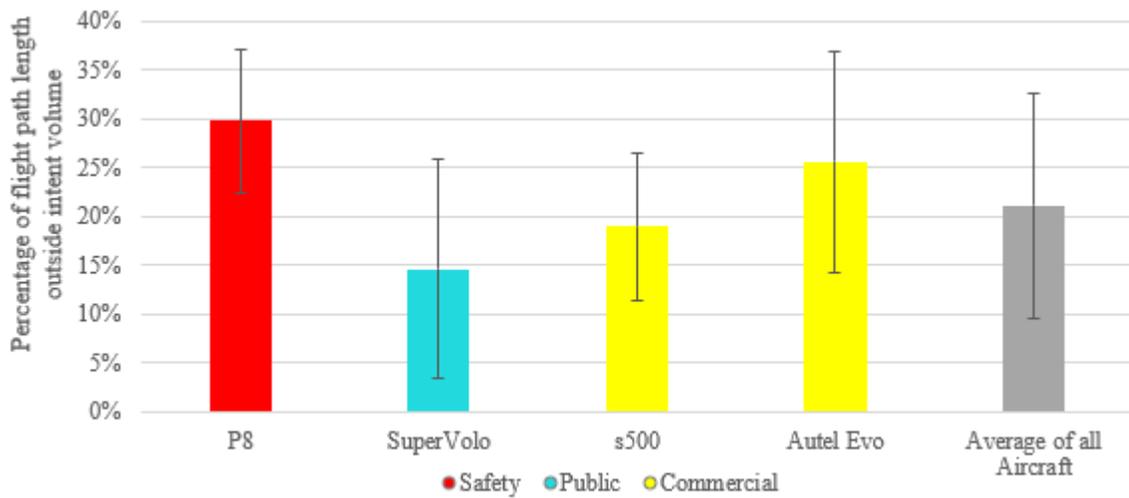


Fig. 12 Average percentage spatial deviation by aircraft.

The pilots were unable to reference the operational intent volumes on their ground control stations because the USS tool was not integrated with the ground control software (i.e., Beeline was on a separate tablet). All pilots predefined their trajectories before taking off by approximating the boundaries of the intent volumes visually, which resulted in greater discrepancies in the spatial deviation metrics. Fig. 13 shows examples of flight paths overlaid on top of the corresponding operational intent volumes for each aircraft. If the intent volumes were integrated into the ground control station planning tool, the spatial deviation would be significantly smaller, unless an unplanned event caused the aircraft to stray off trajectory (e.g., if the pilot needed to take manual control).



(a) Autel Evo (Commercial Flight #14)



(b) s500 (Commercial Flight #15)



(c) SuperVolo (Public Flight #7)



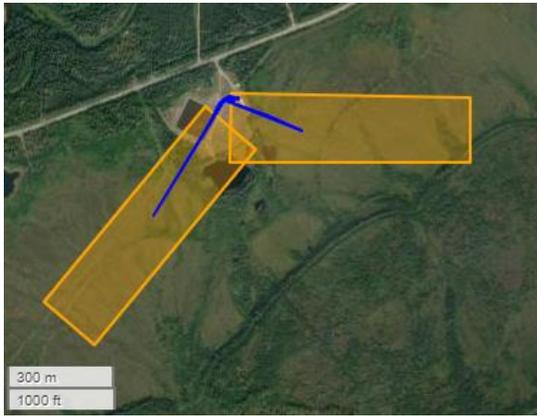
(d) P8 (Safety Flight #5)

Fig. 13 Examples of actual flight paths overlaid on corresponding intent volumes.

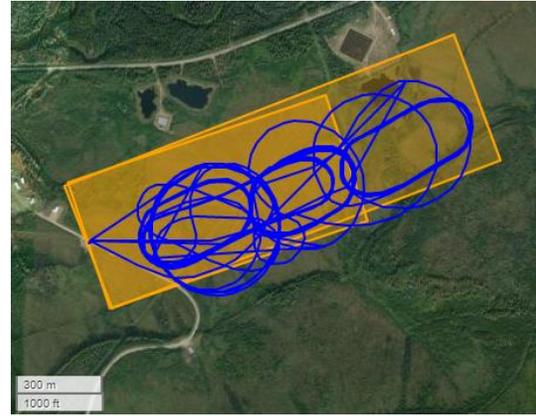
The analysis also indicated that each aircraft has different requirements (e.g., for endurance and turning radius). For example, SuperVolo requires a larger turning radius and barely fits into its operational volume, despite having a 1,500-foot width as compared to the 600-foot width of the other aircraft. Autel Evo and s500 are lower endurance aircraft, with an average path length per flight of 1.6 and 0.7 miles, respectively, as opposed to the average 32.9 and 16.7 miles of the SuperVolo and P8, respectively. The Autel Evo and s500 were not always programmed to traverse the entire operational volume to reduce the need to swap batteries. The pilots also noted high winds during some days, which further increased the turning radius of the SuperVolo and lowered the flight duration of the smaller aircraft (Autel Evo and s500).

The analysis demonstrated that each pilot had different preferences for defining flight paths on their ground control software. For example, the P8 pilot maximized the range of the aircraft by defining trajectories along the perimeter of the operational intent volume. However, because the pilot did so visually, the flight path was often outside the volume, resulting in a higher metric.

For some scenarios, the pilots conducted multiple missions without landing because the flight departure times were back-to-back or overlapping, with no time to reset. Fig. 14 shows flights with multiple missions for the s500, SuperVolo, and P8.



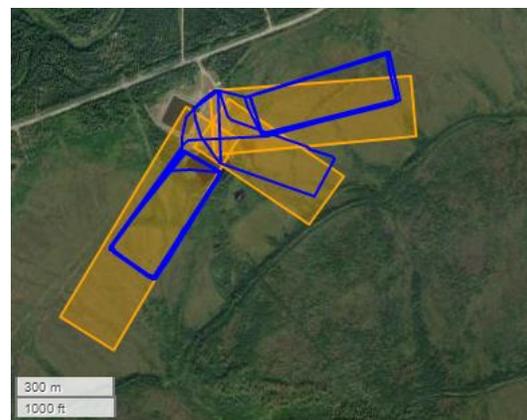
(a) s500 (Commercial Flights #11 and #12)



(b) SuperVolo (Public Flights #8 and #9)



(c) P8 (Safety Flights #3 and #4)



(d) P8 (Safety Flights #3, #4, and #5)

Fig. 14 Examples of actual flight paths overlaid on multiple corresponding intent volumes.

Finally, the flight trajectories with and without segmentation were indistinguishable, so we were unable to calculate the metrics by segmented volumes. The pilots found it difficult to follow segmentation as defined in the flight intents. The segmented P8 intents were split into the following components: takeoff to target site, task at target site, and return to launch site. The takeoff and return segments took only two minutes to traverse, however, so the pilots chose to spend more time circling the target site. In the case of SuperVolo, the segmented volumes were too small for the aircraft to realistically operate within.

4.2.3 Assess iUSF system performance

For each scenario, we collected system-level performance data from ATAA's Beeline and AirDEX systems and calculated the four metrics: internal processing time of messages, latency of network data exchanges, system traffic

load, and message malformation rate. In each of the metric summaries that follow, the Scenario 4 results are shown as “4(t)” to indicate that Scenario 4 was conducted as a tabletop exercise. All other results are from live demonstrations. In addition, the metrics were calculated on an hourly basis and averaged for the active duration of the demonstrations.

4.2.3.1 Internal processing time of messages

We analyzed two sets of metrics to determine the internal component processing time of messages. The first set of metrics represents the time needed for AirDEX to process flight intents (“plan”) from Beeline and for Beeline to process intents (“plan” and “update”) from UCATS or through the pilot interface. As shown in Fig. 15, the AirDEX plan messages are processed quickly because they are simply ingested for redistribution. The Beeline plan and update messages take longer to process because the submitted flight intents are extracted and parsed, and processing for update messages requires additional time to map and delete old flight intents in the backend database. However, all latencies were within the five-second tolerance in ASTM F3548-21 [2].

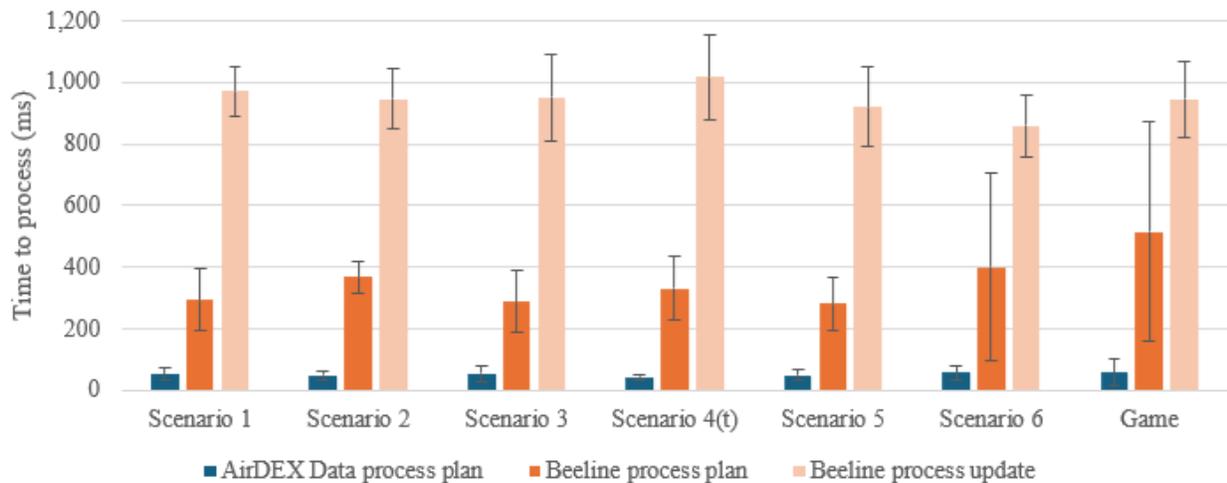


Fig. 15 Average processing time of plan and update messages per scenario.

The second set of metrics we analyzed in the processing time latency are “acknowledge” messages, which represent the time elapsed from when a replan popup message is shown on the Beeline interface and when a user (i.e., pilot) clicks to acknowledge it. Fig. 16 shows the average time to acknowledge, plotted on a logarithmic scale. The time to acknowledge decreases on average throughout the demonstrations from more than two minutes to less than one minute because the pilots become more accustomed to checking the tablet for updates over time.

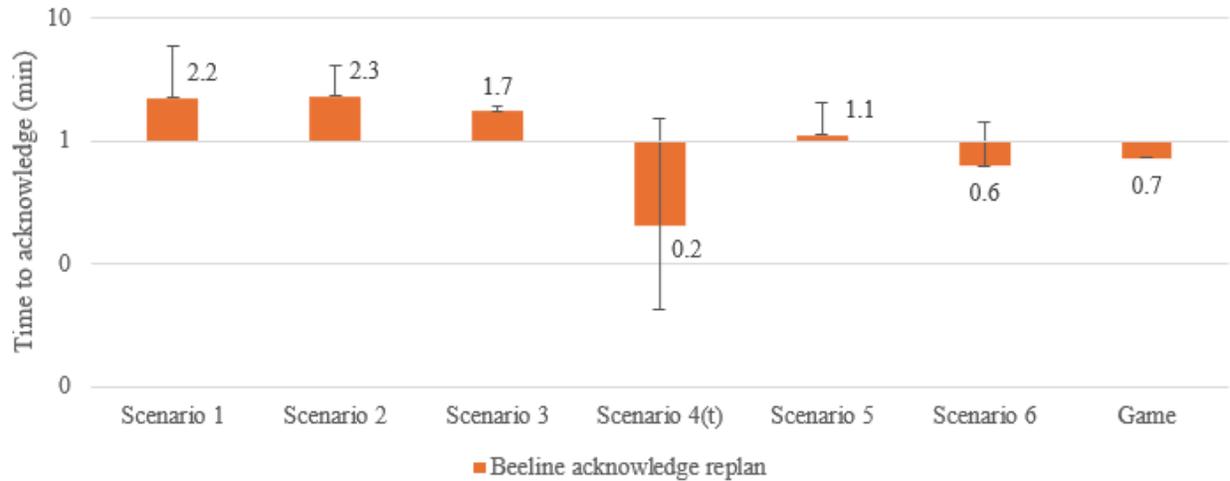


Fig. 16 Average processing time of acknowledge messages per scenario.

Scenario 1 had one outlier data point, where one replan message was not acknowledged until the next day (1.7 days). This data point was removed from the average in Fig. 16. The maximum time for other scenarios is between 3 and 17 minutes. The time to acknowledge for Scenario 4 is very low because the pilots were focused on their tablets for the entire duration of the tabletop exercise and could immediately address replan popups; in the live demonstrations, the pilots were largely away from their tablets to prepare for flights and did not immediately see the popups. Similarly, the standard deviations are large because at times, the pilots were flying or otherwise occupied when popups appeared, so they did not see notifications on their tablets. This issue highlights the challenges of human interactions with highly automated flight planning systems.

4.2.3.2 Latency of network data exchanges

We calculated the latency of data exchanges within the network to determine the efficiency of messages exchanged between iUSF components. These messages include plan messages from UCATS and Beeline to AirDEX as well as websocket messages from AirDEX to Beeline. As shown in Fig. 17, the time-in-network averages for all scenarios are less than 500 milliseconds. The variations in latency were likely increased because of connectivity issues, and they highlight the very real challenges of network availability for automated flight planning and deconfliction tools in the field. The data below show that field network latency issues accounted for approximately half of all system-based latency. For example, the Scenario 4 tabletop was conducted in an office with a shared internet connection, which was slower than the dedicated Starlink kits used for the live scenarios in the field.

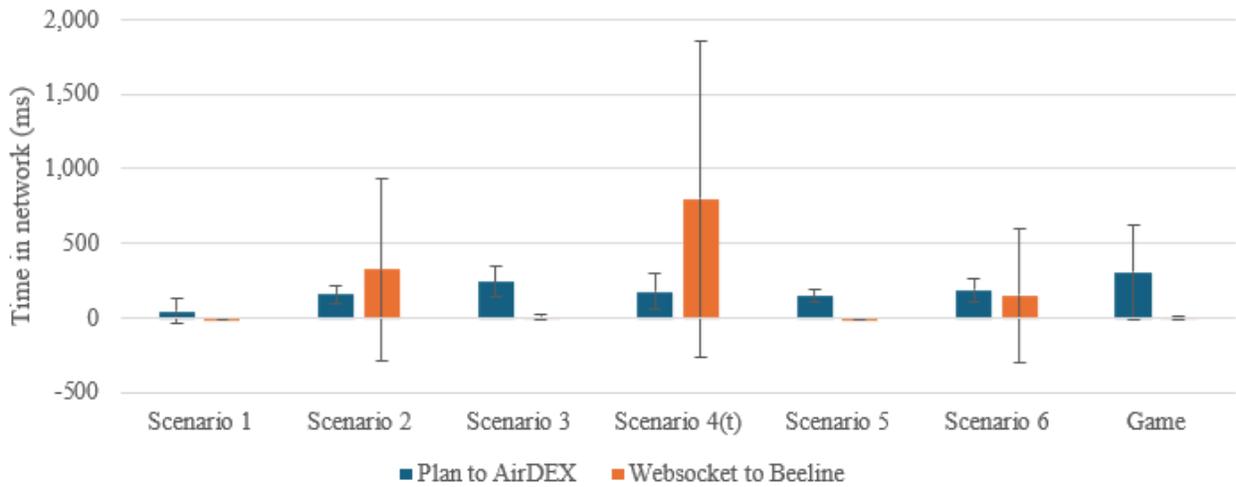


Fig. 17 Average latency of network data exchanges per scenario.

4.2.3.3 System traffic load

We calculated the total system traffic load for AirDEX and Beeline for the demonstrations. The traffic counts in Fig. 18 show total system traffic, including from iUSF components and non-iUSF components. AirDEX and Beeline are both live, commercial systems, so other non-iUSF systems (e.g., other LAANC USSs) exchanged messages with the systems during the demonstration timeframe. Overall, the two systems successfully processed iUSF messages alongside other non-iUSF messages at a rate of up to 5,000 messages per hour.

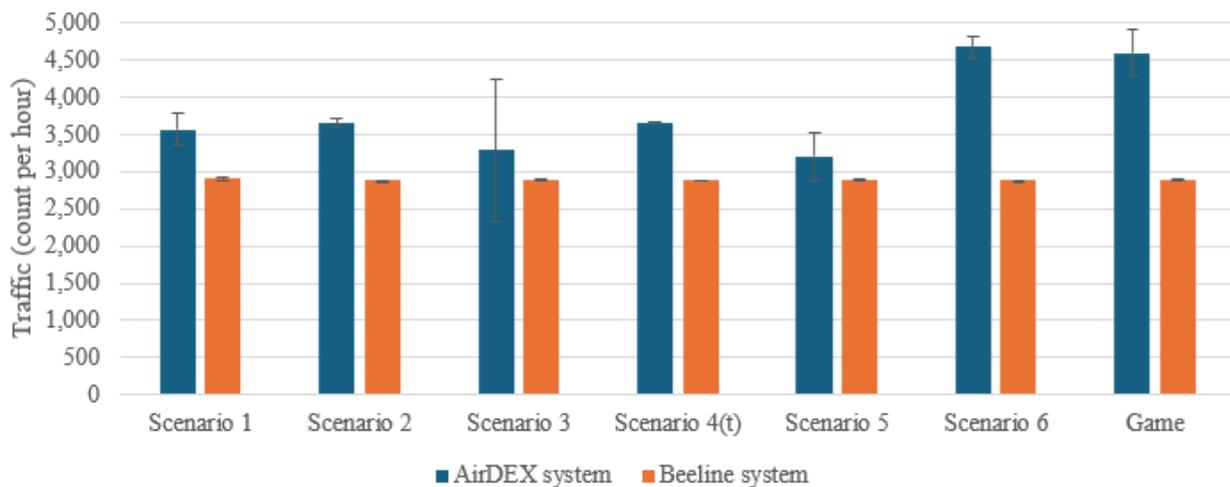


Fig. 18 Average system traffic load per scenario.

Based on the messages analyzed in the processing metrics, the iUSF-related messages were approximately 3 percent of the total AirDEX traffic and 1 percent of the total Beeline traffic (see Fig. 19). Although the demonstrations represented a limited complexity (i.e., 20 flights), the systems successfully processed 100 times the amount of traffic required for the iUSF demonstrations, which implies the ability to support future demonstrations on a greater scale.

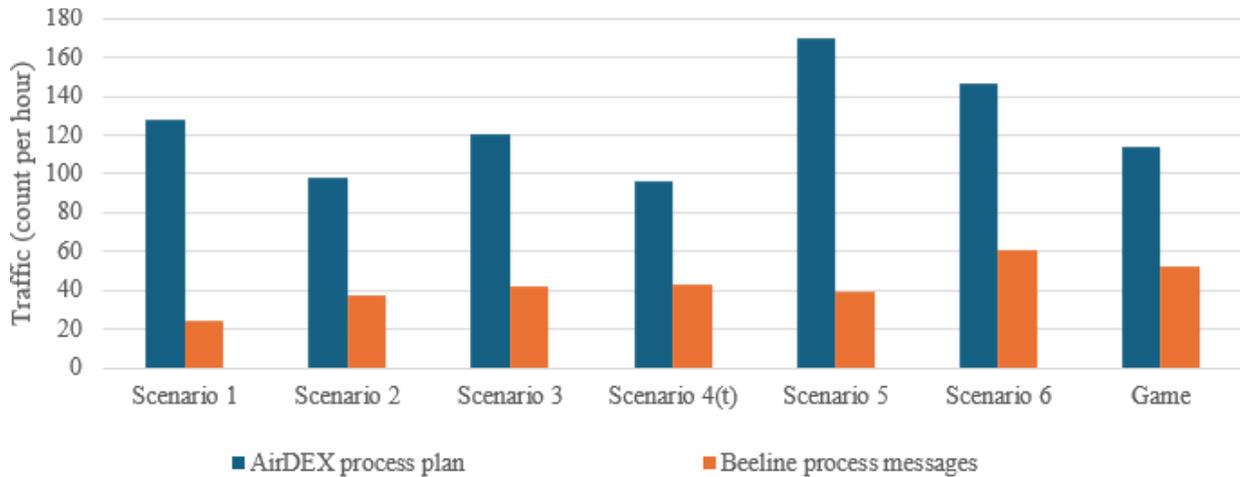


Fig. 19 Average traffic counts for iUSF process messages per scenario.

4.2.3.4 Message malformation rate

Similar to the system traffic load metric, the message malformation metric was also calculated using the total traffic experienced by AirDEX and Beeline, including data sent from systems not related to this project. Beeline did not receive any malformed messages during the demonstration. The malformed messages received by AirDEX were less than 0.1 percent of the total traffic, and we manually observed that none of these malformed messages came from UCATS.

4.3 High-Capacity Simulation Results and Data Analysis

The results of the high-capacity simulations represent averages across the various densities simulated at 50 iterations per density: 50 flights, 100 flights, and 250 flights. This section draws general conclusions about the key concepts and scenarios.

4.3.1 Maximum airspace capacity

To determine the maximum airspace capacity, the primary feature we investigated was the proportion of canceled intents as shown in Fig. 20. Because our principal investigation involves the implementation of prioritization, we

focused our analysis on Scenario 1—the closest scenario to the baseline that implemented the new scheduling protocol. We treated all subsequent scenarios as protocol stressors (i.e., addition of constraints) or as mitigation strategies (i.e., segmentation) on the baseline prioritization scenario. Because of the high proportion of low-priority flights, we used a 50 percent cancellation rate of all flight intents the threshold for determining the maximum airspace capacity. Based on our simulations, we determined the maximum daily airspace capacity to be between 100 and 250 flights. We concluded that the use of the prioritization protocol increased the rate of canceled intents in low-priority flights, which in turn increased the total rate of canceled intents because of the high proportional volume of lower priority intents.

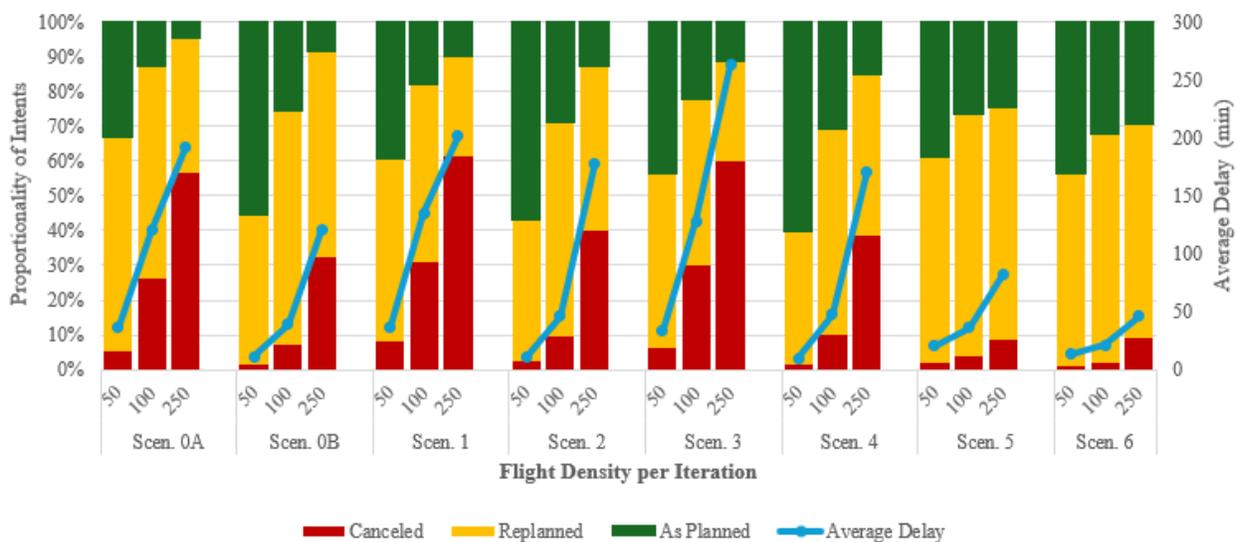


Fig. 20 Proportion of replanned and canceled intents with average delay overlay n= 250.

4.3.2 Effect of prioritization on various priority operators

Figure 21 shows the average proportion of flight intents scheduled as planned, replanned, and canceled for Scenarios 0A, 0B, 1, and 2 when simulating 50 iterations of 250 flight intents per day. The scenarios using prioritization (Scenarios 1 and 2) showed an average of 20 percent reduction in proportion of replanned intents and an average 16 percent increase in proportion of canceled intents overall, regardless of whether segmentation is used. With prioritized scheduling, high-priority intents are more likely to complete their missions with fewer replans throughout the day at the expense of low-priority flights. Because of the use of a large proportion of low-priority intents, the overall results skew to a higher proportion of cancellations despite the 91 percent reduction in cancellations and 12 percent reduction in replans in high-priority flight intents.

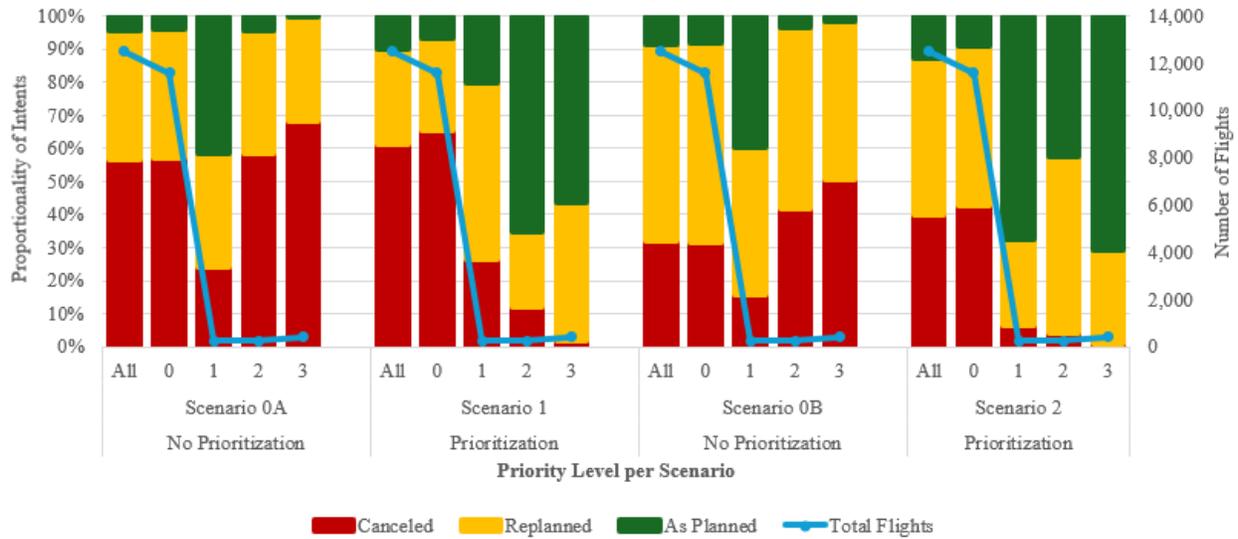


Fig. 21 Proportion of replanned and canceled intents by prioritization n= 250.

4.3.3 Effect of segmentation on resolvable and nonresolvable conflict rate

After implementing segmentation, we observed an average increase in proportion of replanned intents by 63 percent and an average decrease in proportion of canceled intents by 35 percent across all FFFS scenarios (Fig. 22). However, when using the LOTT protocol the proportion of replans decreased by an average of 5 percent and the proportion of cancellations by an average of 22 percent. This outcome is to be expected because a single volume with a start and end time associated with the intent’s takeoff and landing time requires a large area for a long duration. By splitting the large single segment into three smaller concurrent segments comprising takeoff, mission target, and landing segments, other intents can be scheduled in between these segments (i.e., while a flight is operating within its mission target segment, another intent can be scheduled through the takeoff or landing segments). We concluded, therefore, that as the number of segments increases, so does the number of scheduled flights within a given timespan.

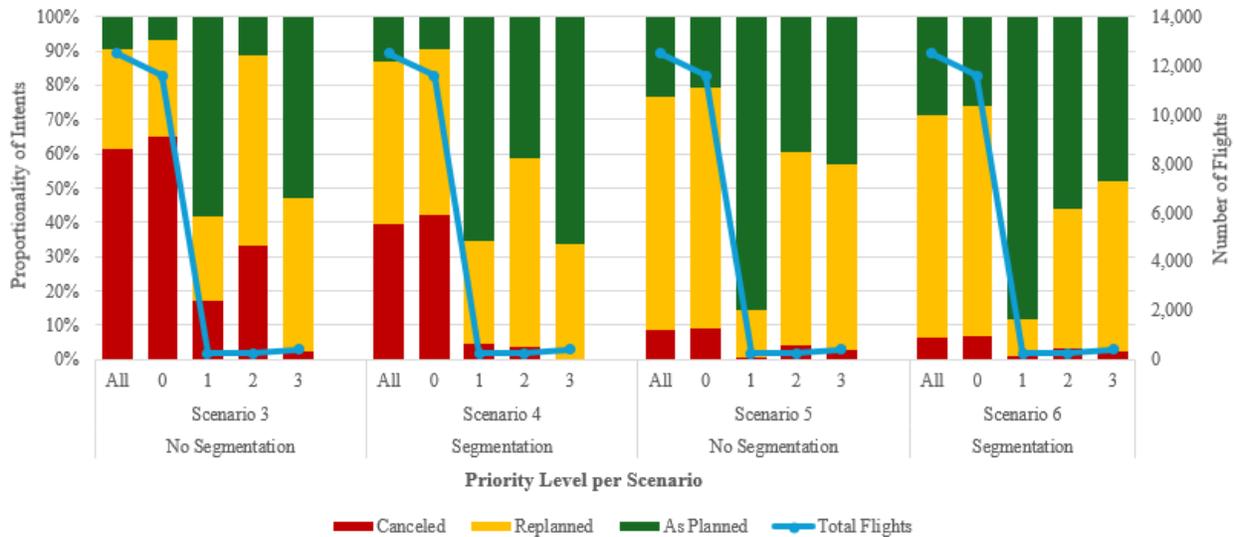


Fig. 22 Proportion of replanned and canceled intents by segmentation n= 250.

4.3.4 Effect of varying conflict resolution protocols on resolvable and nonresolvable conflict rate

When the conflict resolution protocol of flight intents was changed to LOTT, we observed an 84 percent decrease in the proportion of canceled intents but an 86 percent increase in proportion of replanned intents (Fig. 23). When the FFFS conflict resolution protocol was used, the proportion of replanned and canceled intents decreased dramatically as the prioritization of the flight increased. In addition, with FFFS, low-priority flights—which make up the majority of the total flight intents—are deconflicted whenever a higher priority intent is submitted. The result is a cascading deconfliction in which a replanned low-priority flight may then conflict with another low-priority flight that was submitted later in the FFFS protocol.

However, this effect of cascading deconfliction is mitigated in the LOTT protocol, in which flight intents are deconflicted in batches at a predetermined time interval, meaning that all low-priority flights that are scheduled to fly within an active block are protected when a higher priority intent is submitted within the active block. For example, a priority zero flight scheduled at the start of the active block set to depart 30 minutes into the block will not be replanned if a priority one intent with the same departure time and airspace requirements is submitted within the active block. In the example, the priority one intent would be replanned to the start of the next active block and would be deconflicted with other intents scheduled for that block. This process adds a layer of protection for low-priority intents without great sacrifice to the average proportion of replanned and canceled high-priority intents.

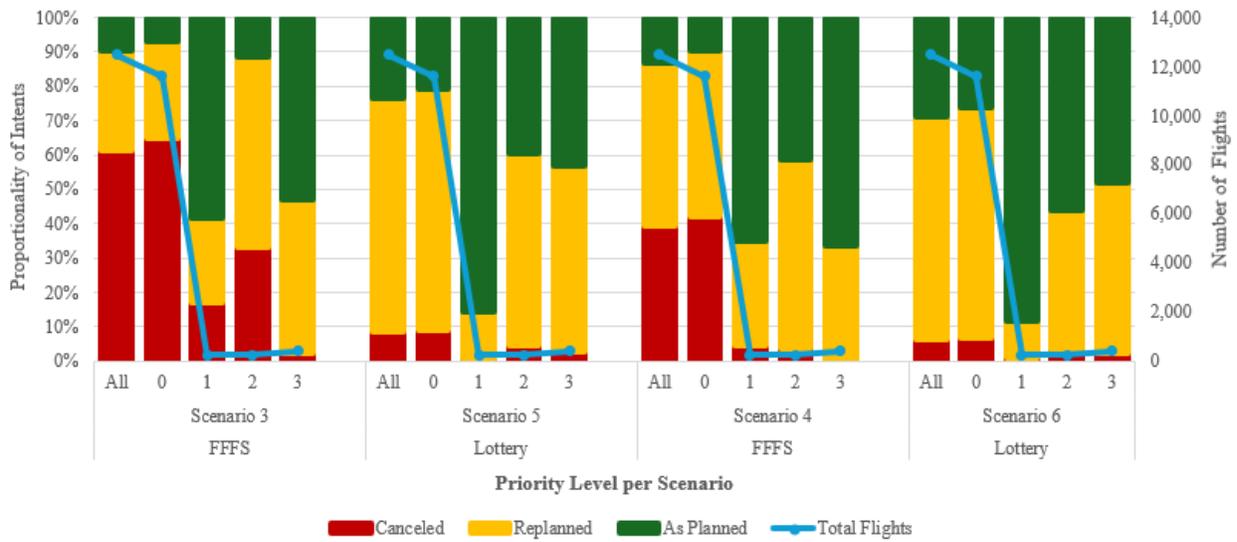


Fig. 23 Proportion of replanned and canceled intents by conflict resolution protocol n= 250.

4.3.5 Effect of constraints on resolvable and nonresolvable conflict rate

For each of the scenarios in which constraints were included, the proportion of replanned or canceled flight intents did not significantly increase or decrease in the aggregate, as seen in Fig. 24. Because of the UCATS algorithm, constraints are added as their own infinite priority flight intents; therefore, when deconflicting, constraints have the same effect on priority three intents as priority three intents have on priority two intents. Because only five constraints were used, the effect of the constraint on the overall proportionality of replanned and canceled intents was minimal.

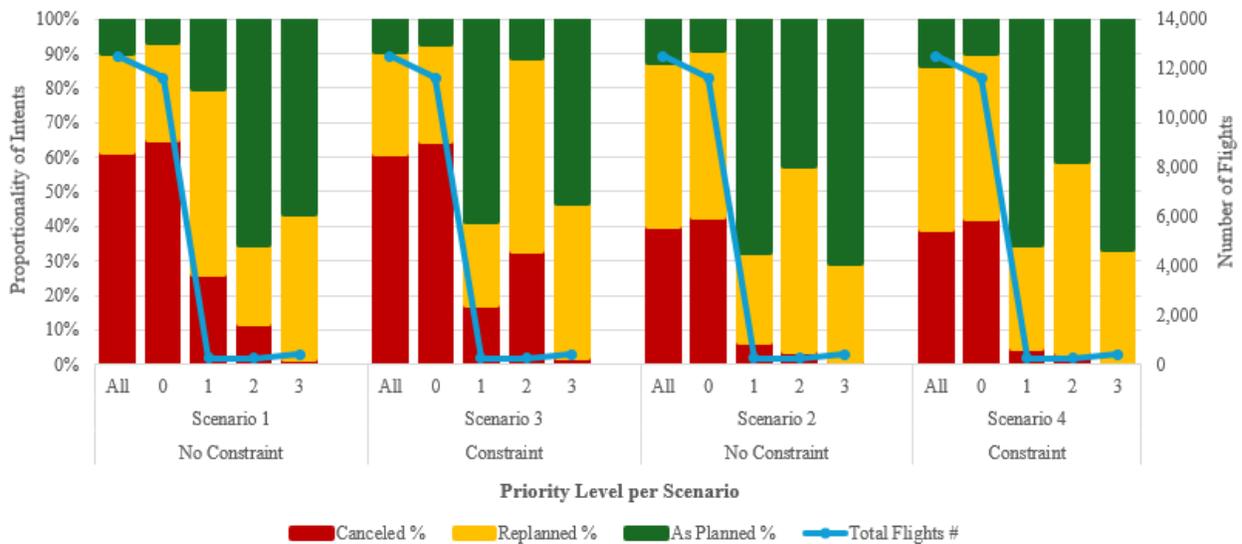


Fig. 24 Proportion of replanned and canceled intents by inclusion of constraints n= 250.

4.4 Challenges and Lessons Learned

We compiled qualitative lessons learned and commentary on the introduction of live flights with the simulations as a validation exercise. These lessons learned provide insights for future validation efforts of technologies similar to the iUSF. The insights discussed in this section are divided into five categories: key concepts, scenario design, demonstration preparation and execution, software execution, and high-capacity simulations.

4.4.1 Key concepts

Here, we describe lessons learned regarding the key concepts from this project.

Prioritization. As expected, prioritization allowed public safety and public pilots to complete their missions earlier than scheduled. This effect was exemplified in the Game scenario, in which the commercial pilot had significant difficulty scheduling the commercial flight intents. Overall, the pilots were interested in having access to more information (e.g., other flight intents, operational intent volumes, constraints) so that they could adjust their own flight intents around higher priority flights or better understand why they were replanned. During the high-capacity simulations, the effect of prioritization became more pronounced, showing an inversely proportional relationship between a flight intent's prioritization and the number of replans or failures experienced.

Segmentation. The segmented approach was not as applicable as the prioritization approach to our specific missions and test site. Because of the relatively small test area, the takeoff and landing segments were completed faster than planned, and the intended timings were unrealistic. The segmented approach was also not intuitive to the pilots in the context of the test scenarios. However, the segmented approach proved highly effective during the high-capacity simulations, which model BVLOS flights more closely. Scenarios using segmented flight intents experienced fewer replans and failures compared to their unsegmented counterparts. More research should be conducted to find the optimal balance between segment duration and segment area.

Constraints. The pilots were unable to see constraints on Beeline and were not told when the constraints were activated; therefore, constraints were effectively treated as priority 4 flights. In fact, the UCATS conflict resolution algorithm resolves constraints by assigning them to infinite priority; no matter how many prioritization levels are used, constraints will always take the highest priority. Without additional attributes or considerations, constraints could be treated as the highest level priority flights from an implementation perspective. Because we used only five constraints, the low proportion of constraints to total flight intents submitted had a small effect on the proportion of replanned or

canceled intents. As the total number of intents submitted throughout the day increased, the effect of the five constraints used decreased.

Lottery. The LOTT conflict resolution protocol resulted in a lower overall proportion of intents replanned and canceled than the FFFS. The intents were replanned at regular intervals (five minutes before each hour) because of the active block restriction preventing the active block schedule from being deconflicted when a flight intent is submitted during the block. The pilots preferred receiving messages at more predictable times because they cannot monitor Beeline continually. With the FFFS protocol, pilots could receive replan messages within minutes of their expected departure time if a higher priority flight was submitted. During the high-capacity simulations, the proportion of canceled intents decreased across all priorities. When an intent was submitted with a departure time within an active block, the intent was delayed to the start of the next block because of the blocking restriction, thus protecting lower priority flights within the active block that had been scheduled but had not departed. As a result, the total density of low-priority flights within a timespan increased. High-priority flights were more likely to depart earlier in the block, freeing up the remainder of the block for lower priority flights. In the future, a hybrid approach using lottery-based and prioritized scheduling should be studied to investigate the effect of allowing emergency flights to be scheduled upon receipt when using lottery block scheduling for all other flight intents.

Analysis limitations. Despite extensive planning, actual flight conditions will not allow for perfect execution of the live demonstration plan and scenarios because of connectivity, weather, and other uncontrolled issues. Any data collected from demonstrations will result in a limited sample size that is dependent on the conditions present during the demonstration; resulting metrics may not be applicable beyond the live demonstration conditions. As such, simulations are needed to generate a more comprehensive set of metrics to evaluate key concepts. The random-access memory (RAM) needed to run parallel simulations increases exponentially in high-capacity simulations because of the discretization of both spatial and temporal ranges. The increased RAM requirement results in more time needed to complete a larger number of iterations for each scenario.

4.4.2 *Scenario design*

The lessons learned related to scenario design come from flight test planning and demonstration planning.

Participant input. Feedback from pilots on the mission and flight planning process was invaluable in identifying gaps and incorrect assumptions. The shakedown campaign in May 2025 provided us with critical feedback to adjust

the flight designs and assumptions for the final demonstrations. The final demonstrations further provided input for the design of the high-capacity simulations.

Missions. Each of the live flights had a corresponding mission card (see the sample mission card in section A of the appendix) that gave pilots context on which to base their decisions and feedback. Each scenario had the same original flight intents and missions, which served as a helpful reference when discussing differences between scenarios (e.g., why was the lost hiker mission delayed today but not yesterday?).

Simulated flights. The use of simulated flights concurrent with live flights in a demonstration may not be necessary in a smaller airspace. In fact, simulated flights can cause confusion as pilots attempt to confirm deconfliction and replanning with other pilots via radio for safety reasons. In a larger airspace, simulated flights could be used to represent BVLOS operations.

Unlimited operators. In our conflict resolution protocols, we assumed an unlimited number of pilots and aircraft for each role (public safety, public, commercial). As such, intents for the same role could be replanned so that their departure times overlapped. In the demonstration, each role had only one pilot and one aircraft. The pilots were responsible for arranging their own flights, so overlapping missions were combined or flown without landing. This situation aligns with the LAANC rules implemented in Beeline, which allows up to five flights per user and requires users to deconflict their own flights. In reality, a role may be an organization (e.g., law enforcement agency, drone delivery company) with multiple operators and aircraft.

Tabletop exercises. Tabletop exercises proved helpful for collecting initial data and feedback from the pilots and engineers. For example, during tabletop exercises, pilots could provide more thorough feedback on the iUSF interface and scenarios without the added pressure of preparing and executing live flights. The pilots could also communicate openly and discuss feedback on the iUSF—such communication would be impossible in the field. Scenario 4 was conducted only via tabletop because of weather conditions. In the future, tabletop exercises can be incorporated into the main demonstration plan (instead of as a contingency activity) to provide additional testing and validation of the iUSF and key concepts.

Game scenario. The pilots expressed that the scripted schedules for intent submission and live flights were restrictive and not aligned with the way they would plan their own missions. Based on this feedback, during the second week of the demonstration, we used the last day of the campaign to run a less restricted Game scenario. This extra scenario provided insight into the pilots' preferred flight scheduling methods and the resulting effect of more

individualistic actions. The pilots improvised to meet their mission objectives, providing an indication of the way agents in a realistic scenario might make decisions.

All pilots attempted to schedule their flights as early as possible. In the scripted scenarios, flights were scheduled so that each pilot had approximately one flight departing per hour. In the Game scenario, the safety flights were flown back-to-back, and the public flights were also completed relatively quickly, with a few replanning disruptions. The commercial pilot received more, shorter flights than the other two pilots and was unable to schedule flights without constant replanning from higher priority flights, leading to significant frustration. The commercial pilot then decided to combine deliveries in adjacent areas into a single flight to complete all missions. The resulting combined flight path was outside the boundaries of the original operational volumes and not compliant with the flight intents.

In the future, demonstrations and supporting shakedown campaigns can incorporate Game scenarios after required data collection is complete to allow participants to attempt to break or “game” the original system. This type of exercise will enable better understanding of the uses, limitations, and possibilities of the system.

Contingency planning. Incorporating contingencies into the demonstration plan was important to adapt to unfavorable situations. Although we planned six scenarios, we needed a two-week flight campaign (i.e., 10 working days) to buffer against poor flight conditions. In addition, we prepared a complete package of demonstration materials (e.g., alternative flight intents and missions) for a backup site and arranged tabletop exercises to collect data in case live flights could not be accommodated. These preparations allowed us to conduct all the scenarios with feedback from participants, despite multiple days of canceled flights.

Adaptation. Although the shakedown campaign in May 2025 resulted in adjustments to the flight designs for the final demonstrations, we still needed to make ad hoc adjustments during the demonstrations. For example, the pilots needed to change aircraft to accommodate weather conditions and data collection needs. We were also required to make last-minute changes to the flight intents and perform impromptu, manual validation of operational volume conflicts. In the future, establishing procedures and automated processes ahead of time to propagate and validate adjustments will allow us to better accommodate unplanned changes in the field.

4.4.3 Demonstration execution

The lessons learned regarding live flights and field testing came from insights gained while conducting the onsite demonstration.

Visual observers. The visual observers' primary role was to observe each aircraft. They also assisted the pilots in monitoring the tablets for submissions and replanning notifications, and they helped document additional feedback from the pilots, who were too busy to write extra notes on the test cards.

Aircraft. Each of the five aircraft used in the shakedown and live demonstration campaigns have their own requirements and limitations and are affected by environmental conditions in different ways. We considered these differences in the scenario design as well as in the demonstration execution and analysis. For example, the SuperVolo and P8 aircraft are capable of longer flights than the other aircraft, which allowed the pilots to combine multiple 30-minute missions within a single flight. Limitations due to poor visibility, high winds, and refueling needs influenced pilot decisions to adjust flight start and end times.

Connectivity. The iUSF solution required reliable internet for the Beeline tablets. Although the local network at the test site was sufficient during the shakedown, the internet speed was degraded during the demonstration (perhaps because other groups were using the test site at the same time). We used backup Starlink kits to provide the necessary connections at each launch site. As can be seen in the data, substandard network speeds in the field (which are not uncommon) meaningfully affect the performance of automated flight planning and replanning tools.

Safety. Because of errors by users or software, deconflicted flight intents still occasionally overlapped. Thus, pilots relied on verbal communication (via radio) and altitude separation for safety. Furthermore, we observed conformance issues in discrepancies between the flight intent volumes and actual flight trajectories because the iUSF software was not linked to the ground control stations.

Communication. Before the demonstration, we set up a series of shared cloud folders for the engineering team to collect input files and output files for each day. Because of the changing environment, the scenarios for the next day were not confirmed until the morning of (based on flight conditions). Setting up a cloud filing system to clearly organize each day's data was vital to managing all data—the flight intent inputs, system outputs, telemetry logs, and test cards—at the end of each day. Asynchronous communication between engineering team members on- and offsite was also important, especially during the first few days of the demonstration.

Training. We reserved the first day of the demonstration for conducting in-person training and dry runs of the iUSF software with all participants. Although the same pilots participated in the shakedown, the training was necessary to familiarize the pilots with new features and to solicit initial feedback on the new scenario designs.

Realistic expectations. Despite being refined based on lessons learned from the shakedown, the assumptions we used in the scripted scenarios were affected by changing conditions. For example, environmental conditions affected the choice and behavior of aircraft (e.g., SuperVolo exceeded its operational volume because of high winds that required a larger turning radius), and unforeseen software issues arose (e.g., unexpected messages from non-iUSF systems were sent to UCATS and could not be processed). As such, the team's agility and contingency plans helped us adjust to changing circumstances each day.

Pilot interactions with tools. As shown and discussed in the data regarding pilot acknowledgement time, automated systems process information much faster than humans do, which can lead to challenges for human operators conducting flight intents in a hybrid human-automated system. Additional research is necessary to ensure that these systems allow pilots sufficient time and flexibility to interact with the system.

4.4.4 *Software execution*

The lessons learned regarding software come from insights gained during testing and demonstrating the iUSF solution.

ASTM. We leveraged the Operational Intent and Constraint data models as defined by ASTM F3548-21 [2] to exchange information between all three iUSF components. We removed unused data fields (e.g., off_nominal_volumes) from the models to simplify message processing, but we did not add new fields. UCATS successfully performed conflict resolution using the existing fields in the data models.

Data collection. We compiled results from the iUSF at the end of each day to ensure that data were not lost, but some data were lost because of unplanned data corruption or system failures. Although some metrics were automatically calculated in the outputs, additional post-processing was required for others, including manually relating the outputs (e.g., from telemetry logs, test cards, and system logs). In the future, additional planning and organizational improvements can help reduce post-processing needs.

Adaptation. The iUSF system components could be adjusted to unexpected situations (e.g., unplanned actions to change a flight's priority to "emergency" to fly immediately because of time constraints). In addition, we fixed issues we identified regarding conflict resolution at the end of the day, if needed. Changing the code during the demonstrations could have resulted in code errors without time for testing, but baseline versions of the code were retained and could be reinstated at the start of the day if needed.

Checklists. We loaded the appropriate flight intents and scenario parameters into the iUSF system components at the beginning of each day. We unintentionally loaded the files for Scenario 3 into the system on July 14, when those for Scenario 4 should have been loaded. In the future, a checklist should be created to ensure that all inputs are correct because final decisions for which scenarios to run for the day are communicated rather quickly at the start of each day based on flight conditions.

Dedicated environment. The Beeline and AirDEX systems are commercial, production-level tools that other non-iUSF systems interact with. The two systems were adapted for this project successfully, without compromising their intended functionality. However, as production-level systems, Beeline and AirDEX were limited in changes that could be made to functionality (e.g., ignoring military operations areas). AirDEX also received advisory messages from other non-iUSF systems during the demonstration. Because UCATS is subscribed to AirDEX as a typical client, UCATS receives these unexpected, non-iUSF messages, which caused errors when UCATS tried to process them. The messages were filtered out in subsequent days, but new unplanned messages on the last day bypassed the filter and resulted in errors. In the future, a dedicated environment should be used for a prototyping phase so that external interactions do not interfere with iUSF processes.

Dry runs. We conducted multiple dry runs with different participants before the demonstration to confirm that the iUSF components were integrated successfully. However, the dry runs were run in “quick time” to save time. During the demonstration, we found that some assumptions made in quick time did not hold true in real time (e.g., clock synchronization). In the future, shortened real-time dry runs should be conducted to identify any discrepancies between quick-time and real-time executions.

4.4.5 *Simulations*

The lessons learned regarding simulations come from insights gained while testing and simulating the high-capacity scenarios.

Simulation boundary. At start-up, UCATS loads the simulation boundary in the form of a list of vertices defined by latitudinal and longitudinal coordinates. The larger the simulation boundary, the longer it takes to load the cached map between iterations. Because UCATS can parse irregular polygons as the simulation polygons, the smallest possible simulation boundary should be drawn to encompass all flight intent volumes, reducing the total volume of unused airspace.

Deconfliction. As mentioned in the previous section, UCATS creates a grid of sectors encompassing the simulation boundary to track flights through the airspace. When parsing flight intent volumes (i.e., a list of vertices with a start and end time), UCATS stores the list of sector IDs occupied for each time t the flight is airborne. Because UCATS uses time/sector pairs for deconfliction, it spends a majority of the deconfliction time looking up keys to compare a flight's time/sector pairs against the simulation airspace tracking set of time/sector pairs. In the future, UCATS should use a nondiscrete form of deconfliction that does not require storing large sets of time/sector pairs.

Memory optimization. When updating a flight with a new departure time, UCATS creates a new set of time/sector pairs for tracking a flight through the airspace. Some scenarios may result in a high number of conflicts when randomly sampling flights. If UCATS is processing multiple high-conflict iterations at a time, it will consume significantly more memory for a brief period. In future versions, UCATS should edit the set of time/sector pairs in place to consume less memory.

5 Conclusion and Recommendations

The “Enabling UTM Airspace Equity Using an Agent-Based Model” project aimed to address the challenges of managing operational capacity and ensuring equitable prioritization in a future higher density UAS airspace. As the demand for UAS operations increases and technology evolves to support various UAS operators and applications, developing effective methods for managing and deconflicting UAS flight intents will become crucial. The current lack of guidance on prioritizing and managing these operations equitably presents obstacles that must be resolved to ensure a safe and fair UAS environment. In this project, we matured and demonstrated a framework for UAS flight planning operations, the iUSF, using a series of test scenarios to provide insights into UAS capacity management and equitable prioritization. A summary of our key research findings is listed in Table 14. These findings are relevant to the specific scenarios and assumptions that we defined in this project. Additional work is needed to understand how these findings may hold against other scenarios and assumptions.

Table 14 Summary of key research findings

Research Question	Research Findings	Real-World Effects
Effect of a tiered prioritization schema on higher priority operators	More higher priority missions achieved their objectives	Enabled public safety and public pilots to complete missions earlier
Effect of a tiered prioritization schema on lower priority operators	Less lower priority missions achieved their objectives	Commercial pilots learned to expect delays, which could be frustrating
Effect of segmentation on rate of conflict	Reduction in overall number of replanned and failed flight intents	Effect limited and not physically practical for shorter flight durations and volumes
Effect of varying conflict resolution protocols on rate of conflict	FFFS: Higher total rate of failed flight intents but lower rate of replanned intents Lottery: Lower total rate of failed flight intents but higher rate of replanned intents	Lottery protocol preferred by pilots because replan times were fixed (i.e., once an hour)
Effect of constraints on rate of conflict	No effect on total replanned or failed flight intents because of few constraints defined in the scenarios	Low impact due to small number of constraints used

Overall, our live flight demonstrations and high-capacity simulations were successful in (1) providing insights into the ability of the iUSF to address the project research questions, (2) evaluating the effects of replanning, and (3) assessing iUSF system performance. The demonstrations allowed us to observe the real-world effect of the tested key concepts on the iUSF’s performance and effects on operators. The simulations allowed us to test the key concepts of our research in higher density scenarios to better understand how the key concepts affect UAS flight planning at a system level. Based on the lessons learned, we provide the following key recommendations from this work:

- 1) Higher capacity simulations should be executed to generate a more comprehensive set of metrics to evaluate key concepts for UTM over a broader, more distributed simulation area.
- 2) A major objective of live demonstrations should be to gather real-world feedback from participants to influence the assumptions and parameters of simulations.
- 3) Scenarios (e.g., flight intents, launch sites) should be carefully designed and simulated before live demonstrations to ensure meaningful results.
- 4) Participants should be given the opportunity to stress-test the system in a live demonstration.
- 5) Tabletop exercises should be incorporated into the demonstration plan and used for testing and validation.
- 6) A dedicated software environment should be used to execute the demonstration and to avoid interference from unrelated systems.
- 7) Data networking in the field should be robustly addressed early in the execution of the research.

- 8) The demonstration materials and plan should be agile to address unplanned conditions and adjustments.
- 9) Additional research should be conducted on the ways humans interact with highly automated flight planning and replanning systems.
- 10) Additional research should be conducted on hybrid approaches to prioritization and conflict resolution to leverage advantages from multiple protocols.
- 11) Additional research should be conducted to validate the research findings with more scenarios.

The insights gained from this project can help inform future decision-making for UAS flight planning rules and forecasts. However, the findings from this research should be validated further with other scenarios and assumptions. Additional questions should also be addressed before UTM can be fully integrated into the NAS. The following are a few areas of future work that the iUSF can help investigate:

- 1) The iUSF was demonstrated in a semi-urban area in Fairbanks, Alaska. Additional simulations could be conducted to test the key concepts in regions with different population densities (e.g., rural, urban).
- 2) The iUSF considered only delay as a solution to conflict resolution. Other types of solutions, such as altitude separation and rerouting, will enable more optimized methods of resolving conflict.
- 3) The iUSF did not consider non-UTM participating aircraft (e.g., general aviation, helicopters), which were deconflicted visually in the live demonstrations. A SDSP with Automatic Dependent Surveillance–Broadcast data could be integrated into the iUSF to provide this capability.
- 4) UAS flight planning should consider new requirements and protocols for BVLOS operations. The iUSF can be adapted to consider the effect of proposed or possible BYLOS requirements (e.g., population density categories, deconfliction with noncooperating aircraft, weather constraints).

6 Appendix: Example Cards

A. Example Test Card



Initials: _____ Date: _____

iUSF Performance / System Evaluation Report Test Card

Basic Information							
Flight #:		File Time:		Begin Time:		End Time:	
If applicable, Segment Times	S2 Start Time:			S3 Start Time:			
Pilot Role:	<input type="checkbox"/> Commercial <input type="checkbox"/> Public <input type="checkbox"/> Safety						
Location:	<input type="checkbox"/> Site 1 (Herder Burner)			<input type="checkbox"/> Site 2 (Balloon Inflation)			
Crew	RPIC:				Observer(s):		
Aircraft Model:	<input type="checkbox"/> SuperVolo <input type="checkbox"/> SkyHunter <input type="checkbox"/> P8 <input type="checkbox"/> X6A <input type="checkbox"/> Alta X <input type="checkbox"/> Autel Evo Other: _____						
Limitations and Other Notes:							

#	Action	Response and Comments
1.	Observations of actions taken by pilot in the event of <u>re-planning</u> .	
2.	Confirm safe <u>completion</u> of flight intent (or alternate).	<input type="checkbox"/> Orig. Intent <input type="checkbox"/> Re-Planned Intent <input type="checkbox"/> Alternate <input type="checkbox"/> Canceled Comments:

Question	Response and Comments
Did the structure of the <u>original</u> flight intent make achieving the mission objective difficult?	<input type="checkbox"/> Yes <input type="checkbox"/> No Comments:
Did the <u>re-planned</u> intent allow for completion of the mission?	<input type="checkbox"/> N/A <input type="checkbox"/> Yes <input type="checkbox"/> No Comments:
To what degree did the <u>re-planned</u> intent alter the effort to compete the mission?	<input type="checkbox"/> N/A <input type="checkbox"/> Not at all <input type="checkbox"/> Somewhat <input type="checkbox"/> Significantly Comments:

B. Example Mission Card



iUSF Flight Demonstration Mission Card

Basic Information	
Flight #	4
Title	Find Hiker
Duration	30 minutes
Mission	<p>This is an <u>emergency</u> public safety mission. A hiker in distress has been reported at the location indicated.</p> <p>Search for the group of hikers. Drop a radio and other supplies to the hikers, and stay in the area to provide follow up assistance and situational awareness as needed.</p>
	

7 References

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