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# Strategic Deconfliction Simulation (SDS) Final Report

*Hanbong Lee*
*NASA Ames Research Center, Moffett Field, CA*

*Alan G. Lee*
*NASA Ames Research Center, Moffett Field, CA*

*Chin H. Seah*
*Metis Technology Solutions, Moffett Field, CA*

*John E. Robinson III*
*Crown Innovations, Inc., Moffett Field, CA*

*Daiven D. Patel*
*Noblis, Moffett Field, CA*

*Kushal A. Moolchandani*
*Crown Innovations, Inc., Moffett Field, CA*

*Samuel Santiago*
*NASA Ames Research Center, Moffett Field, CA*

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*Samuel Santiago*
*NASA Ames Research Center, Moffett Field, CA*

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, CA 94035-1000

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# Executive Summary

Urban Air Mobility (UAM) is expected to introduce highly automated passenger and cargo operations in metropolitan areas, requiring new airspace services, cooperative procedures, and interoperable systems to ensure safe and efficient operations at scale. NASA's Strategic Deconfliction Simulation (SDS) was conducted to evaluate mid-term strategic planning and predeparture deconfliction capabilities within a multi-operator UAM environment. SDS integrated NASA-developed airspace services with industry partner's services for data exchanges within the Provider of Services for UAM (PSU) network according to the draft American Society for Testing and Materials (ASTM) PSU Interoperability Standard to assess whether UAM operators could strategically plan, schedule, and safely deconflict flights within shared UAM corridors and vertiports. The simulation used representative Dallas 2040 airspace constructs, realistic traffic scenarios, and a federated service network to test Demand-Capacity Balancing (DCB), Sequencing and Spacing (S&S), data exchange protocols, and flight replanning capabilities when the capacity of an airspace resource shared by multiple users like vertiport is reduced.

SDS demonstrated that coordination through the PSU network enables successful information exchange of operational intents, pre-flight scheduling, and strategic conflict management between multiple UAM operators. Across medium- and high-density traffic scenarios, DCB resolved predicted demand-capacity imbalances at vertiports and corridor entry/exit points, while NASA's S&S reduced the severity of proximity events at control waypoints. The vertiport capacity reduction use case validated that the architecture could accommodate flight schedule updates to resource availability through replanning and controlled cancellations. The simulation also revealed important insights regarding operator fairness, differences in operator-specific DCB logic, combining DCB with S&S, Discovery and Synchronization Service (DSS) behaviors, Resource Information Service (RIS) implementation, and the sequencing of flight state transitions in replanning, which would inform both technical evolution and standards refinement.

Below is the summary of the SDS achievements:

- Evaluated the efficacy of Demand-Capacity Balancing (DCB) for strategic deconfliction of UAM flights,
- Tested NASA's UAM services like Sequencing and Spacing (S&S) service, Discovery and Synchronization Service (DSS) for UAM, and Resource Information Service (RIS),
- Validated PSU requirements and data exchange protocols defined in the draft ASTM PSU Interoperability Standard,
- Integrated and tested industry partner's UAM services on NASA's simulation environment and UAM system architecture, and
- Conducted simulations for UAM strategic planning and deconfliction as a precursor toward Technical Capability Level 1 (TCL-1) simulations.

The simulation results and lessons learned from SDS will provide key technical evidence to guide the maturation of PSU standards, support NASA's upcoming TCL-1 simulation efforts, and inform future UAM research activities. The findings also offer valuable direction for industry partners and standards bodies working toward safe, scalable, and equitable UAM operations.

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# 1 Background

Urban Air Mobility (UAM) is an emerging concept that envisions highly automated, cooperative, passenger or cargo-carrying air transportation in metropolitan areas, enabled by innovative aircraft, air traffic technologies, and business models [1, 2]. UAM focuses on short duration flight operations in and around urban areas to reduce door-to-door travel time and uncertainty, compared to ground transportation alternatives.

The Federal Aviation Administration (FAA) released a UAM Concept of Operations (ConOps) document to describe an envisioned operational environment that supports the expected growth of UAM operations and provide guidance to the UAM industry [3, 4]. In this document, the FAA proposed UAM Corridors (and the more general term, 'Cooperative Areas'), which are performance-based regions of airspace with defined dimensions in which aircraft abide by UAM-specific rules, procedures, and performance requirements. The FAA UAM ConOps provides details about how the proposed UAM Corridor concept would function and evolve over time. The FAA ConOps document describes a framework that evolves through initial, midterm, and mature state operations based on key indicators, including operational tempo, UAM structure (airspace and procedures), UAM-driven regulatory changes, UAM Cooperative Operating Practices (COPs), aircraft automation levels, and the location of the pilot-in-command (PIC). Based on the NASA-developed Unmanned Aircraft System (UAS) Traffic Management (UTM) paradigm, the Provider of Services for UAM (PSU) was introduced for efficient data exchanges and information sharing between multiple UAM operators. The FAA UAM ConOps also emphasizes the need for COPs which are industry-defined, FAA-approved practices that address how operators cooperatively manage their operations within UAM cooperative areas. The COPs include expectations for conflict management, equity of airspace usage, and Demand-Capacity Balancing (DCB). With these new concepts and the notional system architecture for a UAM ecosystem, more research and development are needed for both effective UAM airspace design and cooperative airspace management services.

NASA has conducted a series of simulations to support the development of airspace procedures and services for UAM operations and to assess the FAA's UAM ConOps. The "X1" simulations (2017-18) explored UAM stakeholder roles, responsibilities, and communication needs using helicopter routes in the Dallas-Fort Worth metropolitan area for initial UAM operations [5]. In 2019, NASA conducted the "X2" simulations with an industry partner to see if UTM-based operational volumes and data exchange protocols could be applied to UAM operations in the shared airspace [6]. The subsequent "X3" simulation in 2020 evaluated airspace systems like PSUs developed by NASA and National Campaign partners [7, 8]. In 2021-22, NASA and seven industry airspace service partners completed the "X4" simulations to develop strategic conflict management services for UAM operations and prepare for UAM flight tests [9-13]. The X4 simulation focused on the pre-departure scheduling of UAM operations at capacity-constrained airspace resources like vertiports. Participants, including NASA and partners, developed airspace services to schedule UAM flights strategically and ensure demand did not exceed capacity. These capabilities were tested in NASA's collaborative simulation environment for multiple UAM operators. Recently, NASA conducted PSU Prototype (X5) Simulations to extend and validate UAM airspace management capabilities, including DCB and Sequencing and Spacing (S&S) at control waypoints and a prototype NASA-FAA connection service for future PSU-ATM interface requirements. The lessons learned from the "X5" simulations and the requirements and Application Programming Interfaces (APIs) for information exchange through the PSU interoperability network were shared with the UAM industry and standard bodies (e.g., ASTM) [14, 15, 16].

Leveraging the results of these simulations with other UAM research and development activities such as National Campaign flight tests, the ATM Interoperability Simulation (AIS) and the Automation Enabled Pilot (AEP) simulations [17, 18], NASA is planning to conduct the Technical Capability Level 1 (TCL-1) simulation with multiple industry partners in 2026. TCL-1 focuses on the anticipated technical challenges that will be encountered as UAM operations mature. TCL-1 will leverage existing Live, Virtual, Constructive (LVC) simulation capabilities, NASA and industry partner PSU services, high-fidelity flight simulators, and fleet management systems.

# 2 Strategic Deconfliction Simulation Overview

The Strategic Deconfliction Simulation (SDS) is part of a broader set of TCL-1 simulation activities to evaluate the extent that strategic planning, pre-departure deconfliction, and COPs maintain safe and efficient traffic flow at midterm operational tempos. As part of SDS, UAM airspace services supporting strategic planning and pre-departure deconfliction will be developed and evaluated for the safe and efficient traffic management of UAM aircraft at midterm operational tempos. SDS specifically focuses on PSU services and the related PSU interoperability requirements. It will advance the development of consensus-based PSU standards by assessing the efficacy of strategic scheduling and deconfliction functions of UAM operations.

## 2.1 Objectives

The UAM industry, NASA, and the FAA have made progress to operationalize the UAM concept. The UAM industry has been developing new technologies like quiet electric Vertical Take-Off and Landing (eVTOL) aircraft, PSUs, and UAM fleet management systems. The FAA published the UAM Concept of Operations v2.0 document [4]. The FAA and industry partners conducted simulations to evaluate the PSU DCB functions at the entry and exit points of UAM corridors during the FAA's UAM Demo series. As described above, NASA conducted a series of simulations for UAM research and continued to enhance the airspace services. NASA introduced additional functions such as Sequencing and Spacing (S&S) for Strategic Conflict Management of UAM operations and modified the existing UTM-based Discovery and Synchronization Service (DSS) to accommodate UAM operations. In addition, standard bodies like American Society for Testing and Materials (ASTM) International's PSU Specifications working group are also developing the PSU interoperability standard. Currently, the UAM industry, NASA, and the FAA are actively working together to develop the draft ASTM PSU Interoperability standard. This standard focuses on DCB for strategic planning and conflict management of UAM operations, defines the requirements for the core PSU functions and relevant interfaces, and integrates the Vertiport Operator (or Resource Operator in general) and the associated Resource Information Service (RIS) in alignment with the FAA UAM ConOps v2.0 document.

The SDS test objectives were established based on the state-of-the-art technologies and R&D activities from UAM community and on the industry's needs for validating the PSU requirements and APIs developed in the first draft of the ASTM PSU Interoperability standard. They were also designed to align with the TCL-1 goal to collaborate with industry partners in NASA's simulation environment. The SDS objectives were defined as follows:

- Evaluate Demand-Capacity Balancing (DCB) both at vertiports and waypoints
- Evaluate Sequencing and Spacing (S&S) and the Modified DSS for UAM
- Integrate a Vertiport Operator and the associated Resource Information Service (RIS) per the draft ASTM PSU Interoperability standard
- Integrate industry partner's services (PSU, DCB, vertiport management system, etc.)

The following key SDS research questions were defined in conjunction with the SDS test objectives:

- Does the proposed SDS test architecture for the UAM system support strategic flight planning, scheduling, data exchange, and data archiving between UAM operators in a manner that is consistent with the draft ASTM PSU Interoperability standard?
- Does Strategic Conflict Management (e.g., Demand-Capacity Balancing, Sequencing & Spacing) ensure safe UAM operations at a midterm operational tempo?
- What are the information exchange requirements to achieve integration of multiple UAM operators (and their associated PSUs) in a shared UAM airspace?

To achieve the SDS test objectives and answer the research questions, NASA developed a UAM system architecture that integrates the current industry-vetted capabilities for UAM air traffic management and selected one industry partner, ANRA Technologies, for the collaborative simulations. The simulation runs were implemented for UAM traffic operated in an abstracted version of the Dallas-Fort Worth airspace, called "Dallas 2040" representative airspace, which was designed to procedurally minimize interactions with crewed aircraft operating in that airspace.

## 2.2 Scope

NASA defined the SDS scope to satisfy the test objectives and be aligned with the current development status of the UAM airspace management capabilities and the progress on the PSU Interoperability standard. Table 1 shows the minimum and full success criteria for each feature of the simulated UAM flight planning process. Most features met the full success criteria as an outcome of SDS, as marked with green color text in the table. A few features only met the minimum success criteria during SDS and will be fully implemented in future simulations (e.g., TCL-1), highlighted in yellow in the table below.

*Table 1: SDS success criteria*

| Category | Minimum Success Criteria | Full Success Criteria |
|---|---|---|
| Multiple UAM Operators | Have two UAM Operators using separate NASA PSUs | Have two UAM Operators using one NASA PSU and one industry partner's PSU |
| Flight Planning | Submit flight plans in advance (strategic planning) | Submit flight plans within pre-tactical time horizon (e.g., 1-2 minutes before takeoff) |
| Demand-Capacity Balancing (DCB) | Apply DCB at vertiports only | Apply DCB at vertiports and UAM corridor entry/exit points |
| Sequencing & Spacing (S&S) | Introduce S&S at control waypoints such as crossing/merging points and UAM corridor entry/exit points | Introduce S&S at all control waypoints with different separation minima |
| Discovery & Synchronization Service (DSS) | Use the Modified DSS for UAM (new operational states for DCB per draft ASTM PSU Interoperability standard) | |
| Vertiport Operator | Monitor vertiport availability (using the DCB Monitor Tool) | Monitor timelines (Estimated Time of Arrival (ETA) and Scheduled Time of |

| | | |
|---|---|---|
| | | Arrival (STA)) at vertiports (using the Timeline GUI) |
| Traffic Level | Simulate traffic scenarios at a medium traffic level | Simulate traffic scenarios at both medium and high traffic levels |
| Resource Capacity | Use static resource capacities | Change resource capacities during the simulation run, causing replanning |
| Air Traffic Control (ATC) Interactions | N/A | Monitor potential conflicts with conventional air traffic in controlled airspace (e.g., near airports), requiring ATC intervention |
| Data Visualization | Use data visualization tools for traffic monitoring and situational awareness (for simulation researchers) | Use data visualization tools for various human actors (observer mode) |
| Airspace Construct | Predefined routes between a fixed set of origin-destination pairs based on the "Dallas 2040" representative airspace to evaluate strategic planning and deconfliction in cooperative areas | Predefined routes between a fixed set of origin-destination pairs based on the "Dallas 2040" representative airspace to evaluate strategic planning and deconfliction in cooperative areas and Cooperative Operating Practices (COPs) |
| ETA Prediction / Conformance Monitoring | Deterministic ETA predictions (i.e., perfect match between predicted ETAs and simulated ATAs) | Uncertain ETA predictions within a given tolerance (i.e., predicted ETAs and simulated ATAs are reasonably different) |
| Vehicle Model | A single eVTOL model for all flights, regardless of UAM Operators (i.e., apply the same vehicle performance model (e.g., same cruise speed) for scheduling) | Two or more eVTOL models, depending on UAM Operator (e.g., different cruise speeds by operator) |

## 2.3 Assumptions

SDS focuses on the information sharing between two UAM operators for strategic flight planning and deconfliction through the PSU interoperability network. This simulation effort does not model all elements of the real-world UAM operational environment such as human actors, vehicle performance, and weather conditions. This means that the SDS simulations are in a more deterministic condition and work with fully automated systems for flight plan submission, DCB check, flight activation and maneuvers, without any manual inputs, so that there are no uncertainty factors affecting simulation results. Table 2 lists the assumptions associated with the SDS test environment.

*Table 2: SDS assumptions*

| Category | Assumption |
|---|---|
| Airspace | Cooperative areas for UAM operations (i.e., UAM Corridors) are established. The Dallas 2040 airspace for the DFW metropolitan area is used. |
| ATC interactions | ATC does not provide separation services, traffic advisories, or safety alerts to UAM aircraft within UAM cooperative areas. |
| Communications | Digital communications for entire nominal operations; No voice communications between human pilots, fleet managers, and air traffic controllers |
| Pilot Modality | Pilot onboard (i.e., crewed operations; no uncrewed operations yet); Pilot communication with fleet manager assumed, but not simulated |
| PSU | Flight planning and strategic conflict management functions; Operational Intent data sharing with others; Data archiving |
| UAM Operator | Submit flight plan automatically at the given time (i.e., no uncertainty in flight plan submission time) |
| Vehicle | A single, representative eVTOL aircraft model from the Revolutionary Vertical Lift Technology (RVLT) project for all flights. Aircraft will meet the Required Times of Arrival (RTAs) at control waypoints within a tolerance for Conformance Monitoring. |
| Vertiport Operations | Ground operations, such as taxiing, parking, and battery charging, are neither modeled nor considered. Simultaneous operations for takeoff/landing are allowed. |
| Weather Conditions | Good weather conditions; Calm winds |

# 3 System Architecture

## 3.1 UAM Architecture – Level 0

In 2023, the FAA published UAM ConOps v2.0 [4], outlining the expected operational environment for UAM operations. This document provided the FAA's notional UAM system architecture (*Figure 1*), which served as the foundation for the UAM airspace management system architecture modeled in the Strategic Deconfliction Simulation (SDS).

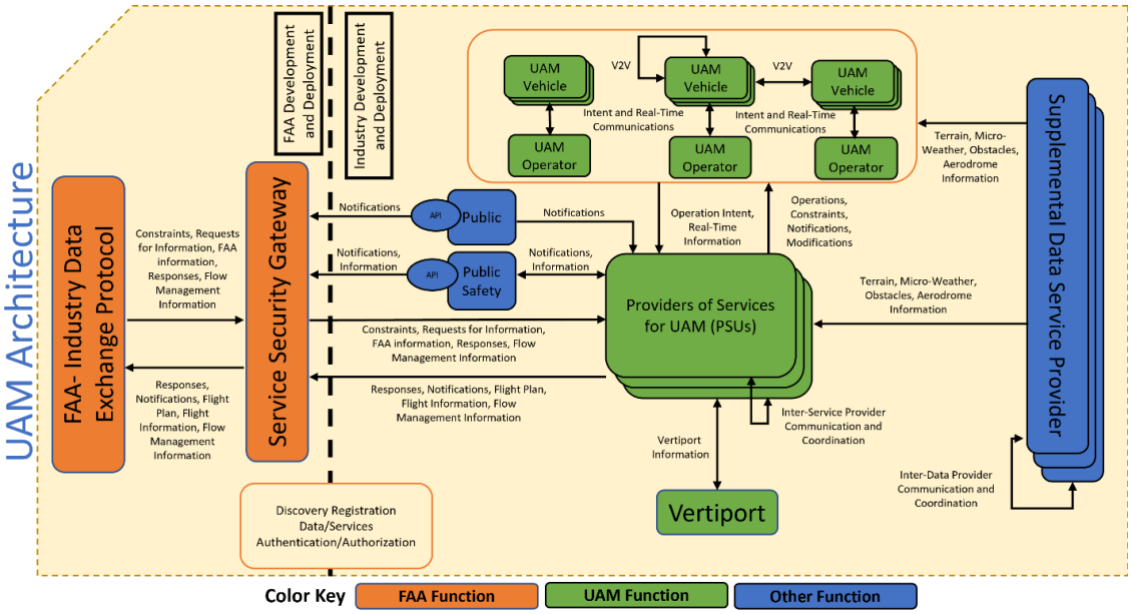



*Figure 1 Notional UAM Architecture from FAA UAM ConOps [4]*

While the notional UAM system architecture served as a starting point for the SDS simulations, the UAM test architecture simulated for SDS included refined "Provider of Services for UAM (PSU)" capabilities as well as other services and technologies to support strategic planning and deconfliction for UAM operations.

Figure 2 shows the UAM test architecture simulated for SDS, which is aligned with the FAA UAM ConOps and reflects the draft ASTM PSU Interoperability standard. This "Level 0" test architecture includes the fleet management systems for two UAM operators (i.e., NASA and industry partner ANRA Technologies), the associated PSUs, the resource management systems, and the target generators to implement the planned capabilities and exchange the necessary information for UAM flight planning and strategic conflict management.

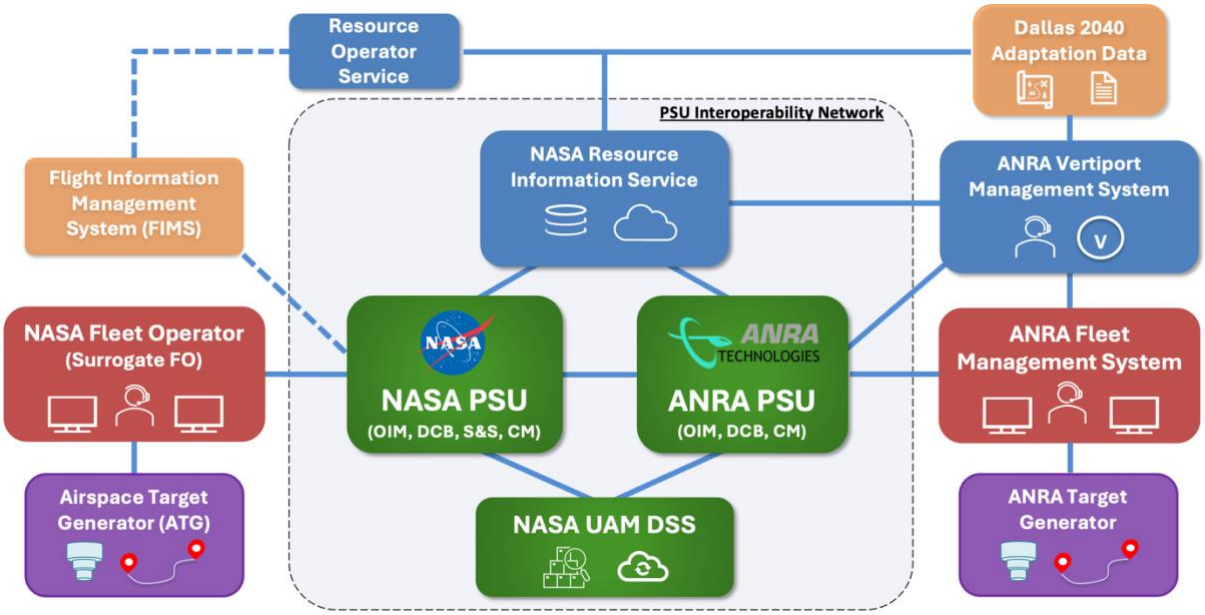



*Figure 2 UAM Test Architecture – Level 0*

## 3.2 UAM Architecture – Level 1

This section describes the more detailed "Level 1" test architecture (Figure 3). It is derived from the Level 0 test architecture (Figure 2). The main SDS system functions are decomposed into specific software modules and services. The UAM airspace services and system components run by industry partner, ANRA, are shown on the right.

The resource management services provide capacity constraints at the vertiports and other airspace resources. The baseline Dallas 2040 airspace definition – waypoint locations, routes/track data, corridors, and conformance bounds is provided in a static "adaptation" file. Fleet management services such as NASA's Surrogate Fleet Operator (S-FO) and ANRA's Fleet Management System manage UAM operations and coordinate with the associated PSUs. The core PSU services are shown within the PSU Interoperability network (dashed line). They include operation intent management (OIM), strategic conflict management (DCB and S&S), and conformance monitoring (CM). The SDS test architecture includes a single Resource Information Service (RIS) provided by NASA to collect and share the resource status and capacity information. A single Discovery and Synchronization Service (DSS) is also provided by NASA. Aircraft position data are provided by target generators like NASA's Airspace Target Generator (ATG) and ANRA's flight simulation model.

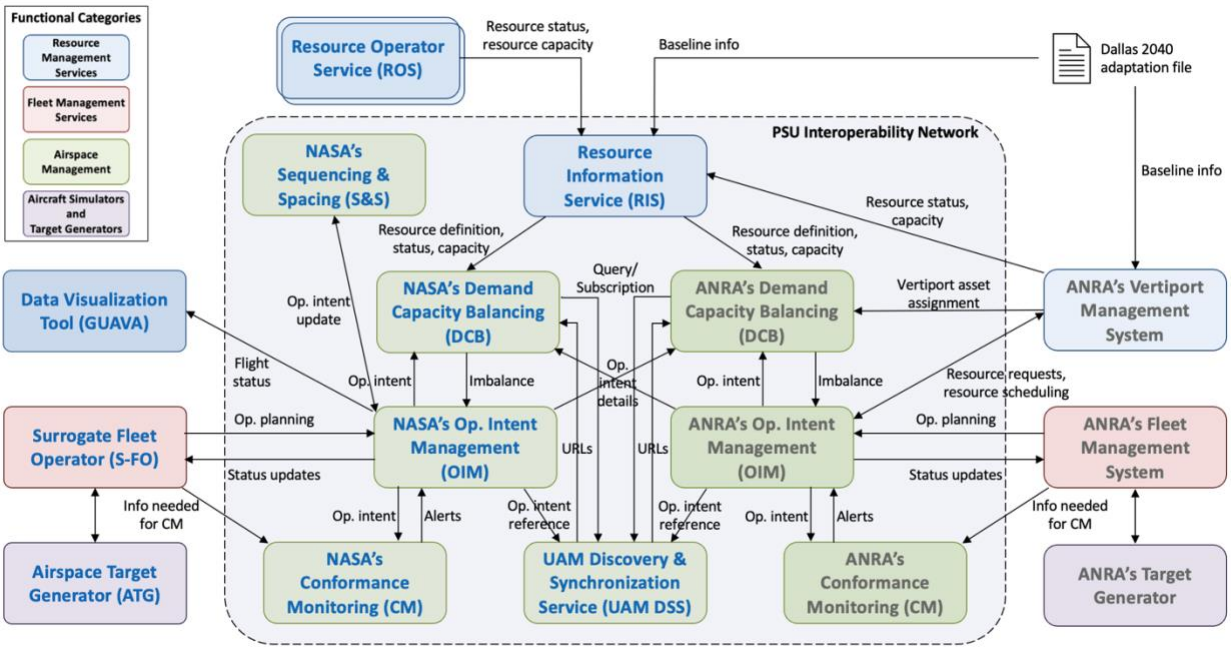



*Figure 3 UAM Test Architecture – Level 1*

The UAM simulation environment requires data model definitions and APIs for information exchange among PSUs and with other airspace services. The SDS APIs are based on the PSU Prototype Simulation (X5) APIs, and the additional DCB-RIS API for resource capacity and status updates. The SDS APIs are available in the public NASA GitHub repository [19].

## 3.3 NASA's UAM Airspace Services and System Components

This section describes the airspace services and system components that were developed and used by NASA to conduct the SDS simulations. NASA's capabilities included all elements of the UAM test architecture.

### *3.3.1 Surrogate Fleet Operator (S-FO)*

The Surrogate Fleet Operator (S-FO) is a simulation tool to emulate the role of the fleet management system and Fleet Operator (FO) for UAM operations such as flight plan creation, modification, and submission to the PSU. S-FO runs a traffic scenario and connects with other airspace services to execute the UAM operations. S-FO acts as a fully automated Fleet Operator (i.e., wholly without a human actor or a Graphical User Interface (GUI)).

### *3.3.2 PSU - Operation Intent Management (OIM)*

Operation Intent Management (OIM) is one of the core PSU functions defined in the draft ASTM PSU Interoperability Standard. The OIM is the central point for coordinating and communicating operational intents within the PSU network. It handles the dissemination of operational intent details with other authorized entities. Note that in the UAM/PSU context, the operational intent takes the form of a 4-dimensional trajectory (4-DT), in contrast to the operational intent volumes in the UAS Service Supplier (USS) interoperability for UTM.

### *3.3.3 PSU - Conformance Monitoring (CM)*

Conformance Monitoring (CM) is one of the core PSU functions defined in the draft ASTM PSU Interoperability Standard. The CM monitors the 4-D trajectory of an active UAM operation for compliance to defined spatial and temporal conformance bounds associated with its approved operational intent. It notifies the PSU when nonconformance is detected. It is critical for maintaining safety and replanning by other operators. In SDS, those conformance bounds were applied to specific control waypoints only such as corridor entry/exit points and crossing and merging points.

### *3.3.4 Demand-Capacity Balancing (DCB) service*

Demand-Capacity Balancing (DCB) service is an airspace service to check existing demand and capacity at the shared airspace resources used for UAM operations such as vertiports and UAM corridor entry/exit points and provide advisories to resolve demand-capacity imbalances when detected. The DCB service contributes to strategic conflict management by managing airspace capacity at constrained resources. It determines whether the constrained resources are at- or over-capacity and communicates this information to the PSU OIM role for operation replanning to prevent demand from exceeding capacity.

### *3.3.5 Sequencing and Spacing (S&S) service*

Sequencing and Spacing (S&S) service is an airspace service to check sequencing criteria and spatial/temporal spacing constraints at the shared airspace resources used for UAM operations such as crossing and merging waypoints between routes and provide advisories such as adjusted timings. The S&S service contributes to strategic conflict management by synchronizing traffic at constrained resources. It can be used in combination with DCB to more effectively distribute traffic demand by assigning ground delays than DCB alone. S&S is currently not part of the draft ASTM PSU Interoperability Standard but is mentioned as a possible future topic.

### *3.3.6 Discovery and Synchronization Service (DSS) for UAM*

Discovery and Synchronization Service (DSS) is a tool that allows PSUs to identify relevant information that may be owned by another PSU ("Discovery"), ensures that information was consistent across each PSU ("Synchronization"), and supports strategic confliction detection by identifying operational volumes that intersect each other. The DSS for UAM is based on an open-source implementation meeting certain ASTM standards for UTM [20] that has been built and maintained by industry. NASA modified the existing UTM-based DSS for use in SDS to support strategic planning and deconfliction of UAM operations such as DCB. Detailed modification and verification are described in Appendix A.

### *3.3.7 Resource Information Service (RIS)*

Resource Information Service (RIS) is one of the core PSU functions defined in the draft ASTM PSU Interoperability Standard. Within the PSU interoperability network, the RIS provides discovery capabilities for UAM stakeholders to identify the definition, current status, and current and future capacities of shared UAM resources. The dynamic status and capacity of each shared resource is determined by individual resource operators. In SDS, a single RIS is provided and run by NASA to collect and share the resource status and capacity information for both fleet operators.

### *3.3.8 Resource Operator Service (ROS)*

NASA's Resource Operator Service (ROS) is an airspace service to provide the status and capacity of UAM resources like vertiports and enroute control waypoints for DCB. The draft ASTM PSU Interoperability Standard defines the Resource Operator as the entity responsible for operating one or more UAM resources. Each resource has a single resource operator. A vertiport operator is the resource operator associated with a vertiport. In SDS, the Postman API platform (either its User Interface front-end or command line interface) is used to perform the resource operator functions. The baseline definition, initial status, and initial capacity of the resource are defined in static adaptation files.

### *3.3.9 Airspace Target Generator (ATG)*

The Airspace Target Generator (ATG) is the NASA-developed system to provide simulated conventional and UAM operations for NASA air traffic simulations. These virtual operations use aircraft performance models to fly from their origin to destination along realistic prescribed trajectories. ATG runs as a separate software process and has its own set of API functions through which it communicates with other services.

### *3.3.10 Graphic-based UAM Airspace Visualization Assistant (GUAVA)*

The Graphic-based UAM Airspace Visualization Assistant (GUAVA) is a NASA developed engineering graphical display used to visualize and monitor UAM operations and resources in real time during simulation runs. Figure 4 shows the basic GUAVA display that was used for SDS. GUAVA provides useful information to support debugging, simulation observation, and demos on two displays – the DCB Monitor (shown on the top left) and the Situational Viewer (shown on the bottom right). The DCB Monitor displays demand and capacity status and information in tabular form. The Situational Viewer shows a map-based view of the UAM airspace and airborne operations.

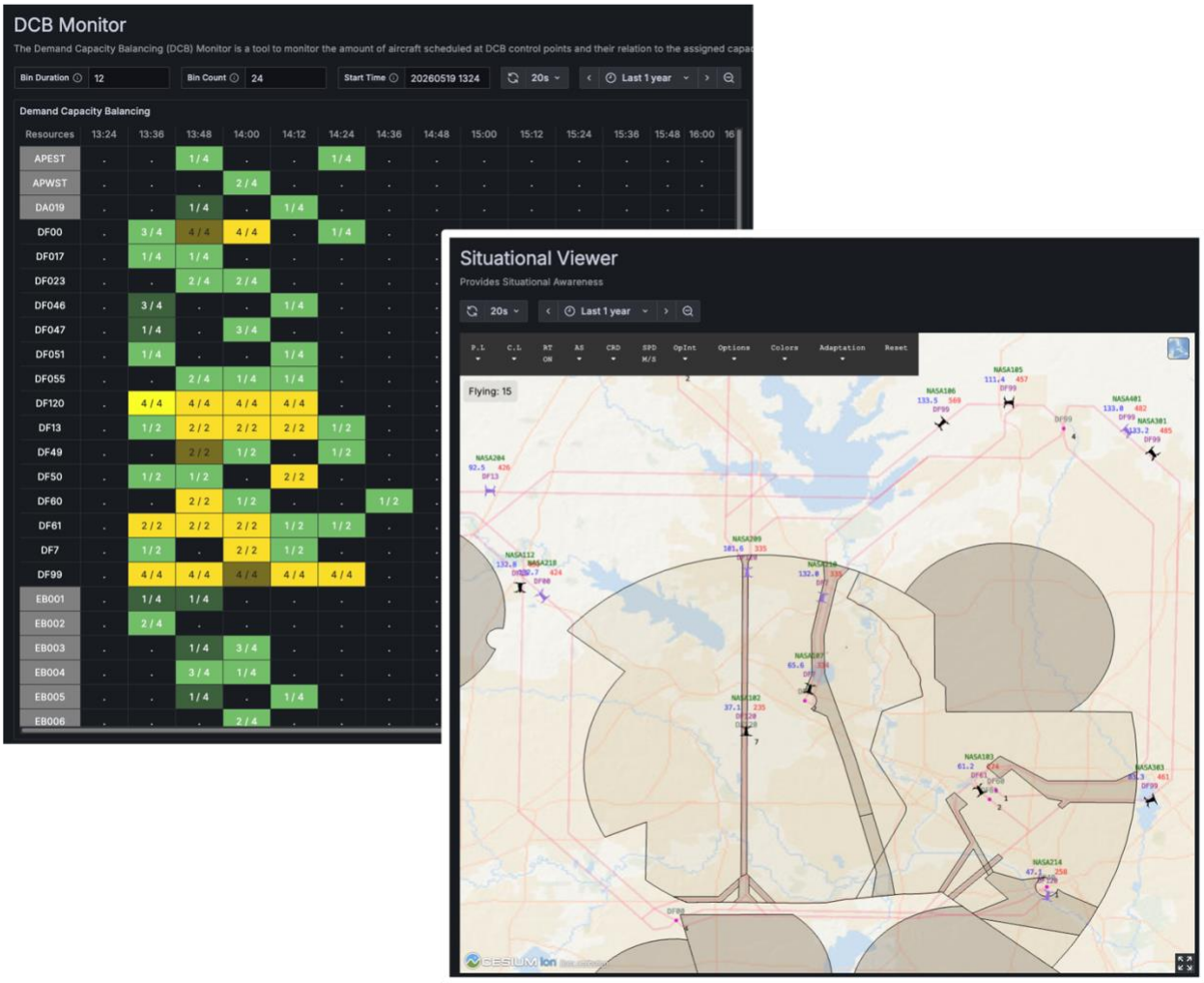



*Figure 4 UAM Data Visualization Tool (GUAVA)*

## 3.4 ANRA's UAM Airspace Services and System Components

This section describes the airspace services and system components that were developed and used by ANRA to conduct the SDS simulations. These services and systems included a fleet management system, PSU functions, Demand-Capacity Balancing (DCB) service, and a vertiport management system, which are connected to NASA's services and systems. NASA and ANRA conducted a series of integration tests to ensure the connectivity between systems and information exchanges before the simulations for data collection were performed.

### *3.4.1 ANRA's Fleet Management System*

ANRA's Fleet Management System provides comprehensive fleet management capabilities for UAM operations, including mission planning, execution, and monitoring, optimizing operational workflows and resource allocation. It is integrated with airspace management systems and regulatory compliance tools, and it provides operators with real-time tracking, analytics, and automated workflows to enhance operational efficiency and safety [21].

#### *3.4.2 ANRA's PSU functions (OIM, CM)*

ANRA's PSU functions for SDS included an Operation Intent Management service and a Conformance Monitoring service. ANRA's PSU serves as a hub of all functions associated with planning and execution of UAM operations, including single, integrated operating picture for operator situational awareness, management of flight requests and amendments, strategic coordination of operations through demand capacity balancing, operational intent exchanges and coordination with other PSUs, discovery and display of dynamic airspace constraints, and live telemetry and surveillance display.

#### *3.4.3 ANRA's Demand-Capacity Balancing (DCB) service*

ANRA's Demand-Capacity Balancing (DCB) service provides a strategic airspace management function that ensures safe and efficient UAM operations by aligning air traffic demand with available resources like vertiports. It uses real-time and predictive data to detect imbalances and assess resource availability.

#### *3.4.4 ANRA's Vertiport Management System*

ANRA's Vertiport Management System serves as a focal point for coordinating and monitoring operations on and around the vertiport. It receives operation requests from the PSU and uses the resource management service and DCB service to check vertiport availability. It can also provide interfaces that enable the vertiport manager to monitor and engage vertiport management functions.

# 4 Simulation Execution

## 4.1 UAM Airspace and Procedures

This section describes the specific UAM airspace and procedures in the Dallas-Fort Worth metropolitan area, which are used for SDS, leveraging the Dallas 2040 representative adaptation. The Dallas 2040 adaptation is based on prior studies of UAM airspace design and analysis of representative modifications for proposed UAM operations in the Dallas-Fort Worth region [12, 13]. The UAM airspace used in SDS includes Class B corridors, vertiport, and arrival and departure procedures in the airspace around Dallas-Fort Worth metropolitan area airports such as Dallas-Fort Worth (DFW), Dallas Love Field (DAL), Fort Worth Alliance (AFW), and Addison (ADS), as well as population centers like downtown Dallas, Texas Motor Speedway, and AT&T Stadium. For SDS, it was assumed that these major airports are operating in a South Flow configuration with UAM operations conducted under Visual Flight Rules (VFR). UAM Cooperative Areas (i.e., UAM corridors) in DFW Class B airspace are marked in orange in Figure 5. These corridors allow UAM vehicles to operate safely and efficiently without burdening the conventional air traffic control system. The corridors were not constructed outside of DFW Class B airspace, though in future simulations they could be. UAM routes and corridors are primarily constrained below 1,500 feet Above Ground Level (AGL) to reduce the need for deconfliction with conventional flights and to minimize ATC workload. Where UAM routes cross, procedural separation is achieved via altitude restrictions.

Figure 5 illustrates the airspace defined in the Dallas 2040 adaptation. The airspace includes five vertiports inside the DFW Class B airspace and another five vertiports outside it. All corridors are 3,000 feet wide permitting bi-directional tracks separated laterally by 1,500 feet and 750 feet from the edge of the corridor. For UAM operations within Class E and G airspace, predefined

UAM corridors are not required. However, for the simplicity of the simulation, NASA created potential routings between vertiports for operational planning.

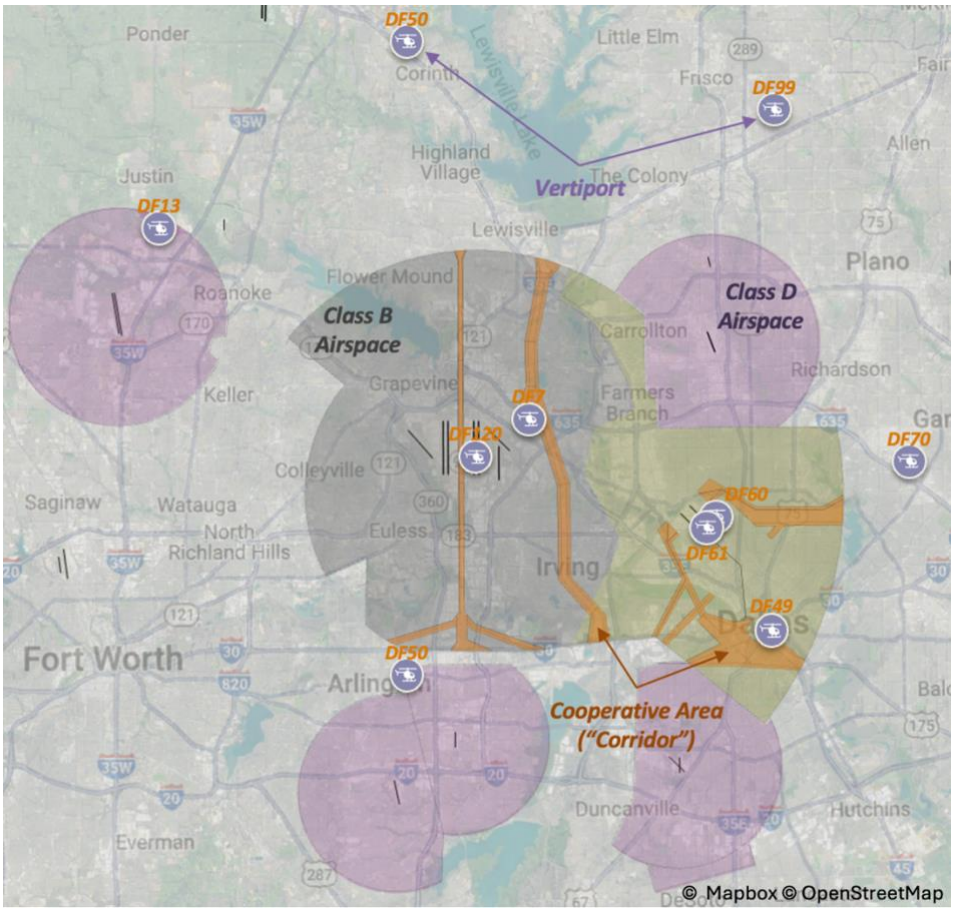



*Figure 5 Dallas-Fort Worth Airspace*

A set of vertiports and routes between the Origin-Destination (OD) pairs in the Dallas-Fort Worth metropolitan area were defined to explore both DCB and S&S functionalities for this simulation. Figure 6 shows the selected 18 OD pair routes with eight vertiports whose names start with “DF” used in the simulation. The DFW Class B airspace is shown in pale yellow (DFW tower) and pale green (DAL tower). Nearby Class D airspaces are shown in light blue. Vertiports are represented as grey helicopter symbols. Routes are shown as blue, green, red, or brown solid lines. Corridors are shown as royal blue, turquoise, and goldenrod polygons within the DFW Class B airspace. Corridor entry points are shown by orange gate symbols, and corridor exit points are shown by magenta open-door symbols. There are 23 corridor entry/exit waypoints for DCB in total, and there are 10 crossing waypoints and 16 merge/diverge waypoints where Sequencing and Spacing (S&S) is applied.

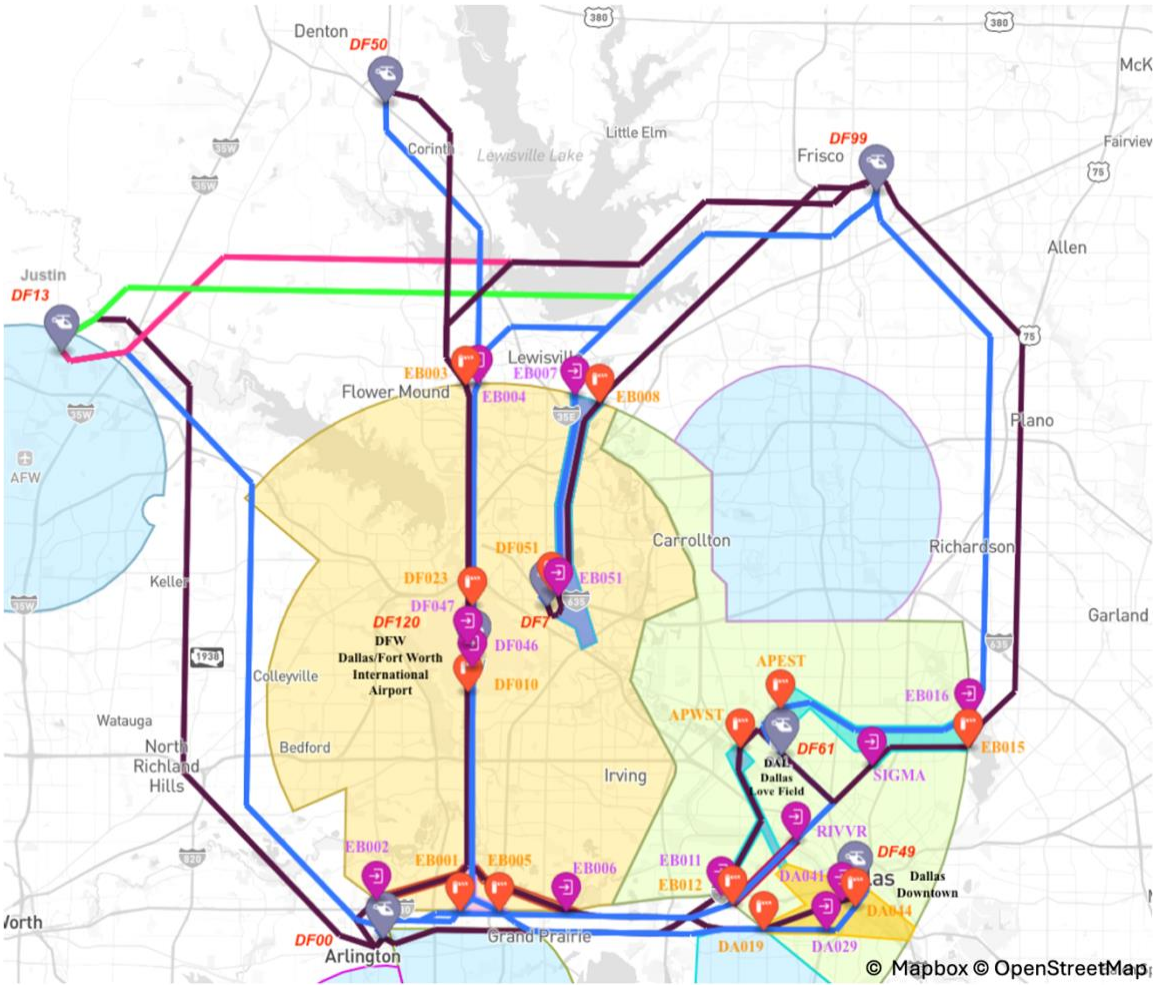



*Figure 6 UAM Routes in Dallas-Fort Worth Metropolitan Area*

## 4.2 Use Cases and Traffic Scenarios

The SDS traffic scenarios consist of two use cases. Use Case 1 represents normal operations to test and validate basic Strategic Conflict Management capabilities (i.e., DCB and S&S) through the PSU network. In Use Case 1, resource capacity does not change during the simulation run. Use Case 2 introduces resource capacity reductions to cause flight replanning. In this use case, a capacity reduction at a specific vertiport or waypoint occurs at a predefined time with an advance notice, leading to replanning of affected flights not yet activated. The replanning results in additional delay or cancellation of some flights. An indefinite closure of the vertiport (i.e., resource status = INACTIVE) was not considered in SDS.

For both use cases, two UAM operators shared the airspace resources such as vertiports, corridor entry/exit points, and enroute waypoints, while their flights operated on the 18 OD pair routes covering the Dallas-Fort Worth metropolitan area. The traffic demand was designed to cause demand-capacity imbalances at vertiports and corridor entry/exit points, which needed to be resolved by assigning pre-departure delay. The traffic demand also created potential proximity events between flights at enroute waypoints like cross/merge/diverge waypoints, requiring additional pre-departure delay by sequencing and spacing.

For the simulation runs, two full traffic scenarios were developed, which represent the medium- and high-traffic demand levels. The medium- and high-traffic level scenarios included 36 and 54 operations in total, respectively. These scenarios would take 60-75 minutes for medium traffic and 75-90 minutes for high traffic to complete a simulation run. Each operator managed one half of the operations, which were evenly distributed among the given routes, with different desired departure times. The desired departure times were defined relative to the start of the simulation run, and each simulation run started at the beginning of a scheduling time bin. The full traffic scenario data are provided in Appendix D.

## 4.3 Simulation configurations

The strategic scheduling constraints were configured the same for all SDS simulation runs by both participants. The DCB time bins had a 12-minute duration and were aligned to the top of the hour (e.g., HH:00, HH:12, HH:24, etc.). The default vertiport capacity was four operations per time bin for DFW Airport (DF120), Frisco, Texas (DF99), and AT&T Stadium (DF00). It was two operations per time bin for all other vertiports and at DCB-constrained waypoints. During Use Case 2, the DFW Airport (DF120) capacity was reduced to two or three operations per time bin. The S&S spacing value was two minutes for S&S-constrained waypoints. Vertiports were not S&S-constrained. Note that the parameters used in this simulation environment such as capacity value and temporal spacing value were set to evaluate the system performance for strategic conflict management, but the system has flexibility to adjust those parameter values for future simulations and tests.

For SDS, both participants provided the DCB services, but only NASA provided the S&S service. The DCB behavior for strategic scheduling was configured the same for all SDS simulation runs, but there were some minor differences between the NASA and ANRA services. Both NASA's and ANRA's DCB functions were performed six minutes before the desired departure time. ANRA's DCB was also performed immediately prior to activation, whereas NASA's DCB was performed only once. For the runs with NASA's DCB + S&S, NASA's S&S was performed one minute before the scheduled departure time in which DCB was already applied. Note that ANRA did not perform S&S at all. NASA's flights were canceled if the assigned delay was greater than one hour.

## 4.4 Test Matrix

The SDS test matrix considers four design variables, including 1) use case, 2) traffic level, 3) Strategic Conflict Management (SCM) function, and 4) fleet allocation between NASA and ANRA.

As described in Section 4.2, two use cases were tested in SDS. Use Case 1 for normal operations evaluated the efficacy of the SCM capabilities for UAM operations. Use Case 2 for off-nominal operations investigated the effects of a resource capacity reduction. Two traffic demand scenarios, high and medium, were used to evaluate the effect of UAM traffic density on system performance such as assigned delay, airspace throughput, and proximity events between flights. The simulation results of these two traffic levels were compared to see whether the given SCM approach can work effectively as the UAM traffic increases. The two pre-departure SCM functions for scheduling UAM operations, DCB and S&S, were tested during the SDS runs. By turning NASA's S&S service on or off, the SDS investigated the impacts of operators having different SCM functions (i.e., ANRA with DCB only and NASA with DCB and S&S) on the system performance such as additional delay and potential conflict reduction. The last design variable was the operator swap between two participants. NASA and ANRA developed their own DCB services independently although both were commonly based on the PSU/DCB requirements

defined in the ASTM PSU Interoperability standard. So, it was expected that the flight scheduling outcomes could be different (e.g., assigned delay) when a different DCB service is applied to the same flight group in the traffic scenario. By swapping the flight group assigned to one operator with the other operator in the traffic scenario and repeating the test runs, it would be observed how the flight schedules are affected by different DCB logic, as well as by the additional SCM function for S&S.

Table 3 shows the test matrix for the data collection runs. There were 12 total runs to cover the design variables.

*Table 3: SDS test matrix*

| Run No | Use Case | Traffic Level | NASA's SCM | ANRA's SCM | Fleet Allocation (Operator Swap) | Notes |
|---|---|---|---|---|---|---|
| #1 | Use Case 1: Default Capacity | Medium Traffic Scenario | DCB + S&S | DCB only | Operator 1 = NASA; Operator 2 = ANRA | |
| #2 | | | | | Operator 1 = ANRA; Operator 2 = NASA | |
| #3 | | | DCB only | | Operator 1 = NASA; Operator 2 = ANRA | Aligned with draft ASTM PSU standard scope |
| #4 | | | | | Operator 1 = ANRA; Operator 2 = NASA | Aligned with draft ASTM PSU standard scope |
| #5 | | High Traffic Scenario | DCB + S&S | DCB only | Operator 1 = NASA; Operator 2 = ANRA | |
| #6 | | | | | Operator 1 = ANRA; Operator 2 = NASA | |
| #7 | | | DCB only | | Operator 1 = NASA; Operator 2 = ANRA | Aligned with draft ASTM PSU standard scope |
| #8 | | | | | Operator 1 = ANRA; Operator 2 = NASA | Aligned with draft ASTM PSU standard scope |
| #9 | Use Case 2: Capacity Reduction | High Traffic Scenario | DCB only | DCB only | Operator 1 = NASA; Operator 2 = ANRA | DF120 capacity reduction from 4 to 3 ops per time bin |
| #10 | | | DCB only | | Operator 1 = ANRA; Operator 2 = NASA | DF120 capacity reduction from 4 to 3 ops per time bin |
| #11 | | | DCB only | | Operator 1 = NASA; Operator 2 = ANRA | DF120 capacity reduction from 4 to 2 ops per time bin |
| #12 | | | DCB + S&S | | Operator 1 = NASA; Operator 2 = ANRA | DF120 capacity reduction from 4 to 3 ops per time bin |

# 5 Simulation Results

This section presents post-simulation data analysis results and discussions about the simulation results. The results for Use Case 1 and Use Case 2 are presented in four separate sections, each covering one "dimension" (data analysis variables):

1. Effect of traffic density – compare DCB-only performance for NASA-ANRA medium-density (Run #3) and high-density (Run #7) traffic runs
2. Strategic Conflict Management functions – compare two NASA-ANRA runs for the high-density traffic scenario
    a. Run #7: Both operators using DCB service only
    b. Run #5: ANRA using DCB service only, NASA using both DCB and S&S services
3. Effect of operator swap – compare two NASA-ANRA runs for the high-density traffic scenario, with both operators using DCB service only
    a. Run #7: Operator 1 is NASA, Operator 2 is ANRA
    b. Run #8: Operator 1 is ANRA, Operator 2 is NASA
4. Use case (scenario 1 vs. 2) – compare three NASA-ANRA runs for the high-density traffic scenario, with both operators using DCB service only. The capacity at a selected resource changes during run time.
    a. Run #7: Normal Operations Use Case
    b. Run #9: Off-nominal Operations, where vertiport DF120 capacity is reduced from 4 to 3 ops/12min
    c. Run #11: Off-nominal Operations, where vertiport DF120 capacity is reduced from 4 to 2 ops/12min

The metrics used for system performance evaluation include:

- Number of operations by flight state and number of simultaneous operations
- Number of demand-capacity imbalances detected and resolved
- Departure delay statistics due to DCB and S&S
- Average and minimum spatial separations between aircraft at waypoints

## 5.1 Use Case 1 – Normal Operations

### 5.1.1 *Effect of Traffic Density*

This section compares the results of the two NASA-ANRA DCB service-only runs, one with medium-density traffic scenario (Run #3) and another with high-density traffic scenario (Run #7). An analysis of flight states and operational measures is shown in Table 4. In both runs, all operations transitioned through the flight states nominally. Figure 7 shows the number of simultaneously airborne aircraft during the simulation. After performing demand-capacity balancing, the peak airborne traffic was 20 operations in the medium-density scenario and 23 operations in the high-density scenario. The average number of airborne operations was calculated as the number of operations that were airborne per minute in the range of time in a run when any operation was airborne, i.e., in the period between when the first operation activated and when the last operation landed. The average airborne traffic was calculated to be 9.6 operations/minute and 10.5 operations/minute in the medium-density and high-density scenarios, respectively. The last operation landed at 62 minutes in the medium-density scenario and 83 minutes in the high-density scenario.

*Table 4: Operational intent breakdown*

| Category | State | Medium-density | High-density |
|---|---|---|---|
| Flight States | Proposed | 36 | 54 |
| | Accepted | 36 | 54 |
| | Activated | 36 | 54 |
| | Completed | 36 | 54 |
| | Canceled | 0 | 0 |
| Operational Measures | Max Ops | 20 | 23 |
| | Avg. Ops | 9.6 | 10.5 |
| | Last landing time (min) | 62 | 83 |

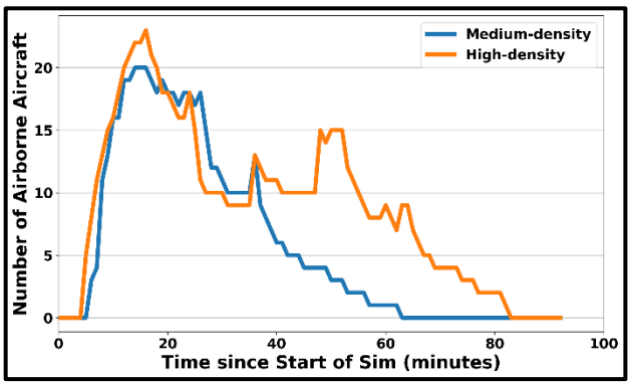



*Figure 7 Count of Airborne Aircraft*

The allocation of traffic at vertiports in each time bin is shown in the heatmaps in Figure 8. The heatmaps on the left show the input demand, while the heatmaps on the right show the scheduled demand. Both medium- and high-density scenarios were designed to have excess demand at the start of the scenario which results in multiple demand-capacity imbalances. The heatmap plots show sequential time bins on the x-axis and vertiports on the y-axis. The number of operations, including both departures and arrivals, is shown in each cell, and the tile is colored based on relative difference to the given capacity (i.e., the imbalanced cells are highlighted in orange color; the darker green the cell is, the closer it is to maximum vertiport capacity).

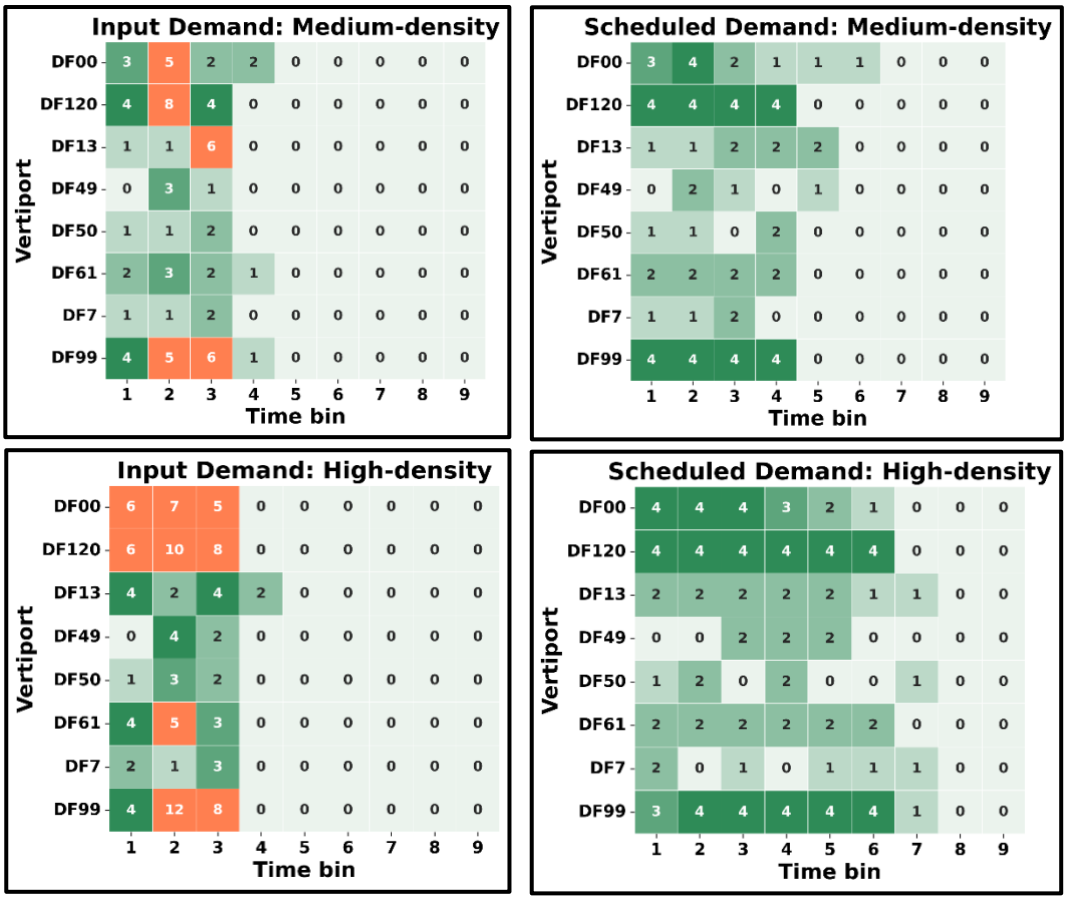



*Figure 8 Traffic Demand Heatmaps*

In both runs, all imbalances were resolved, as shown by the green highlighted cells in the scheduled demand heatmaps on the right-hand side. Note that schedule changes for DCB can affect the demand distribution across the route network. For instance, while the input at DF00 for the Medium-density run is only over by 1 aircraft in the second bin, the operations are shifted several bins due to DCB being applied on both the departure and arrival vertiports.

In cases where the DCB service predicted an imbalance, resolution was assigned in the form of pre-departure delay. From the pre-departure delay statistics for the combined NASA and ANRA operations shown in Table 5, it can be inferred that the increased traffic in the high-density scenario led to increased values of mean, median, and maximum total delay, as well as a higher proportion of operations with assigned delay. In the high-density scenario, 37 operations, 69% of the total of 54 operations, were assigned a total delay of 844 minutes, while in the medium-density scenario, 13 operations, 36% of the 36 operations, were assigned 161 minutes of total delay. Note that the mean and median values are calculated for only delayed operations, e.g., the mean delay of 12 minutes in the medium-density scenario is the average delay assigned to the 13 delayed operations. The increase in total delay assigned can also be seen in Figure 9 and Figure 10, which show the delays by operator.

*Table 5: Delay breakdown*

| Metric | Medium-Density | High-Density |
|---|---|---|
| Num. operations delayed | 13 (36%) | 37 (69%) |
| Mean delay (min.) | 12 | 23 |
| Median delay (min.) | 12 | 23 |
| Max delay (min.) | 24 | 48 |
| Total delay (min.) | 161 | 843 |

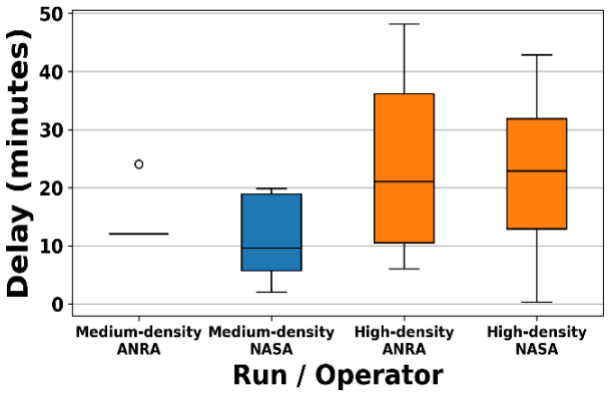



*Figure 9 Delay Spread by Operator*

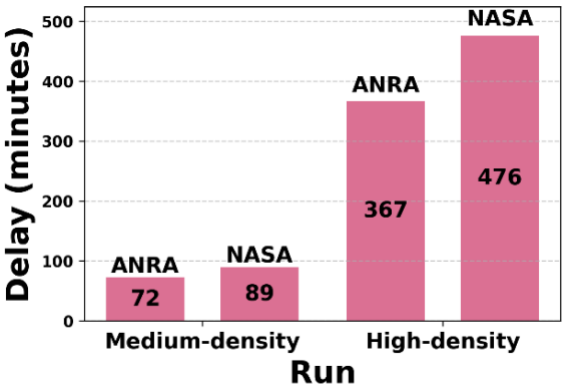



*Figure 10 Total Delay by Operator*

To further examine the effect of traffic density on simulation results, a comparative analysis was conducted for two additional DCB-only runs, Run #4 (medium density) and Run #8 (high density). The only difference in the simulation setup was that in each of these runs, Operator 1 was ANRA and Operator 2 was NASA, i.e., the order of the operators was swapped from that in Run #3 and Run #7. In both runs, all operators transitioned through the flight states nominally, and all predicted demand-capacity imbalances were resolved by the two DCB services. The trends in delay breakdown were similar to those reported above, as the higher density scenario experienced a higher volume and magnitude of pre-departure delays. Section 5.1.3 further examines the impact of operator swap on operational measures.

### *5.1.2 Strategic Conflict Management (SCM) function*

This section presents the results of simulations conducted to evaluate the impact of different airspace services for strategic conflict management (SCM) of UAM operations. The results presented are grouped into two categories: one run where both NASA and ANRA had only the DCB service, and another run where ANRA had the DCB service only while NASA ran both the DCB and S&S services. The differences in throughput, pre-departure delays, demand distributions, and separations at control waypoints in cases where spacing is applied versus when it is not applied are presented.

In SDS, the DCB service was called once a new operation was proposed by the fleet operator, and NASA's S&S service was called 60 seconds before the DCB-validated departure time. If an operation was delayed by the S&S service, the S&S service was called again 60 seconds before its latest scheduled departure time, and this process was repeated until no further S&S delay was assigned. In contrast, the DCB service was called only once upon an operation proposal and was not called again even if S&S assigned further delay. This scheduling design means that additional S&S-assigned delays could cause new demand-capacity imbalances where there were none, in cases when the additional delay moves the flight's schedule into a later time bin.

The traffic density statistics collected under high-density traffic conditions are given in *Table 6*. The "SS-1-Op" label represents Run #5, where NASA's operations had both DCB and S&S services applied and ANRA's operations only had the DCB service applied. The "SS-No-Op" label represents Run #7, where both NASA and ANRA had only the DCB service applied (i.e., no S&S service applied). While all operations transitioned nominally through all flight states during the SS-No-Op run, one cancellation was observed during the SS-1-Op run; this will be described in more detail below. Figure 11 shows the number of simultaneously airborne aircraft during the simulation. A slightly higher maximum and average number of active operations was observed with the absence of the S&S service. Both runs finished in 83 minutes, indicating that, for these two runs, the presence of S&S service did not significantly affect the makespan of the traffic scenario.

*Table 6: Operational intent breakdown*

| Category | Metric | SS-1-Op | SS-No-Op |
|---|---|---|---|
| Flight States | Proposed | 54 | 54 |
| | Accepted | 54 | 54 |
| | Activated | 53 | 54 |
| | Completed | 53 | 54 |
| | Canceled | 1 | 0 |
| Operational Measures | Max Ops | 21 | 23 |
| | Avg. Ops | 10.3 | 10.5 |
| | Last landing time (min) | 83 | 83 |

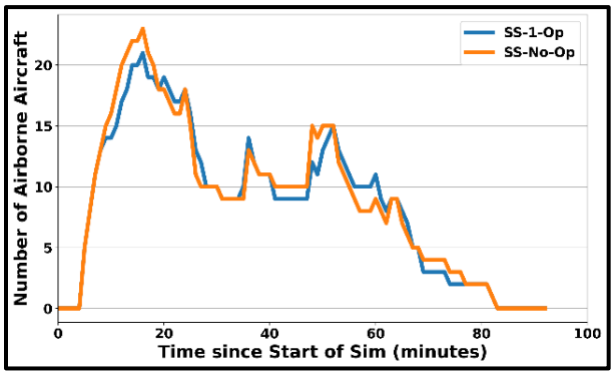



*Figure 11 Count of Airborne Aircraft*

The heatmaps in Figure 12 show the input demand and scheduled demand for the two runs in comparison. The SS-1-Op and SS-No-Op runs are shown on the top and bottom, respectively. As shown in the scheduled demand heatmaps, the SS-1-Op run had one demand-capacity imbalance at the DF61 vertiport in the fourth time bin. This imbalance can be attributed to the active S&S service assigning additional delays for spacing that pushed an aircraft from an earlier time bin into the fourth time bin.

The delay statistics and operator-wise breakdown are shown in Table 7, Figure 13, and Figure 14. As noted above, the delay statistics are calculated only for delayed operations. For operations that are canceled, the assigned delays are included in the calculations except for the last assigned

delay that led to cancellation, which is not recorded. In both SS-1-Op and SS-No-Op runs, all predicted demand-capacity imbalances were resolved when DCB was applied. The application of spacing delay leads to a greater number of operations delayed, with a total of 40 delayed aircraft and a total delay of 852 minutes, while the DCB only run (i.e., SS-No-Op) had a total of 37 delayed aircraft and a total delay of 843 minutes. During the SS-1-Op run, roughly 4% of the total delay was attributed to sequencing and spacing. Despite these 34 minutes of additional delay due to the S&S service, only 9 more minutes of total delay was observed in comparison to the SS-No-Op run. This is because the additional delay assigned by the S&S service is offset by a reduction in DCB delay. Hence, we observe that when spacing delay is assigned, the total DCB delay is lower.

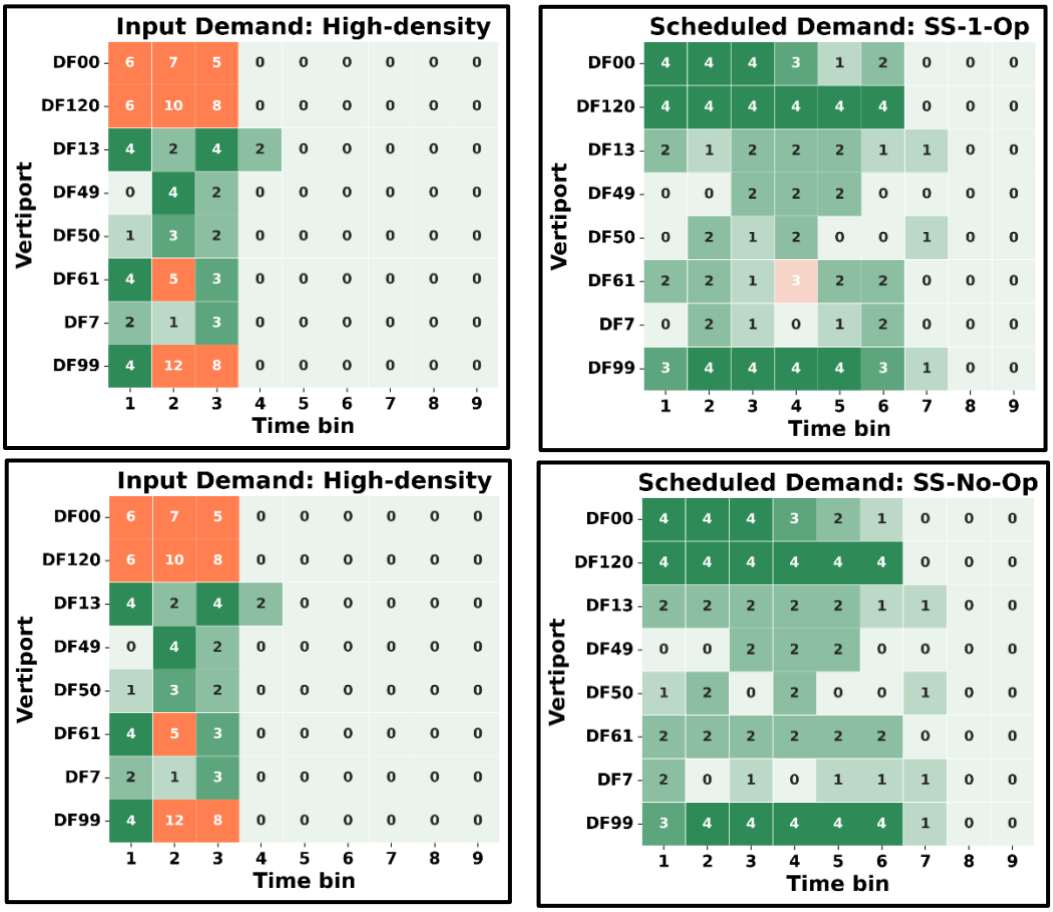



*Figure 12 Traffic Demand Heatmaps*

*Table 7: Delay breakdown*

| Metric | SS-1-Op | SS-No-Op |
|---|---|---|
| Num. operations delayed | 40 | 37 |
| Mean delay (min.) | 21 | 23 |
| Median delay (min.) | 22 | 23 |
| Max delay (min.) | 48 | 48 |
| Total delay (min.) | 852 | 843 |

The imbalanced time bin and the differences in total assigned pre-departure delay between the SS-1-Op and SS-No-Op runs can be explained by the use of S&S service in the former and

not the latter. The canceled operation was ANRA's operation with callsign "ANRA15" that, post-DCB, ended up in an imbalanced cell and was consequently canceled. The post-DCB imbalance was traced back to a series of flight delays that originated in a spacing delay. Similarly, the lower total DCB delay can mainly be attributed to a single operation – NASA's operation with callsign "OPER322" – that had nearly 30 minutes of less DCB-assigned delay in the SS-1-Op run as compared to the SS-No-Op run. Due to the additional delay assigned by S&S, a different flight that had been occupying a time bin moved to a later time bin so that the slot was now available for OPER322. Therefore, OPER322 flight had lower delay when S&S service was applied, compared to when it was not. As further examples of operations whose departure times moved in the SS-1-Op run, OPER312 was scheduled to depart from vertiport DF120 in time bin 4 as opposed to departure in time bin 3 in the SS-No-Op run. Similarly, OPER311 was scheduled to depart from vertiport DF99 in time bin 2, instead of time bin 3. Thus, it can be concluded that due to spacing delays, the flight departure times moved enough to cause an imbalance and even a cancellation.

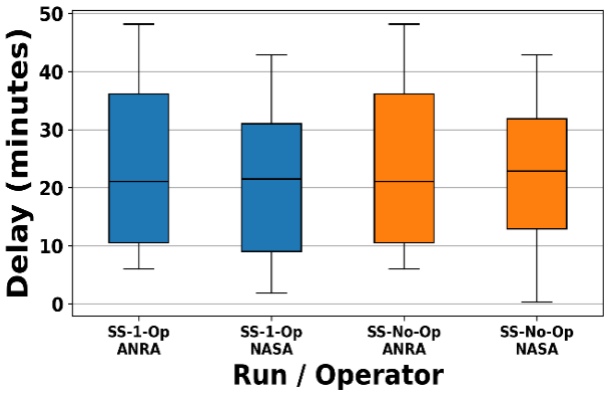



*Figure 13 Delay Spread by Operator*

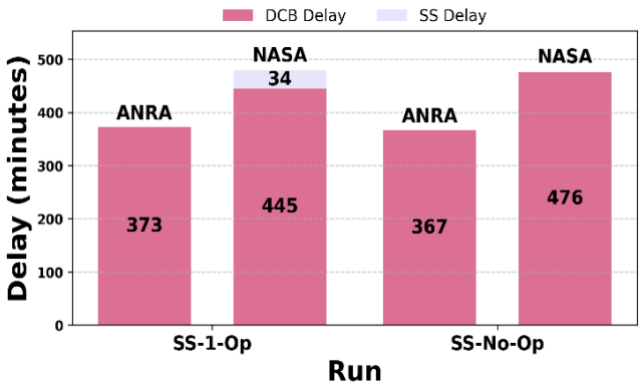



*Figure 14 Total Delay by Operator*

Although the majority of predicted demand-capacity imbalances were resolved by the DCB services, proximity events between flights in the air were observed because tactical conflict management was not introduced in SDS. To see the effectiveness of S&S as the additional SCM, a proximity analysis was conducted for these two runs. The results are shown in Table 8. For both runs, the average and minimum lateral distances to the nearest aircraft were recorded for all aircraft passing through S&S controlled waypoints where the S&S service was applied. Across all types of waypoints, the SS-1-Op system had a significantly lower magnitude of average proximity between aircraft compared to the SS-No-Op system (i.e., DCB only applied). The SS-1-Op system also had less severe minimum separations occurring at controlled waypoints than the SS-No-Op system. Figure 15 shows box plots of the individually observed minimum separation values at S&S controlled waypoints for each run to illustrate the distributions and severity of the spacing between aircraft. Although both systems had severe proximity events reaching near zero feet of separation due to the flights scheduled by DCB only, the minimum separations in the SS-1-Op run generally occurred at greater lateral distances compared to the SS-No-Op run, indicating a higher margin of separation achieved through sequencing and spacing. These values suggest that even when only one operator employs an S&S service, we can expect to consistently observe fewer and less severe proximity events between aircraft altogether.

*Table 8: Separation Breakdown*

| Waypoint Type | Count of Observed Aircraft at Waypoint | Average Separation between Aircraft (feet) | | Minimum Separation between Aircraft (feet) | |
|---|---|---|---|---|---|
| | | SS-1-Op | SS-No-Op | SS-1-Op | SS-No-Op |
| Corridor Entry | 24 | 12,649 | 10,726 | 5,381 | 0 |
| Corridor Exit | 24 | 56,006 | 50,271 | 0 | 0 |
| Merge | 51 | 19,818 | 19,170 | 2,121 | 0 |
| Diverge | 39 | 14,971 | 13,560 | 65 | 0 |
| Crossing | 57 | 31,111 | 25,249 | 485 | 65 |
| All | 195 | 27,473 | 24,099 | 0 | 0 |

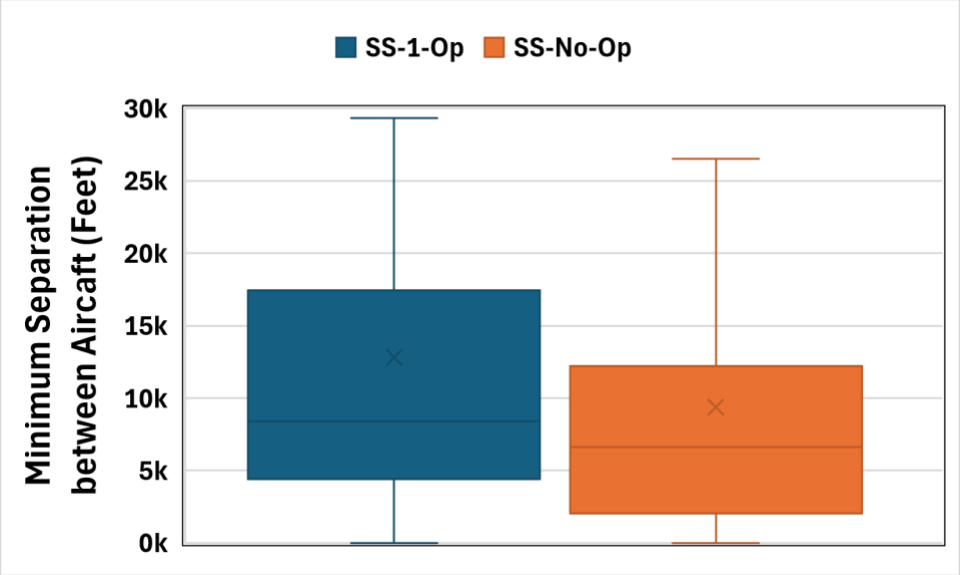



*Figure 15 Minimum Separation at S&S Controlled Waypoints*

### *5.1.3 Operator swap between participants*

This section compares the data from two NASA-ANRA DCB only runs where the only difference was the operations managed by each operator were switched. In the first run, NASA was Operator 1 and ANRA was Operator 2, with the roles reversed in the second run. Both runs simulated the high-density traffic scenario. Since each operator managed the same set of operations once, any demand differences between the operations sets are mitigated. Comparison of the data from these runs shows the fairness of DCB algorithm implementations between NASA and ANRA.

The results presented below are labeled “NASA-ANRA” to denote the run for which NASA was Operator 1 and ANRA was Operator 2, and “ANRA-NASA” to denote the run for which ANRA was Operator 1. Table 9 shows that all operations transitioned nominally through all flight states in both runs. As shown in Figure 16, the peak traffic was 23 operations in both runs, and the average volume of operations was comparable in magnitude. However, two effects of the different DCB algorithms can be observed in Figure 16: that there are two instances where the count of airborne aircraft deviates between the two runs and that the last landing time was 5 minutes earlier in the ANRA-NASA run.

*Table 9: Operational intent breakdown*

| Category | Metric | NASA-ANRA | ANRA-NASA |
|---|---|---|---|
| Flight States | Proposed | 54 | 54 |
| | Accepted | 54 | 54 |
| | Activated | 54 | 54 |
| | Completed | 54 | 54 |
| | Canceled | 0 | 0 |
| Operational Measures | Max Ops | 23 | 23 |
| | Avg. Ops | 10.5 | 11.0 |
| | Last landing time (min) | 83 | 77 |

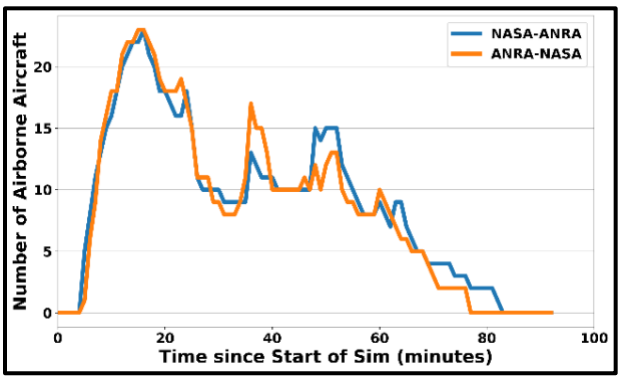



*Figure 16 Airborne Aircraft Count*

The following set of heatmaps in Figure 17 shows the input and scheduled demand of the two runs. The NASA-ANRA scheduled demand heatmap is the same as the high-density heatmap shown in Figure 8. However, the scheduled demand heatmap for the ANRA-NASA run is slightly different, with differences in traffic distribution at 5 of the 8 vertiports. There were no DCB violations since the S&S service was not used in either run.

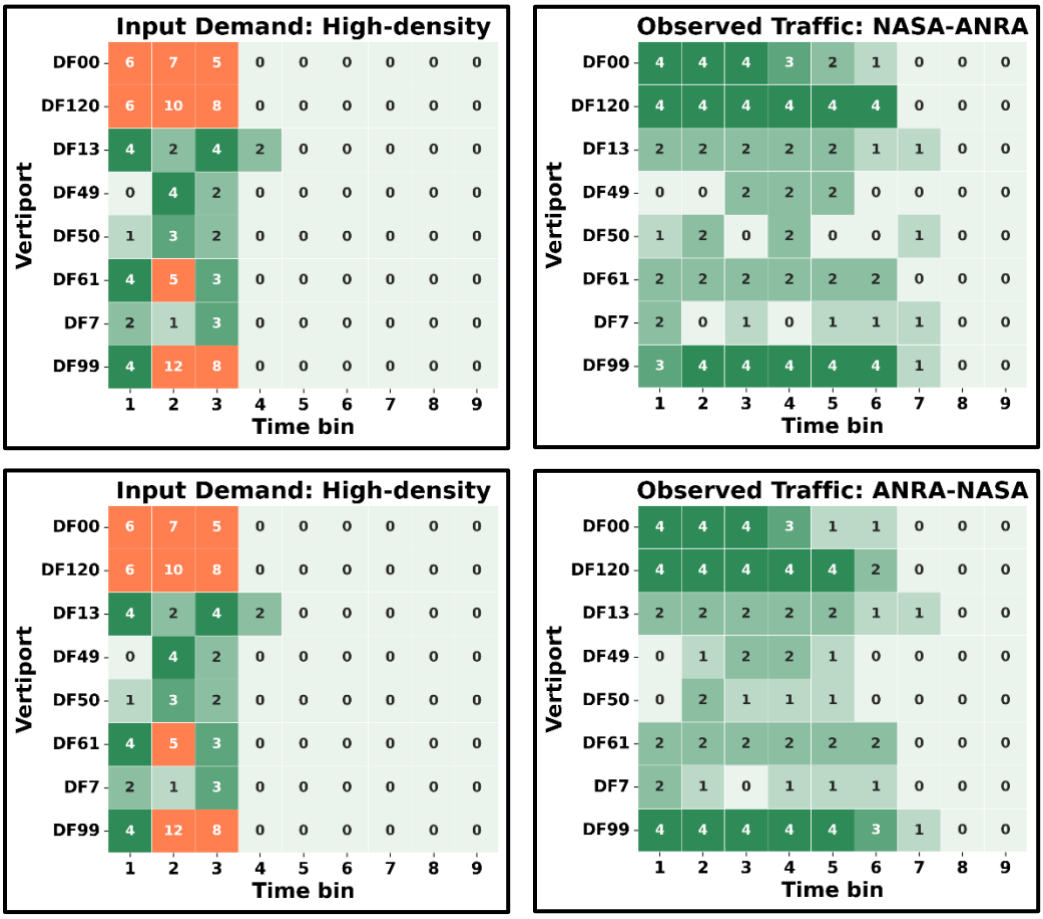



*Figure 17 Traffic Demand Heatmaps*

Table 10, Figure 18 and Figure 19 summarize the delay statistics computed for the two runs. The NASA-ANRA run had one more delayed flight compared to the ANRA-NASA run, slightly

higher mean and median delay, and 44 additional minutes of total delay. The differences that arise both due to the difference in input demand split and the consequent action of different DCB implementations are even more pronounced in Figure 19. This figure shows that, in both runs, Operator 1 had higher DCB-assigned delay to resolve predicted imbalances. Therefore, in the NASA-ANRA run, NASA, which was Operator 1, experienced 109 more minutes of delay than ANRA, while in the ANRA-NASA run, ANRA was Operator 1 and experienced 235 minutes of more delay than NASA.

*Table 10: Delay breakdown*

| Metric | NASA-ANRA | ANRA-NASA |
|---|---|---|
| Num. operations delayed | 37 | 36 |
| Mean delay (min.) | 23 | 22 |
| Median delay (min.) | 23 | 20 |
| Max delay (min.) | 48 | 48 |
| Total delay (min.) | 843 | 799 |

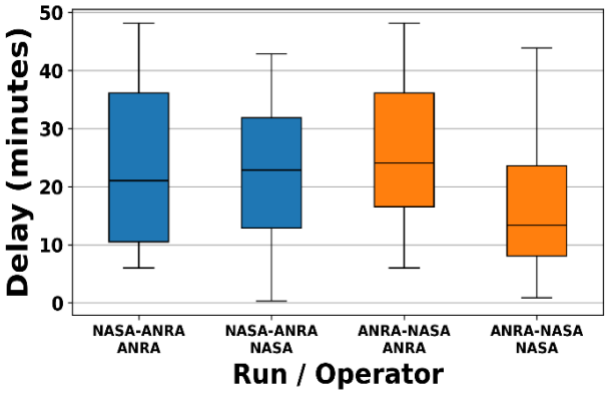



*Figure 18 Delay Spread by Operator*

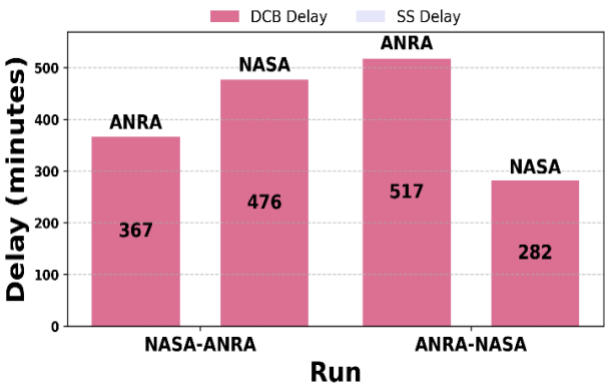



*Figure 19 Total Delay by Operator*

## 5.2 Use Case 2 – Vertiport Capacity Reduction

During the Use Case 2 test runs, the capacity of a resource was reduced during runtime. The capacity change caused demand-capacity imbalances which prompted the operators to replan previously accepted operations to resolve the new demand-capacity imbalances. These runs were done with only DCB services using the high-density traffic scenario only. Three runs with NASA as Operator 1 and ANRA as Operator 2 are compared below.

1. Reference: This is the high-density traffic scenario run described in Section 5.1.1 with a constant DF120 vertiport capacity of 4 operations per 12-minute time bin.
2. Drop-1-DCB: This run is the same as the Reference run, except that the capacity at vertiport DF120 was reduced from 4 to 3 operations per time bin at 24 minutes after the start of the simulation, i.e., from the start of the third time bin. The capacity change was announced to the operators 22 minutes after the start of the simulation.
3. Drop-2-DCB: This run is the same as the Drop-1-DCB run, but the capacity at the DF120 vertiport was reduced to 2 operations per time bin.

It is expected that as the resource capacities reduce, additional delays will be assigned to operations to maintain the traffic demand at resources within the limits of their capacities. Looking at Figure 20 below, at 24 minutes, we observe a drop in airborne aircraft for the two “Drop” runs. The impact of the capacity reduction stretches to the end of the simulation, having a more severe impact to the Drop-2-DCB run, which is correlated with capacity reduction size. Both “Drop” runs resulted in a decrease in average volume of operations and an increase in last landing time due to additional incurred delay. Because of the increased delay, one operation was canceled during the Drop-1-DCB run and 4 operations were canceled during the Drop-2-DCB run, as shown in Table 11.

*Table 11: Operational intent breakdown*

| Category | Metric | Reference | Drop-1-DCB | Drop-2-DCB |
|---|---|---|---|---|
| Flight States | Proposed | 54 | 54 | 54 |
| | Accepted | 54 | 54 | 54 |
| | Activated | 54 | 53 | 50 |
| | Completed | 54 | 53 | 50 |
| | Canceled | 0 | 1 | 4 |
| Operational Measures | Max Ops | 22 | 22 | 22 |
| | Avg. Ops | 10.5 | 9.9 | 9.2 |
| | Last landing time (min) | 83 | 86 | 88 |

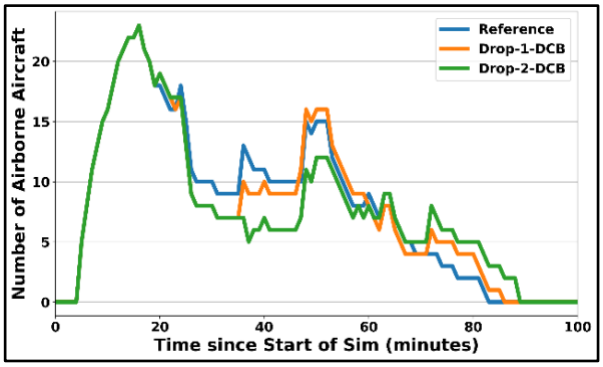



*Figure 20 Airborne Aircraft Count*

The input demand and scheduled demand heatmaps for these three runs are shown in Figure 21. The input demand for the DF120 vertiport is 24 total operations during the first three time-bins. In the Reference run, the DCB service assigned the default capacity of 4 operations to time bins 1 through 6, and there were no cancellations. The impact of the DF120 vertiport capacity reduction, which occurred during the third time bin, can be observed in the demand heatmaps for the following runs. In the Drop-1-DCB run, the capacity reduction led to operations being further delayed and pushed into future time bins, with three operations in each bin from the third to seventh time bin. One NASA operation was canceled because its pre-departure delay exceeded 60 minutes. This pattern is further amplified in the Drop-2-DCB run, where capacity loss leads to two operations per 12 minutes in time bins 3 through 8, and 4 operations were canceled, all belonging to NASA.

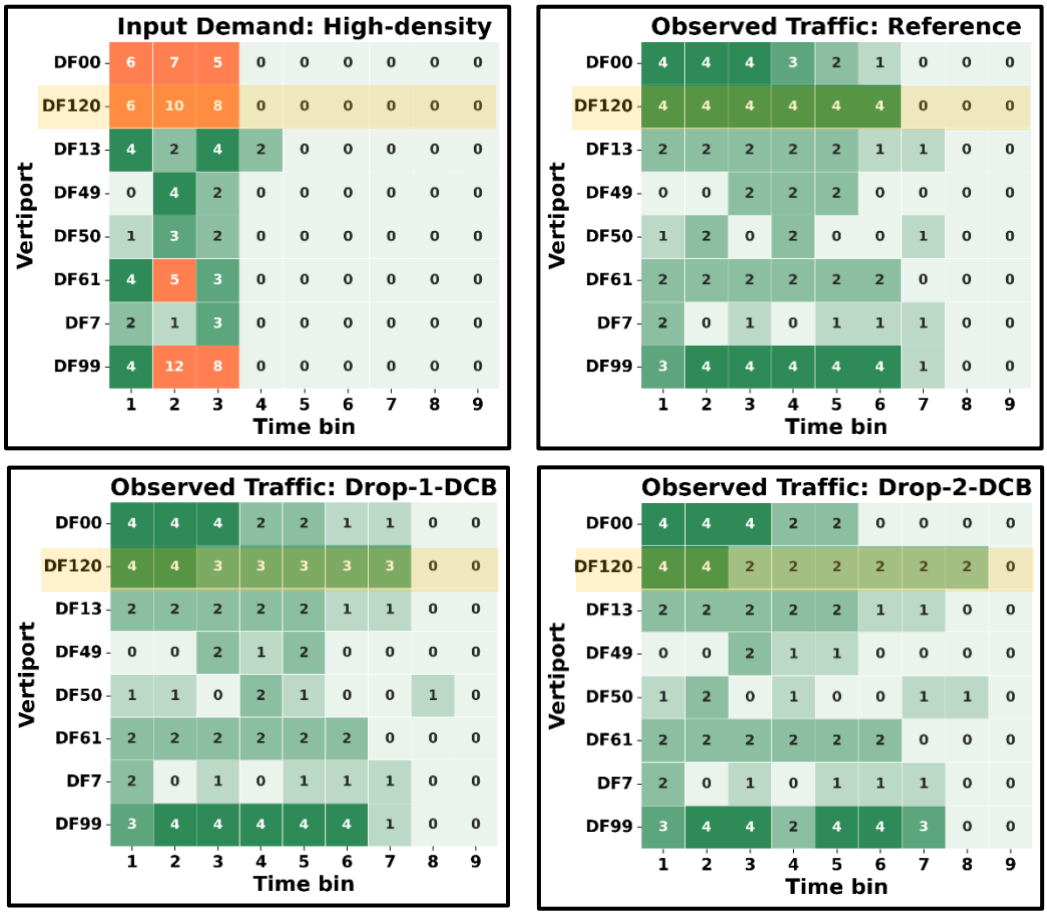



*Figure 21 Traffic Demand Heatmaps*

The delays assigned for operations departing from DF120 are examined in Table 12 below. In response to reduction in resource capacity at DF120, total delay assigned in the Drop-1-DCB run increases to 248 minutes as compared to 175 minutes in the Reference run. This coincides with increases in average and maximum delay. For the Drop-2-DCB run, the total delay at DF120 increases to 325 minutes along with higher mean and maximum delays. Note that operations delayed by 60 minutes or more were canceled.

Figure 22 illustrates pre-departure delay for each individual aircraft that departed from DF120 for all runs, omitting aircraft that experienced no delay. Operations that were eventually canceled are outlined in red dashes, and the sublabels underneath each callsign denote the original time bin that the operation was meant to depart during. In each run, there were 5 ANRA operations, each set to depart in the first time bin. The only delayed ANRA operation, ANRA12, took off prior to the capacity reduction event, and experienced a 6-minute delay in each run. In contrast, all seven of the NASA operators departing from DF120 were scheduled to leave after the ANRA operators, with six of the seven operations scheduled for the second time bin. These seven NASA operations were all delayed and experienced significantly higher delays across all runs.

The effects of capacity reduction were explored further by comparing the observed delay for NASA operations in the Reference versus the two Drop runs. NASA operations in the Reference run that were pushed out of the second time bin by DCB logic experienced significantly longer delays in the two Drop runs. OPER317 was canceled in both the Drop-1-DCB and Drop-2-DCB run, and OPER315 was canceled in the Drop-2-DCB run only. In the Reference run, each of these operations were originally scheduled to depart in the second time bin but was delayed 12 minutes

by DCB, pushing the operations into the third time bin. In the Drop-1-DCB run, with DF120 capacity reduced from 4 to 3, OPER315 was delayed from the second to the fourth time bin, and OPER317 was canceled because it needed delay from the second to the eighth time bin.

*Table 12: Delay breakdown of flights departing from DF120*

| Metric | Reference | Drop-1-DCB | Drop-2-DCB |
|---|---|---|---|
| Num. operations delayed | 8 | 8 | 8 |
| Num. operations canceled | 0 | 1 | 2 |
| Mean delay (min.) | 22 | 31 | 41 |
| Max delay (min.) | 43 | 54.9 | 59.9 |
| Total delay (min.) | 175 | 248 | 325 |

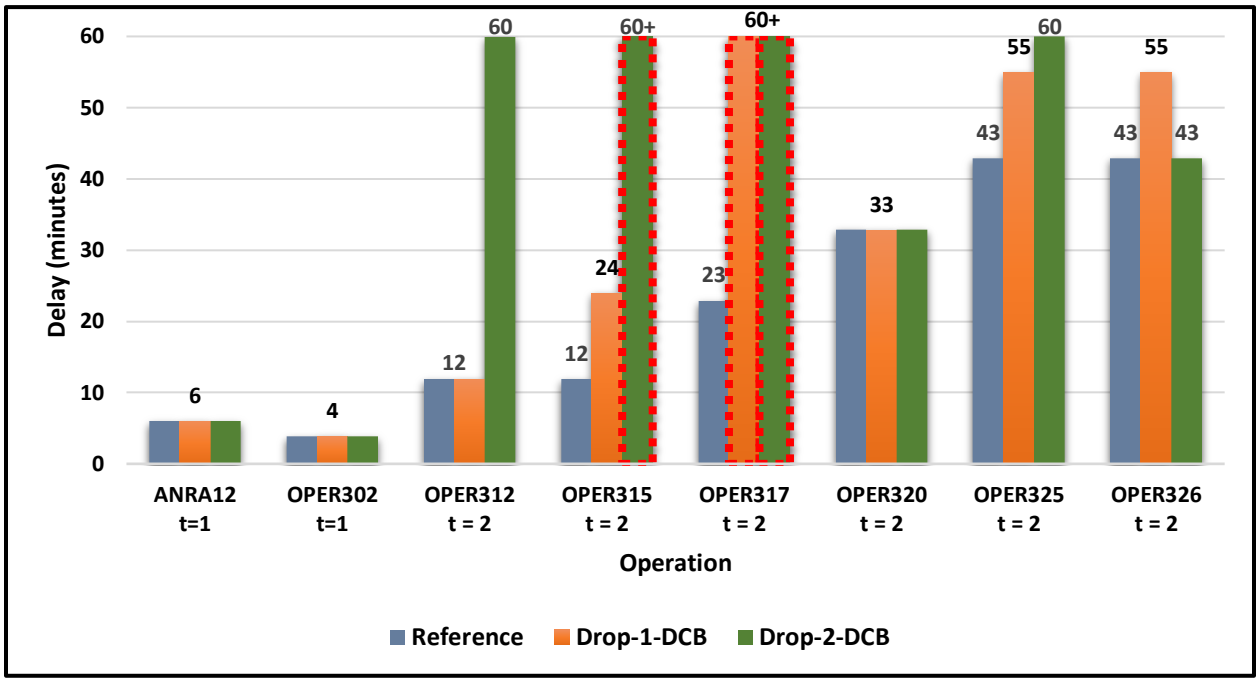



*Figure 22 Delay Comparison of Operations Departing from DF120*

# 6 Lessons Learned

This section captures lessons learned from this simulation through discussions with the industry partner during simulation planning, system architecture development, integration testing with the partner, and simulation implementation for data collection, as well as post-simulation data analysis.

## 6.1 General Lessons for System Integration and Collaborative Simulation

### *6.1.1 Integration test plan (Sprints)*

NASA developed the detailed integration and test plan with a series of Sprints, and the integration test plan and testing Sprints were helpful for simulation participants (i.e., NASA and industry partner) to make connections between systems and test core features needed for SDS data collections step by step. The series of Sprints had a good tempo to prepare the required functions and systems at each Sprint with proper intervals depending on the technical difficulties. The detailed Sprint descriptions provided adequate foresights on the test scope, and the test procedures were developed based on them.

### *6.1.2 Traffic scenario development*

Full traffic scenarios were developed through many iterations of desktop fast-time simulations, taking into consideration various attributes such as route structure, traffic density, spatial and temporal demand distribution, resource capacities, generated demand-capacity imbalances, and expected delay. However, software developers needed a set of test scenarios earlier to test and validate their airspace services. Having a few mini test scenarios, a subset of full traffic scenarios, in early phases would be very helpful for software development and internal testing.

### *6.1.3 Data collection*

Discussing and establishing a comprehensive data collection strategy during the early planning phase is essential, particularly for a federated system architecture like a PSU interoperability network. Simulation participants must clearly define the metrics to be measured, specify the data elements, types, sources, and formats to be collected and archived, and set up the necessary data pipelines between systems before beginning actual data collection simulations. Sharing data-related documentation, such as a data dictionary, can greatly facilitate both data collection and post-simulation analysis. Additionally, running post-simulation scripts to quickly check data sanity is crucial for identifying the need to rerun a test scenario and ensuring stable and reliable data collection.

### *6.1.4 Data visualization tool (GUAVA)'s usability*

Since many software components were involved in the simulation, sometimes it was hard to recognize any system malfunctions during a run. A data visualization tool (GUAVA) was useful to monitor the system health. GUAVA's DCB Monitor helped check whether the DCB services worked as desired and understand how the replanning was done when vertiport capacity was reduced. The Situational Viewer was useful to track flights and check if system was receiving telemetry data correctly. Additional data like flight plan details and operations count were also used to check whether there were any missing data in real time during the simulation run. It would be better if this tool can show operation's nonconforming state by connecting to the PSU CM function in the future simulations.

## 6.2 Strategic Deconfliction Approach

### *6.2.1 Different DCB logic by operator*

During the integration test and data collection runs for SDS, some differences in the DCB implementation between NASA and ANRA were identified. When detecting demand-capacity imbalances, NASA pushed the impacted flight to the beginning of the next available time bin (e.g., from 10:04 to 10:12). On the contrary, ANRA delayed its flight by the pre-defined delay parameter (e.g., from 10:04 to 10:10 with 6-min delay parameter). ANRA also tested 12 minutes as the delay parameter, but it decided not to use it because it resulted in large discrete delays like 12, 24, 36, and 48 minutes.

Another difference was related to DCB re-check. Before transitioning to Activation Horizon, NASA did not check DCB again, but ANRA checked DCB again 1 minute before departure time. ANRA's process followed the flow chart described in the draft ASTM PSU standard (Figure 5). In several test runs, after DCB, NASA applied Sequencing & Spacing (S&S) for better traffic synchronization and safe separation 1 minute before the departure time, while allowing a potential DCB violation due to S&S delay. With the DCB re-check logic, ANRA may cancel its flight due to NASA's S&S-delayed flight (observed these cases in Run #1 and #5, when NASA turned on S&S service) to resolve the last-minute DCB violation.

### *6.2.2 Integration of DCB and S&S*

Although the draft ASTM PSU Interoperability Standard focused on DCB, NASA developed and tested the S&S service as additional strategic conflict management method [14, 15]. During the SDS, NASA investigated how NASA's S&S service integrated with DCB could work with a fleet operator running DCB only. SDS results showed that NASA's S&S could provide additional separation buffer at control waypoints before takeoff with minimal impacts (e.g., few DCB violations due to S&S delay). However, more discussions about the S&S introduction are required to define the related requirements and COPs and reach a consensus in the UAM community such as data flow and scheduling sequence combined with DCB, implementation approach, separation parameters, and fairness.

### *6.2.3 Resource Information Service*

As the draft ASTM PSU Interoperability Standard introduced the RIS, the SDS incorporated the RIS in the system architecture and tested how the RIS could communicate with other services and provide the DCB services with the updated resource capacity and status information.

While preparing for SDS, NASA's RIS has improved to support the start/end time parameters of the future resource capacity query. Also, there was confusion regarding how and when the RIS communicates future vertiport capacity changes to DCB services during simulation runs, specifically about the need for a "lead time" in submitting these changes. In the initial simulation setup, when a Resource Operator submitted a future capacity change, RIS immediately informed DCB services which then used this information to schedule incoming requests based on the anticipated reduced availability. To properly trigger re-planning of operations due to a dynamic capacity change, the Resource Operator should delay submitting the change until DCB services have already scheduled flights under the previous capacity, ensuring that the system recognizes the need to adjust existing schedules.

### *6.2.4 DSS for UAM*

The SDS results confirmed that the new DSS for UAM that was modified from the UTM-based DSS by adding new flight states worked for DCB checks. Further details on the modified DSS for UAM can be found in Appendix C. Throughout test runs, it was found that the previous setting of five retry attempts for NASA's fleet management system (S-FO) to submit operational intents to

the DSS was inadequate, often resulting in operation cancellations since the DSS rejected operation state updates, typically due to missing operational intents for overlapping flights from multiple operators in the federated service network. To address this, the number of allowed retries in the S-FO configuration was increased from five to twenty, mitigating issues related to accumulating overlapping volume notifications and ensuring more robust handling of operation state updates during high-density traffic scenarios.

#### *6.2.5 Flight cancellation*

Flight cancellation should be considered in scheduling, but it can affect the DCB process in the federated service network, as well as the system performance metrics in simulation data analysis (e.g., less total delay with reduced operations).

If one fleet operator cancels operations without informing others in the federated service network, it can lead to missing operational intents and subsequent scheduling failures, especially during high-density traffic scenarios or capacity reduction events. For example, all the flights in replanning might be canceled because one cancellation wasn't shared with others in a timely manner, leaving outdated references that led to further problems in DCB check. The recommended fix is for the other fleet operator, upon receiving a 404 error from DSS for a canceled operation, to clear its 'missing*operation*-intent_list' and retry, allowing the DSS to return the updated notifications that exclude the canceled operation.

When fleet operators are required to replan flight schedules due to reduced resource capacity, operation cancellations should be determined by whether the delay from the original proposed departure time exceeds a predefined threshold (one hour in SDS, though this limit may change), regardless of any further delays imposed by the DCB process. This approach can be used to prioritize customer's experience like ride-sharing app users who are likely to abandon their ride if the wait becomes excessively long compared to their initial request.

#### *6.2.6 Uncertainty impact*

Without human actors involved in simulations, SDS does not have uncertainties in flight operations such as deviations from the scheduled departure times and variations in flight durations along the same route, which may affect system performance. This limitation of SDS will be addressed in the future simulation activities. Nevertheless, even in simulations with no human participants, SDS has observed challenges with consistency in simulation results under the distributed, multithreaded systems. The fleet management system's frontend clients and backend airspace services run concurrently across multiple machines and communicate over PSU network. This setup can cause variations in outcomes, even with identical inputs, due to issues like message ordering, thread concurrency, asynchronous state updates, and fault-recovery mechanisms. The potential impacts of uncertainty should be explicitly accounted for when setting up future systems and simulation environments, and they should be designed to remain robust against such uncertainties.

### 6.3 ASTM PSU Interoperability Standard Enhancements

#### *6.3.1 API reference harmonization*

Some PSU Interoperability APIs contain redundant information (e.g., within flight details, trajectory points are defined by Name, UUID, and Lat/Lon). This is helpful for rapid processing and human consumption, but the information redundancy may raise a few issues such as inconsistencies in entity references across the APIs and potential inconsistencies/mismatches in the data. A couple of ideas such as harmonized entity references across API requests and identification and reevaluation of redundancy instances has been proposed to address this issue in the ASTM PSU working group, leading to PSU API updates.

### 6.3.2 Global ordinal priority framework in replanning

When replanning is required due to demand or capacity change, a DCB check and operational intent rollback to the "Proposed" state is enacted. The current requirements related to the ordinal priority in the ASTM PSU Interoperability Standard draft have ambiguity as to which operations need to roll back to Proposed when multiple operations are replanned. If one operation rolls back first, it creates a fairness issue. If two operations roll back at the same time, the system may encounter new race conditions. The ASTM PSU working group discussed complementing requirements for enacting the transition or encapsulating causes for rollback to Proposed, implications in the S&S service behavior, prioritization framework to break the priority tie condition and be robust to latencies, and regulators' engagement for validation.

### 6.3.3 Operation times during transitions

When an operation is forced to roll back to the Proposed state, there are no requirements regarding the times that it needs to refer to for replanning. More specifically, the reference time can be either the time when the operation is identified to be out of compliance with DCB or the new time that has already been determined to be DCB compliant. Also, there are no requirements for the timing when replanning is executed. When resource capacity is reduced, for example, Operator 1 may reschedule the impacted operations immediately in the order of their original proposed departure time (pre-DCB). On the contrary, Operator 2 may start replanning process when DCB is re-performed just prior to departure based on the accepted departure time (post-DCB). The SDS results showed that Operator 1's operations would be pushed to the next available time bin by taking actions right away, whereas Operator 2's operations generally stayed in the current time bin. The ASTM PSU working group had consensus that the original departure time should be added to the API as an optional parameter, the rollback of affected flights to Proposed should be made immediately, and all PSUs need to follow the same prioritization rules.

### 6.3.4 Time bin synchronization

The SDS assumption to use the same time bin size at all DCB resources (i.e., 12 minutes) raised a question if ASTM PSU standard needs to include requirements to synchronize time bins across a PSU ecosystem. In an ecosystem with multiple constrained resources that are connected to each other, it helps significantly if the resource time bins are synchronized (i.e., all resource time bins are bucketized with the same logic). Discussions in the ASTM PSU working group agreed that instead of stating minimum and maximum time windows for bin durations, a simple bin duration in minutes, that is evenly divisible within an hour (e.g., 6 or 12 minutes), along with number of operations within a time bin can help synchronize available resource capacities among PSUs. However, several ASTM working group members disagreed that all DCB resources within a particular airspace have the same time bin size (e.g., 12 minutes like SDS assumption) reasoning that different resources may have shorter or longer bin durations.

# 7 Conclusions

The Strategic Deconfliction Simulation (SDS) demonstrated that NASA's UAM system architecture and the PSU requirements and APIs defined in the draft ASTM PSU Interoperability Standard can effectively support strategic planning and deconfliction of UAM flights operated by multiple fleet operators within a shared UAM airspace. Throughout the medium- and high-density traffic scenarios, both participants, NASA and ANRA, successfully exchanged operational intent information, performed Demand-Capacity Balancing (DCB), and coordinated the activation and completion of the simulated UAM operations using the PSU interoperability network. The results confirmed that the system functions and data exchange mechanisms defined in the draft ASTM

PSU Interoperability Standard are sufficient to enable interoperable strategic conflict management across independently developed airspace services for UAM (i.e., PSUs).

The simulation runs showed that DCB consistently resolved predicted demand-capacity imbalances at vertiports and corridor entry/exit points across all use cases. The introduction of NASA's Sequencing and Spacing (S&S) service provided additional temporal spacing at constrained waypoints and reduced the severity of proximity events, with only limited impact on overall delay. These findings indicate that a layered Strategic Conflict Management (SCM) approach (i.e., DCB complemented by S&S) can enhance safety margins while maintaining throughput and schedule integrity. Analyses of operator-swap runs highlighted that differences in assigned delay and schedule outcomes were primarily driven by operator-specific DCB logic and traffic set allocation. This emphasizes the importance of evaluating multiple permutations of traffic distributions when assessing fairness and performance in future simulations. The capacity reduction scenarios further showed that the SDS architecture can support strategic replanning in response to reduced resource availability, with expected impacts on delay, cancellations, and distribution of traffic across time bins by DCB.

The SDS activities identified some meaningful lessons learned spanning system integration, strategic deconfliction approaches, PSU core functions, and ASTM standard considerations. System integration activities with industry partner emphasized the importance of structured integration test plans, early scenario development, clear data collection strategies, and the value of real-time data visualization tools for system behavior monitoring during simulation runs. Strategic deconfliction lessons highlighted differences in DCB logic between operators, feasibility and future directions in the combination of DCB and S&S, challenges with resource capacity change timing in RIS for replanning capability testing, and the need for improved DSS retry handling to prevent cascading scheduling issues. ASTM-related findings underscored the need for harmonized APIs, clearer rules for rollback and priority handling, consistent timing requirements, and refined guidance on resource capacity time bin usage in a multi-operator ecosystem.

Overall, the SDS validated key architectural elements and PSU interoperability requirements, provided insights into system-level performance across multiple test runs and use cases, and identified areas for further development and standardization. These findings directly inform NASA's upcoming Technical Capability Level 1 (TCL-1) activities and contribute to the continued maturation of the ASTM PSU Interoperability Standard. SDS results will support future multi-operator simulations with high-fidelity flight simulators and ATC interactions, expanded testing with uncertainty models, and ongoing collaboration efforts with industry partners to advance safe, scalable, and equitable UAM operations.

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# B. Acronyms/Abbreviations

| Acronym | Description |
|---|---|
| ADS | Addison Airport |
| AEP | Automation Enabled Pilot |
| AFW | Fort Worth Alliance Airport |
| AIS | ATM Interoperability Simulation |
| AMP | Air Mobility Pathfinders |
| API | Application Programming Interface |
| ASTM | American Society for Testing and Materials |
| ATC | Air Traffic Control |
| ATG | Airspace Target Generator |
| CM | Conformance Monitoring |
| ConOps | Concept of Operations |
| COP | Cooperative Operating Practice |
| DAL | Dallas Love Field Airport |
| DAR | DSS Airspace Representation |
| DCB | Demand-Capacity Balancing |
| DFW | Dallas-Fort Worth International Airport |
| DSS | Discovery and Synchronization Service |
| ETA | Estimated Time of Arrival |
| eVTOL | electric Vertical Take-Off and Landing |
| FAA | Federal Aviation Administration |
| FIMS | Flight Information Management System |
| GUAVA | Graphic-based UAM Airspace Visualization Assistant |
| GUI | Graphical User Interface |
| IFR | Instrument Flight Rules |
| LVC | Live, Virtual, Constructive |

| Acronym | Description |
|---|---|
| NASA | National Aeronautics and Space Administration |
| NAS | National Airspace System |
| NC | National Campaign |
| OD | Origin-Destination |
| OIM | Operation Intent Management |
| PIC | Pilot in Command |
| PSU | Provider of Services for UAM |
| RIS | Resource Information Service |
| ROS | Resource Operator Service |
| RTA | Required Time of Arrival |
| RTTA | Reasonable-Time-To-Act |
| RVLT | Revolutionary Vertical Lift Technology |
| SCM | Strategic Conflict Management |
| SDS | Strategic Deconfliction Simulation |
| STA | Scheduled Time of Arrival |
| S&S | Sequencing and Spacing |
| S-FO | Surrogate Fleet Operator |
| TC | Technical Challenge |
| TCL | Technical Capability Level |
| TM | Technical Memorandum |
| UAM | Urban Air Mobility |
| UAS | Unmanned Aircraft System |
| USS | UAS Service Supplier |
| UTM | Unmanned Aircraft System (UAS) Traffic Management |
| VFR | Visual Flight Rules |

# C. Discovery and Synchronization Service for UAM

This appendix describes the development and validation of the NASA-developed Discovery and Synchronization Service (DSS) for UAM. It was developed by modifying the existing open-source InterUSS UTM-based DSS to support UAM applications, based on the lessons learned from NASA's former UAM simulations [12, 14].

## C.1 Lessons learned from NASA's previous simulations

A new or modified DSS for UAM is needed because the current UTM-based DSS is not suitable for UAM operational intent scheduling. NASA's previous PSU Prototype (X5) simulation used the existing DSS based on the UTM paradigm as in the X4 simulation. Therefore, the lessons learned from X4 with respect to DSS, such as handling of past operations, sizing of operational 4-D volumes, synchronization issues in a federated architecture, and distribution of airspace constraint information, were still valid. In addition, the X5 simulation identified other issues when the UTM-based DSS was used for UAM flight planning. Table C1 below shows the list of proposed DSS enhancements to support UAM operations, as summarized in [14].

*Table C1: Potential DSS enhancements for UAM [14]*

| Item | Description | Status |
|---|---|---|
| New operational states | The current UTM-based DSS handles four operational states: "Accepted", "Activated", "Nonconforming", and "Contingent". However, there is a need to add new operational states for DCB and S&S. For initial flight scheduling, a "Proposed" state should be added, in which a flight would perform DCB with the latest airspace information before getting accepted. In addition, "Completed" and "Canceled" states are needed for correct counting of demand in DCB. A flight in either state should be deleted from DSS and relevant PSUs in a timely manner. A "Canceled" operation will immediately clear the time bin, but a "Completed" operation would occupy the time bin until the end time to allow other PSU services to account for its presence. "Nonconforming" was renamed to "DCB-Nonconforming". | Implemented with SDS |
| Conflict evaluation based on 4D volumes | In this simulation, the PSU submitted operational intents with disjoint, small 4-D operational volumes surrounding vertiports and scheduling waypoints. DSS uses these volumes with only one time window for earliest start time to latest end time of all 4-D operational volumes for strategic deconfliction checks. This design may lead to inefficient airspace usage and scalability issues. To determine potential conflicts between UAM flights more effectively, it would be more efficient to use a continuous volume surrounding the entire 4D trajectory. Alternatively, the DSS could check the conflicts of each resource with different time windows associated to the individual 4-D volume. | Future Feature |

| | | |
|---|---|---|
| Operational data storage | The current DSS only checks the relevant operations in a subscribing area. It does not store and share detailed operational data. Since multiple system actors, like PSUs and vertiport operators, access the DSS to get operational data, DSS may need to store and provide operational data history so that PSUs can get an integrated operating picture. However, maintaining historical operational data conflicts with the original DSS design to purposely keep minimal information from multiple operators. Therefore, a consensus from the open-source team, consisting of individuals from industry partners, must be reached regarding this feature. | Future Feature |
| Access to NAS traffic data and non-PSU systems and services | This simulation did not include non-UAM traffic, but it is necessary to share the UAM flight data with other airspace users since UAM and non-UAM flights use the shared airspace resources (e.g., airport transfer use case). For this reason, the DSS may need access to NAS traffic data and non-PSU systems (e.g., USS) in the future, leveraging FAA systems like SWIM for a common operating picture. This would require DSS to be aware of trajectory data from NAS traffic. | Future Feature |
| Grid size adjustment for UAM | DSS sometimes makes false alerts about potential conflicts between operations due to the proximity and overlap of the operational 4-D volumes being contained within the same DSS Airspace Representation (DAR) grid. DAR's grid size may need to be adjusted appropriately for UAM applications since some operational waypoints can be close and be located within the same grid cell (e.g., origin vertiport and departure fix). The original DSS implementation does not support a configurable grid size and uses 1 $km^2$ per cell. Also, reducing current grid size may impact performance of DSS so further testing and evaluation is needed. | Future Feature |

## C.2 Modification of the existing DSS for UAM

NASA modified version v0.15.0 of the InterUSS UTM-based DSS for UAM, and the modified DSS was used for SDS. The open-source repository for the UTM-based DSS can be found at the GitHub link in [22]. As the enhancements of the UTM-based DSS are continued, the current InterUSS DSS version is v0.20.2 as of January 2026.

In the modified DSS for UAM, NASA added three new states – Proposed, Canceled and Completed - as defined in the draft ASTM PSU Interoperability Standard. These new states are shaded green in Figure C1.

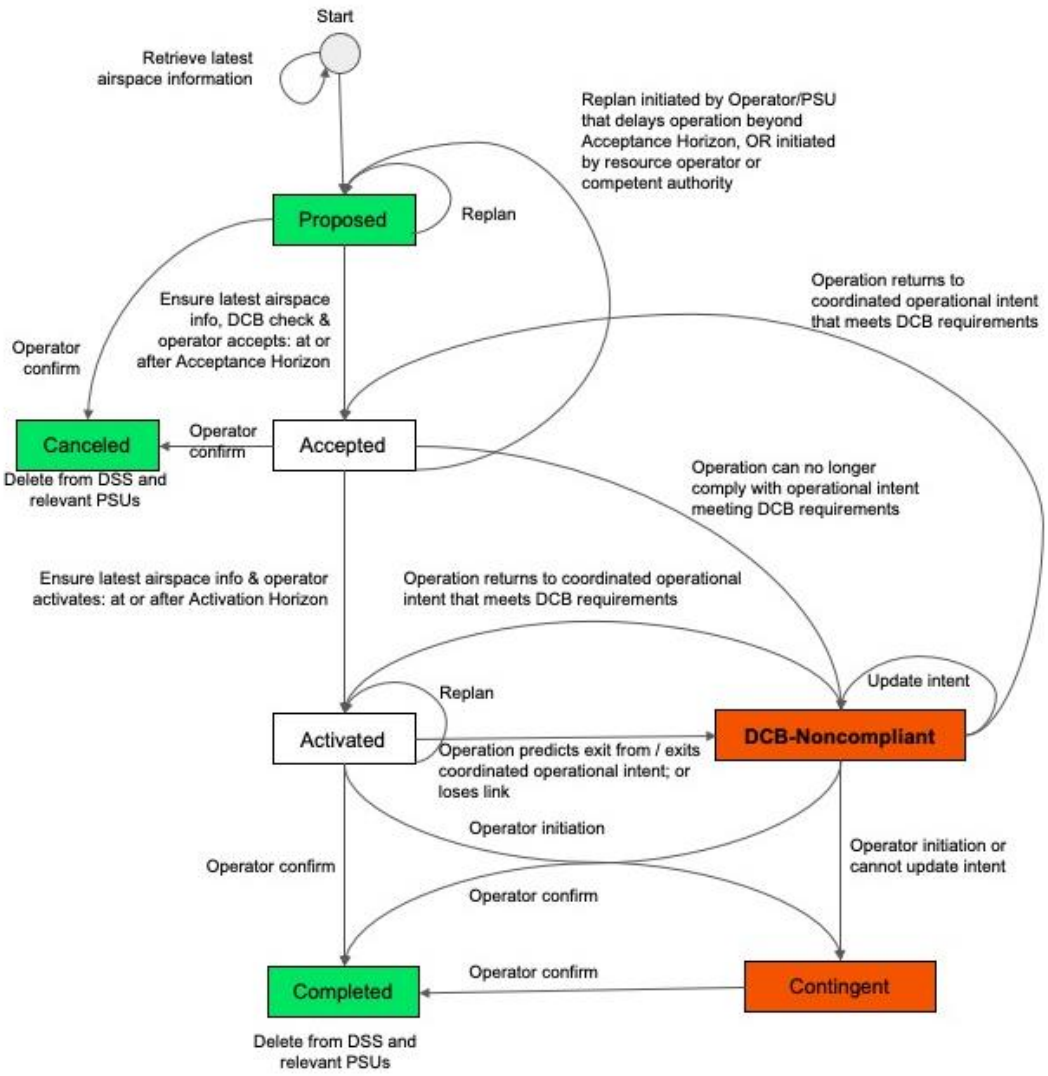



*Figure C1* Operational Intent States Transition Diagram

The UAM operational intent state transition diagram above comes from the draft ASTM PSU Interoperability Standard v2.2 (as of September 16, 2024). It shows the operational intent states and the permitted state transitions. The operational intent states are described as follows in the draft ASTM PSU Interoperability Standard specification:

***Proposed***
*This state is set by the **PSU OIM** role when the operational intent is created and made available to be shared with other relevant PSU DCB roles by submission to the DSS.*

***Accepted (nominal)***
*This state is set by the **PSU OIM** role when the operational intent is strategically coordinated at its Acceptance Horizon, or time before its proposed take-off time after which the operation is permitted to transition to Accepted State. This Acceptance Horizon is similar in concept to the Reasonable-Time-To-Act (RTTA) proposed by the CORUS ConOps [23]. The PSU OIM role must have received and evaluated the latest airspace information and completed a DCB check prior to transitioning the operational intent state from Proposed to Accepted. An operational intent cannot be transitioned to the Activated State without first transitioning to the*

*Accepted state. Figure C2 shows an example timeline for a departure resource with operations in Proposed, Accepted and Activated states. Accepted operations have assigned departure times which have been strategically coordinated and may therefore be different from their originally requested departure times.*

***Activated (nominal)***
*To enter this state, the operator communicates to the managing **PSU OIM** role their intent to commence flight operations within the coordinated operational intent. This action can only be done within a specified time horizon before the operation's accepted take-off time (as described in its accepted operational intent) - called its Activation Horizon. An Activated state indicates that the operation complies with its accepted operational intent but may or may not be in flight. An operator action or operation movement, which may be detected automatically, must occur for the PSU OIM role to transition the operational intent state from Accepted to Activated. The PSU OIM role must have received and evaluated the latest airspace information prior to transitioning the operational intent state from Accepted to Activated. Transition from Accepted to Activated may also require clearance through an authorization process. However, this standard does not prescribe the responsible party for the issuance of such a clearance. Transition to Activated initiates conformance monitoring. Figure C2 shows an example timeline for a departure resource with operations in Proposed, Accepted and Activated states.*

***DCB-Noncompliant (off-nominal)***
*This state indicates that the aircraft is not currently in conformance or is predicted not to be in conformance with the DCB-compliant operational intent that is being or has been shared with the PSU network, as per the conformance bounds specified for each resource. Despite the known imbalance, the **PSU OIM** role still has the ability to estimate and communicate the anticipated flight trajectory to the UAM ecosystem. If the operator cannot return to conformance or modify the intent such that it complies with DCB, the operation remains DCB-Noncompliant. If the operator can return to conformity or modify the intent to comply with DCB, the operation returns to Activated.*

***Contingent (off-nominal)***
*This state indicates that the operation has entered a circumstance in which the PSU CM role no longer has situational awareness of the aircraft position and/or operational intent. Specifically, this state is used to indicate situations in which positional information is no longer being received by the PSU CM role to a degree that is necessary to meet identified conformance monitoring conformance requirements. Additionally, this state represents instances in which the operation can no longer execute its trajectory in a manner that avoids an imbalance of a constrained resource, and the **PSU OIM** role is unable to define an alternative flight plan. This state is a terminal state, meaning that once an operation has entered the Contingent state, it can only transition to the Completed state.*

***Canceled***
*This state indicates that the operation has never been in Activated State and will not use the operational intent. Action on the part of the operator's automation, or the **PSU OIM** role, which may be automated, must occur to end the operation. When an operational intent is canceled, the managing PSU OIM role must delete the operational intent from the PSU network. Details about operational intents in the canceled state are not communicated between PSUs.*

***Completed***
*This state indicates the operation is no longer using the operational intent because it has landed. Action on the part of the operator's automation, or the **PSU OIM** role, which may be automated, must occur to end the operation. Details about operational intents in the completed*

*state are still communicated between PSUs because these operations may contribute to demand for DCB.*

**State Transition Timeline**

Figure C2 is a diagram from the draft ASTM PSU Interoperability Standard illustrating a timeline of when each state is assigned during a typical flight schedule from pre-takeoff through landing, which shows how these states are utilized and changed for an operational intent.

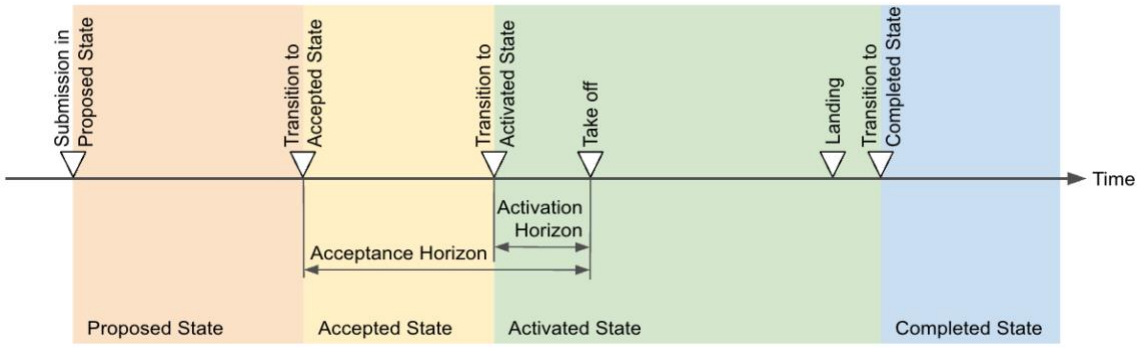



*Figure C2 Timeline for nominal transition of UAM operational intent*

**SDS Implemented States**

A subset of the states defined within the draft ASTM PSU Interoperability Standard were implemented for SDS**.** In the state diagram in Figure C1, the green colored states – Proposed, Canceled and Completed – were implemented. The Accepted and Activated states which were defined both in the draft ASTM PSU Interoperability Standard and prior NASA simulations remain present. Logic was added to enforce the constraint that an operational intent must be submitted in the Proposed state before it can be transitioned to the Accepted state. NASA's DSS for UAM will reject an operational intent if the initial state is not Proposed. The transitions to the "DCB-Noncompliant" or "Contingent" states are not implemented in NASA's DSS for UAM – the red colored states in the state diagram above. These two state definitions are evolving within the standards community, so it was decided to not include them in NASA's DSS for UAM implementation yet.

## C.3 Validation of the modified DSS for UAM

NASA validated the modified version of DSS for UAM by running a simulation using the same airspace configuration used in the PSU Prototype (X5) simulation. The modified DSS simulation results were compared with the prior X5 simulation results, in which the UTM-based DSS had been used with some workarounds for UAM DCB. This comparison revealed that no significant differences in the simulation results were observed and that there were no errors or issues.

The X5 summary and results can be found in [14]. Three of the measured statistics – (1) Number of Operations in each State, (2) Number of Simultaneous Operations over Time, and (3) Ground Delays due to DCB and S&S – are displayed below.

**Number of Operations in each State**

Introduction of the new states – Proposed, Completed, and Canceled – for SDS did not change the total number of operations, as shown in Table C2. Note that the X5 simulation did not have a Canceled state, so it did not display the one canceled flight.

*Table C2: Count of operational intents by state in X5 and modified DSS simulations*

| X5 Simulation | Planned | Accepted | Activated | Closed |
|---|---|---|---|---|
| Number of Operations | 40 | 39 | 39 | 39 |

| Modified DSS Sim. | Proposed | Accepted | Activated | Completed | Canceled |
|---|---|---|---|---|---|
| Number of Operations | 40 | 39 | 39 | 39 | 1 |

**Number of Simultaneous Operations over Time**

The exact times of each flight were slightly different between X5 and the modified DSS simulation. In Figure C3, the number of simultaneous operations in the air at every minute during the simulation run were the same, and the overall pattern of the lines displayed for the total simulation time period were equivalent. The graph only shows X5 results due to the similarities.

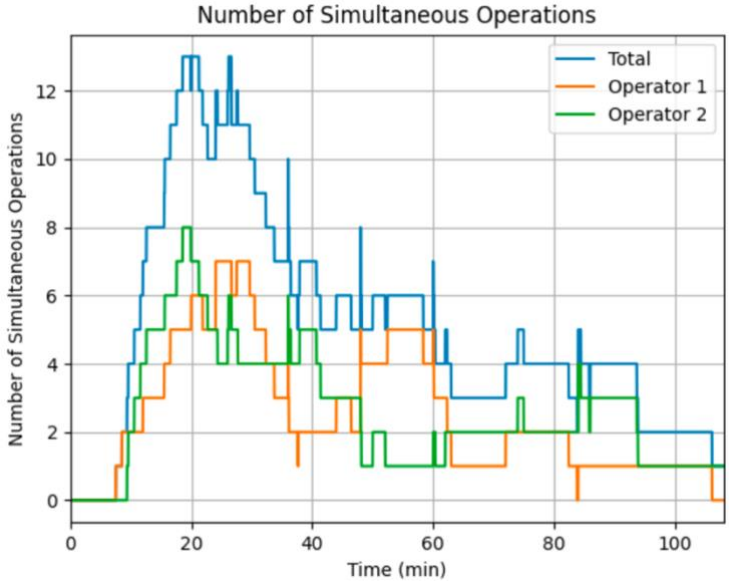



*Figure C3 Number of simultaneous operations from X5 simulation*

**Ground Delays due to DCB and S&S**

As shown in Table C3, the pre-departure delays due to DCB and S&S were also quite similar and did not vary significantly.

*Table C3: Delay statistics in X5 and modified DSS simulations*

| X5 Simulation | DCB | S&S | Total |
|---|---|---|---|
| Total Delay (minutes) | 705.7 | 13.0 | 718.6 |
| Number of Delayed Flights | 25 | 9 | 28 |
| Average Delay (minutes/flight) | 28.2 | 1.4 | 25.7 |

| Modified DSS Simulation | DCB | S&S | Total |
|---|---|---|---|
| Total Delay (minutes) | 721.7 | 16.1 | 737.9 |
| Number of Delayed Flights | 26 | 9 | 28 |
| Average Delay (minutes/flight) | 27.8 | 1.8 | 26.4 |

# D. Traffic Scenarios UAM

This appendix provides the initial flight schedules used as the SDS traffic scenarios. SDS used two flight schedules: medium-density and high-density traffic levels. The traffic demand covers the 18 Origin-Destination (OD) pair routes in the Dallas-Fort Worth metropolitan area. An equal number of operations are distributed to two UAM operators. Each traffic scenario takes about 90 minutes to simulate all flights from take-off to landing.

Tables below list the callsign, origin, destination, and departure timings for each operation.

- callsign: OPER100s for medium density traffic or OPER300s for high density traffic are allocated to Operator #1; OPER200s for medium density traffic or OPER400s for high density traffic are allocated to Operator #2.
- origin: origin vertiport
- destination: destination vertiport
- requestReceived: the time (in seconds since the start of the simulation) when the operator proposes the operation
- depTime: the desired departure time (in seconds since the start of the simulation)

## D.1 Medium traffic scenario

*Table D1: Medium-density traffic scenario for SDS*

| No | callsign | origin | destination | requestReceived (seconds) | depTime (seconds) | proposed_dep (hh:mm:ss) |
|---|---|---|---|---|---|---|
| 1 | OPER100 | DF120 | DF00 | 0 | 360 | 0:06:00 |
| 2 | OPER200 | DF00 | DF120 | 60 | 420 | 0:07:00 |
| 3 | OPER201 | DF120 | DF49 | 60 | 420 | 0:07:00 |
| 4 | OPER101 | DF99 | DF120 | 60 | 420 | 0:07:00 |
| 5 | OPER102 | DF00 | DF13 | 120 | 480 | 0:08:00 |
| 6 | OPER103 | DF99 | DF61 | 120 | 480 | 0:08:00 |
| 7 | OPER104 | DF120 | DF00 | 120 | 480 | 0:08:00 |
| 8 | OPER205 | DF7 | DF99 | 180 | 540 | 0:09:00 |
| 9 | OPER204 | DF99 | DF13 | 180 | 540 | 0:09:00 |
| 10 | OPER203 | DF13 | DF99 | 180 | 540 | 0:09:00 |
| 11 | OPER202 | DF00 | DF120 | 180 | 540 | 0:09:00 |
| 12 | OPER206 | DF120 | DF99 | 240 | 600 | 0:10:00 |
| 13 | OPER105 | DF99 | DF7 | 240 | 600 | 0:10:00 |
| 14 | OPER106 | DF61 | DF99 | 240 | 600 | 0:10:00 |
| 15 | OPER107 | DF61 | DF99 | 240 | 600 | 0:10:00 |
| 16 | OPER207 | DF50 | DF120 | 240 | 600 | 0:10:00 |
| 17 | OPER208 | DF120 | DF50 | 360 | 720 | 0:12:00 |
| 18 | OPER108 | DF61 | DF00 | 360 | 720 | 0:12:00 |
| 19 | OPER109 | DF120 | DF50 | 360 | 720 | 0:12:00 |
| 20 | OPER209 | DF99 | DF120 | 420 | 780 | 0:13:00 |
| 21 | OPER210 | DF99 | DF7 | 420 | 780 | 0:13:00 |
| 22 | OPER211 | DF00 | DF13 | 420 | 780 | 0:13:00 |
| 23 | OPER212 | DF99 | DF61 | 540 | 900 | 0:15:00 |
| 24 | OPER110 | DF00 | DF61 | 540 | 900 | 0:15:00 |
| 25 | OPER213 | DF99 | DF13 | 540 | 900 | 0:15:00 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 26 | OPER214 | DF120 | DF99 | 540 | 900 | 0:15:00 |
| 27 | OPER111 | DF49 | DF120 | 600 | 960 | 0:16:00 |
| 28 | OPER112 | DF50 | DF120 | 600 | 960 | 0:16:00 |
| 29 | OPER113 | DF13 | DF99 | 660 | 1020 | 0:17:00 |
| 30 | OPER114 | DF120 | DF49 | 660 | 1020 | 0:17:00 |
| 31 | OPER115 | DF61 | DF00 | 660 | 1020 | 0:17:00 |
| 32 | OPER116 | DF49 | DF120 | 840 | 1200 | 0:20:00 |
| 33 | OPER215 | DF13 | DF00 | 1140 | 1500 | 0:25:00 |
| 34 | OPER216 | DF00 | DF61 | 1140 | 1500 | 0:25:00 |
| 35 | OPER217 | DF7 | DF99 | 1260 | 1620 | 0:27:00 |
| 36 | OPER117 | DF13 | DF00 | 1320 | 1680 | 0:28:00 |

## D.2 High traffic scenario

*Table D2: Medium-density traffic scenario for SDS*

| No | callsign | origin | destination | requestReceived (seconds) | depTime (seconds) | proposed_dep (hh:mm:ss) |
|---|---|---|---|---|---|---|
| 1 | OPER300 | DF61 | DF99 | 0 | 360 | 13:06:00 |
| 2 | OPER400 | DF00 | DF120 | 0 | 360 | 13:06:00 |
| 3 | OPER401 | DF120 | DF99 | 0 | 360 | 13:06:00 |
| 4 | OPER402 | DF61 | DF00 | 0 | 360 | 13:06:00 |
| 5 | OPER403 | DF13 | DF00 | 0 | 360 | 13:06:00 |
| 6 | OPER404 | DF120 | DF50 | 0 | 360 | 13:06:00 |
| 7 | OPER405 | DF00 | DF61 | 60 | 420 | 13:07:00 |
| 8 | OPER406 | DF61 | DF00 | 60 | 420 | 13:07:00 |
| 9 | OPER407 | DF120 | DF00 | 60 | 420 | 13:07:00 |
| 10 | OPER301 | DF00 | DF120 | 120 | 480 | 13:08:00 |
| 11 | OPER302 | DF120 | DF49 | 120 | 480 | 13:08:00 |
| 12 | OPER408 | DF99 | DF13 | 120 | 480 | 13:08:00 |
| 13 | OPER409 | DF120 | DF99 | 120 | 480 | 13:08:00 |
| 14 | OPER410 | DF99 | DF120 | 120 | 480 | 13:08:00 |
| 15 | OPER411 | DF120 | DF00 | 120 | 480 | 13:08:00 |
| 16 | OPER303 | DF99 | DF61 | 180 | 540 | 13:09:00 |
| 17 | OPER304 | DF00 | DF13 | 180 | 540 | 13:09:00 |
| 18 | OPER412 | DF13 | DF99 | 180 | 540 | 13:09:00 |
| 19 | OPER413 | DF13 | DF00 | 180 | 540 | 13:09:00 |
| 20 | OPER305 | DF7 | DF99 | 240 | 600 | 13:10:00 |
| 21 | OPER306 | DF00 | DF61 | 240 | 600 | 13:10:00 |
| 22 | OPER307 | DF00 | DF61 | 240 | 600 | 13:10:00 |
| 23 | OPER308 | DF50 | DF120 | 300 | 660 | 13:11:00 |
| 24 | OPER309 | DF7 | DF99 | 300 | 660 | 13:11:00 |
| 25 | OPER310 | DF61 | DF99 | 300 | 660 | 13:11:00 |
| 26 | OPER311 | DF99 | DF61 | 300 | 660 | 13:11:00 |
| 27 | OPER414 | DF13 | DF99 | 300 | 660 | 13:11:00 |
| 28 | OPER312 | DF120 | DF50 | 360 | 720 | 13:12:00 |
| 29 | OPER313 | DF00 | DF120 | 360 | 720 | 13:12:00 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 30 | OPER314 | DF99 | DF120 | 360 | 720 | 13:12:00 |
| 31 | OPER315 | DF120 | DF49 | 360 | 720 | 13:12:00 |
| 32 | OPER415 | DF99 | DF7 | 360 | 720 | 13:12:00 |
| 33 | OPER316 | DF99 | DF120 | 420 | 780 | 13:13:00 |
| 34 | OPER317 | DF120 | DF49 | 420 | 780 | 13:13:00 |
| 35 | OPER416 | DF7 | DF99 | 420 | 780 | 13:13:00 |
| 36 | OPER318 | DF50 | DF120 | 480 | 840 | 13:14:00 |
| 37 | OPER319 | DF13 | DF99 | 480 | 840 | 13:14:00 |
| 38 | OPER417 | DF49 | DF120 | 480 | 840 | 13:14:00 |
| 39 | OPER320 | DF120 | DF99 | 540 | 900 | 13:15:00 |
| 40 | OPER321 | DF61 | DF00 | 540 | 900 | 13:15:00 |
| 41 | OPER418 | DF99 | DF7 | 540 | 900 | 13:15:00 |
| 42 | OPER419 | DF99 | DF61 | 540 | 900 | 13:15:00 |
| 43 | OPER420 | DF49 | DF120 | 540 | 900 | 13:15:00 |
| 44 | OPER322 | DF99 | DF13 | 600 | 960 | 13:16:00 |
| 45 | OPER323 | DF50 | DF120 | 600 | 960 | 13:16:00 |
| 46 | OPER421 | DF61 | DF99 | 600 | 960 | 13:16:00 |
| 47 | OPER422 | DF99 | DF7 | 600 | 960 | 13:16:00 |
| 48 | OPER324 | DF49 | DF120 | 660 | 1020 | 13:17:00 |
| 49 | OPER325 | DF120 | DF00 | 660 | 1020 | 13:17:00 |
| 50 | OPER326 | DF120 | DF50 | 660 | 1020 | 13:17:00 |
| 51 | OPER423 | DF13 | DF00 | 660 | 1020 | 13:17:00 |
| 52 | OPER424 | DF99 | DF13 | 660 | 1020 | 13:17:00 |
| 53 | OPER425 | DF00 | DF13 | 900 | 1260 | 13:21:00 |
| 54 | OPER426 | DF00 | DF13 | 1200 | 1560 | 13:26:00 |