# Initial Analysis of Digitally Enabled Cooperative Operations in Class D Terminal Airspace

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**The primary contribution of this paper is an initial analysis of integrating digitally enabled cooperative operations (or digital operations for short) with Visual Flight Rules (VFR) and Instrument Flight Rules (IFR) operations in the terminal airspace around a Class D airport, specifically around Fort Worth Alliance airport (KAFW). Enabled by connected digital technologies and automated information exchange, digital operations as envisioned would utilize cooperative practices and operator-responsible separation to ensure safety. In the present study, three conflict management configurations for digital operations were analyzed: 1) centralized with a single instance of a conflict management service to model a scenario with only one fleet operator conducting digital operations or all fleet operators utilizing the same service, 2) federated with two different instances to model a scenario with two different fleet operators conducting digital operations, and 3) fully distributed with a different instance for each digital operation. In simulations in which recorded tracks for VFR and IFR operations were played back and digital operations were modeled that would nominally arrive at KAFW once every 20 minutes (given no conflict resolution maneuvers), there were one or fewer losses of separation (LOS) across the three conflict management configurations. The same result was seen in simulations in which digital operations would nominally arrive at KAFW once every 10 minutes. However, in simulations in which digital operations would nominally arrive at KAFW once every 5 minutes, the number of LOS ranged between six and ten. This highlights the need for follow-on research to investigate the extent to which additional capabilities for digital operations, such as complexity management and/or flow organization, may be needed.**

## I. Introduction

THE diversity of aircraft and operations—including but not limited to remotely piloted aircraft, higher levels of autonomy, and new types of propulsion, missions, business models, and flight locations—in the National Airspace System (NAS) is expected to increase over time. New and existing aircraft and operations must co-exist or integrate with each other. As stated in a joint publication by Airbus and Boeing "new and adapted flight rules and procedures will be required to efficiently manage these increasingly dynamic operations of differing priority and types" [1], which includes Extensible Traffic Management (xTM) operations [2] such as Unmanned aircraft systems Traffic Management (UTM) [3], Urban Air Mobility (UAM) [4], and Upper Class E Traffic Management (ETM) [5].

The primary contribution of the present study is an initial analysis of integrating digitally enabled cooperative operations [6]-[9] (or digital operations for short) with Visual Flight Rules (VFR) and Instrument Flight Rules (IFR) operations in Class D terminal airspace, specifically around Fort Worth Alliance airport (KAFW). It is the first investigation to identify feasibility challenges for digital operations at a capacity-constrained airport, characterize the scope and magnitude of these challenges, and propose potential mitigations and extensions to explore in follow-on studies. The insights gained through the present study would have been challenging to uncover without the fast-time simulations that were conducted due to the myriad of concurrent and ensuing complex interactions and outcomes involved in conducting digital operations in constrained airspace.

A prior study evaluated the potential benefits of a tailored trajectory management (TTM) capability for a simulated fleet operator of uncrewed aircraft (UA) in KAFW [10]. The purpose of the TTM capability was to preclude spikes in UA fleet operator workload that could occur when concurrent UA conflict situations would require communicating

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with different air traffic controllers on different radio frequencies at the same time by proactively detecting conflicts and developing trajectory-based solutions for UA operations prior to air traffic control (ATC) performing conflict resolution.

The prior study only evaluated the case in which a common conflict management service was utilized for all flights of the new type of operation being analyzed (UA operations). By contrast, the present study also analyzes cases in which different instances of a conflict management service are utilized for different subsets of flights of the new type of operation being studied (digital operations). The latter reflects a concept of operations in which each fleet operator conducting digital operations is responsible for separating their own flights from each other directly and from those of other fleet operators cooperatively. In addition to analyzing centralized conflict management for digital operations with a single instance of a conflict management service, the present study also analyzed federated conflict management with two different instances for different subsets of flights and fully distributed conflict management with a different instance for each digital operation. Furthermore, in addition to the baseline scenario with flights of the new type of operation nominally arriving at KAFW once every 20 minutes (given no conflict resolution maneuvers) as in the prior study, the present study also analyzes two higher-tempo scenarios with digital operations nominally arriving at KAFW: 1) once every 10 minutes, and 2) once every 5 minutes.

Next, Section II describes the digital operations conceptual framework that is the basis of the present study and the fast-time simulation technologies and algorithmic capabilities that were utilized to analyze the integration of digital operations with VFR and IFR operations in the Class D terminal airspace around KAFW. Section III describes the methodology, including the simulation configurations, traffic scenarios, and conflict management parameters. Section IV presents the results, with a focus on safety-related metrics—losses of separation (LOS) and conflict resolution maneuvers—and notable corresponding conflict situations. Section V discusses the results and potential extensions of this study that would be valuable to conduct. Lastly, Section VI summarizes the findings of this study.

## II. Background

There is a risk that multiple new operating modes will be developed to enable the increasingly diverse range of aircraft and operations envisioned in the future airspace. Each new operating mode would add increasingly greater complexity to rulemaking and air traffic management (ATM). To mitigate this risk, NASA is collaborating with stakeholders to research a concept and framework for digital operations that is envisioned to be available to all airspace users, accepted in all airspace classes, and aligned with emerging service-oriented concepts (e.g., xTM). Enabled by connected digital technologies and automated information exchange, digital operations as envisioned would be predicated on four essential elements: 1) information services and connectivity, 2) shared traffic and intent awareness, 3) cooperative practices, and 4) automated conflict management capabilities.

This initial analysis of integrating digital operations with VFR and IFR operations in the terminal airspace around a Class D airport is part of a broader effort to assess the technical feasibility of digital operations and substantiate and refine the digital operations conceptual framework and its attributes. It is part of a set of initial modeling and simulation studies that also includes efforts focused on enroute airspace, Upper Class E airspace [11], and a cloud-based flight management system (FMS) of arrival self-sequencing at non-towered airports [12]. These initial modeling and simulation studies are complementary to existing and ongoing efforts to clarify and refine the digital operations concept and framework with key stakeholders.

### A. Essential Elements of Digital Operations

#### *1. Information Services and Connectivity*

The first essential element of digital operations is information services and connectivity to those services to maintain a digital model of the operating environment for use by decision-making automation. It involves the relevant, timely, and secure exchange of information about current and forecasted aircraft states and intent, the environment (e.g., current and predicted atmospheric conditions), non-traffic hazards (e.g., terrain, obstacles), airspace restrictions (e.g., special activity airspace), flow constraints (e.g., delay predictions, scheduled times of arrival), and terminal arrival information (e.g., runway configurations, approaches in use).

#### *2. Shared Traffic and Intent Awareness*

The second essential element of digital operations is traffic and intent information shared among digital operations to maintain and ensure mutual knowledge and understanding to facilitate compatible decision making, especially for conflict management. The required information includes but is not limited to aircraft state, flight path intent, navigation performance, maneuverability, and performance limits.

*3. Cooperative Practices*

The third essential element of digital operations is a set of cooperative practices that govern the behavior of digital operations to ensure harmonized use of the airspace and safe, orderly, and expeditious operations that are broadly equitable and acceptable. The following set of candidate cooperative practices [8] (grouped by five different purposes) are a starting point for deliberation and refinement through ongoing community engagement and modeling and simulation efforts.

1. Increase predictability, efficiency, stability, and safety
   - Share and update intent
   - Take timely action
2. Minimize disruption to existing operations
   - Respect intent when changing intent
   - Respect VFR and IFR aircraft
3. Increase airspace capacity; reduce actionable conflicts
   - Navigate with intended precision
   - Apply pair-appropriate separation
4. Distribute separation burden; increase safety
   - Respect right-of-way among digital operations
   - Coordinate maneuvering among digital operations
5. Facilitate airspace integration; minimize controller workload; minimize disruptions
   - Coordinate with ATC in controlled airspace
   - Join in appropriate flow management
   - Avoid active protected airspace
   - Respect established operating procedures

*4. Automated Conflict Management Capabilities*

The fourth essential element of digital operations is a set of specific conflict management capabilities enabled by automation. It includes tools for detecting and resolving conflicts while conforming to constraints. Embedding cooperative practices into conflict management automation technologies ensures consistent and reliable application across digital operations for predictable behavior and airspace integration. This element has six envisioned principal capabilities, of which the first is the primary focus of the present study. Planned follow-on studies will model and focus on the other principal capabilities, starting with the second, third, and fourth.

1. Operator-responsible separation for conflict prevention, which includes conflict detection, conflict resolution, and hazard avoidance
2. Cooperative conflict management in which right-of-way and responsibility to maneuver are electronically determined, with coordination of time-critical maneuvers according to established rules
3. Adaptive pairwise separation in which conflicts between digital operations have smaller separation criteria due to sharing performance information and having more capable 4D navigational performance
4. Collaborative utilization of constrained resources in which flow management assigns a Required Time of Arrival (RTA) or time interval from preceding traffic to a digital operation, which the digital operation (or fleet operator) then develops and conducts an optimized route to achieve
5. Self-organization and sequencing among digital operations without a central coordinator
6. Self-limiting of density and complexity among digital operations that ensures traffic volume and traffic complexity remain at a safe scale and operator-responsible separation remains feasible

## B. ATM Test Bed

The NASA ATM Test Bed (or simply Test Bed) [13]-[14] was the software platform utilized in the present study. It provides a foundational environment that enables multi-fidelity, real-time and fast-time, human-in-the-loop and automation-in-the-loop simulations of current and proposed future air traffic concepts. It has a configuration panel, traffic viewer, interfaces for input data (e.g., airspace and airport models, arrival and departure procedures, recorded and live flight tracks and flight plans), and other capabilities. It is an integration middleware that connects aircraft simulators, services (e.g., conflict management), and other technologies.

## C. NAS Digital Twin

Built on the NASA ATM Test Bed software platform, the NAS Digital Twin (NDT) simulation environment [15] was utilized in the present study. It has been employed to verify and validate new technologies, simulate and evaluate changes to the NAS, and uncover unintended consequences and risks of introducing new concepts and technologies. Leveraging decades of research and development [16]-[33], it contains a set of capabilities that enable a Live, Virtual, and Constructive environment with simulated, recorded, and/or live airspace service providers, fleet operators, aircraft, and weather. Its modular architecture facilitates the process of developing, integrating, and evaluating new algorithms, services, and system configurations in a common environment. It has been utilized to study operations in increasingly complex airspace with increasingly diverse aircraft and increasingly autonomous operations in different timeframes, ranging from the present day through the far term.

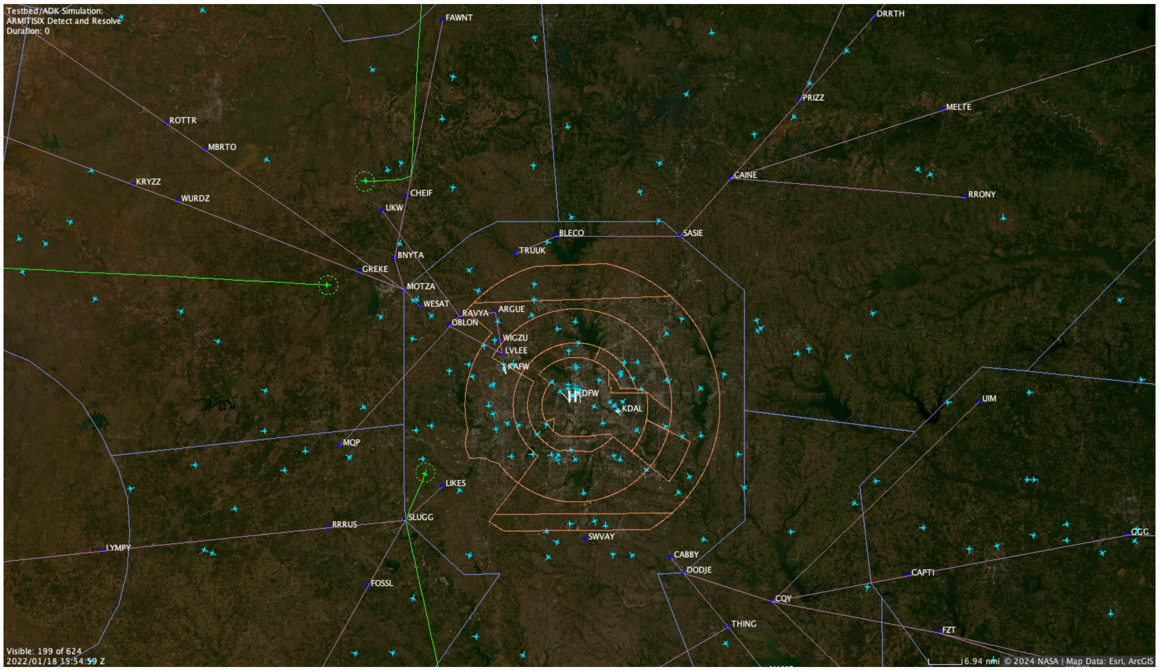


**Fig. 1 NAS Digital Twin Traffic Viewer (green: simulated digital operations; cyan: recorded flights).[1]**

## D. Autoresolver

Autoresolver (AR) was the conflict management service utilized in this study. It is a Test Bed component that detects conflicts and develops coordinated and comprehensive trajectory-based solutions (e.g., horizontal, vertical, speed, pre-departure ground holding, arrival holding patterns) [22]-[24]. It contains capabilities for pre-departure planning, air traffic separation, arrival merging and spacing, terminal area operations, and polygon avoidance (e.g., restricted airspace, severe convective weather). It operates on a longer timeframe than Detect-and-Avoid (a few minutes) and collision avoidance (seconds) and on a shorter timeframe than traffic flow management (hours). All AR conflict management capabilities except polygon avoidance were utilized in the present study to separate simulated digital operations from each other and from recorded flight tracks that were played back (details in Section III). Since AR was and is being developed with the NDT simulation environment, it has the same range of applications described in the prior section. In the present study, AR was utilized in three different configurations: 1) centralized with a single instance managing all digital operations, 2) federated with different instances managing different subsets of digital operations, and 3) fully distributed with a different instance for each digital operation.

## E. Simulation Test Apparatus

All simulations in the present study utilized the software platform, simulation environment, and conflict management service described in this section. Digital operations were simulated using recorded flight plans from the NASA Sherlock Data Warehouse [32]-[33]. Wind data from Sherlock were loaded into the simulation environment and incorporated into the simulation of digital operations and conflict resolution maneuvers. Recorded VFR and IFR traffic data from Sherlock were loaded in as background traffic that the conflict management service needed to maneuver the simulated digital operations away from to maintain safe separation. The simulation environment and

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[1] The map data is from https://services.arcgisonline.com/ArcGIS/rest/services/World_Imagery/MapServer and is used with permission according to the ESRI terms of service: https://www.esri.com/en-us/legal/copyright-trademarks

the conflict management service were both connected to the software platform, with some simulations having one instance of the service to model centralized conflict management (Figure 2), others having two instances to model federated conflict management (Figure 3), and the remaining having a different instance for each digital operation to model fully distributed conflict management (Figure 4). (If desired, the simulation environment can be set up for different instances of the conflict management service to utilize different trajectory predictors.)

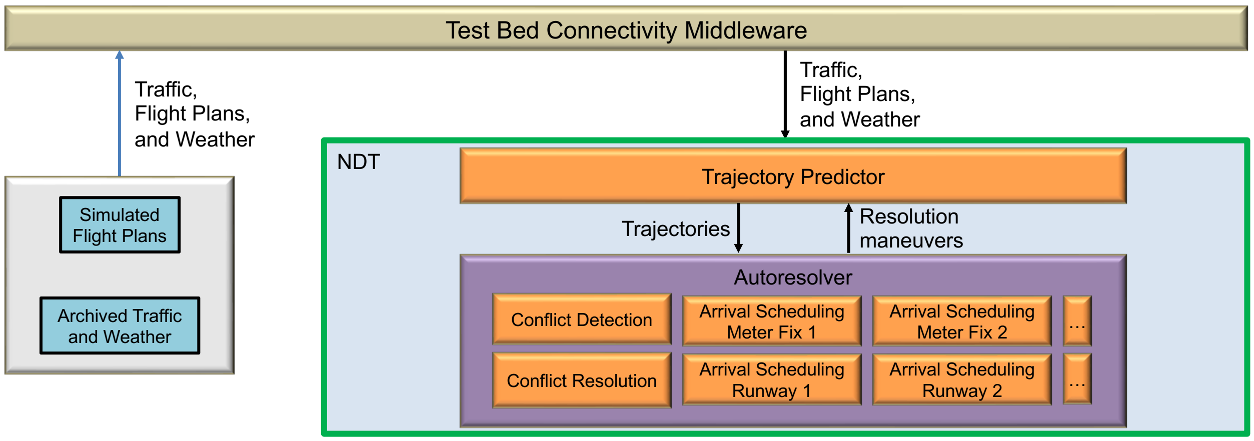


**Fig. 2 Simulation Test Apparatus with Centralized Conflict Management for Digital Operations.**

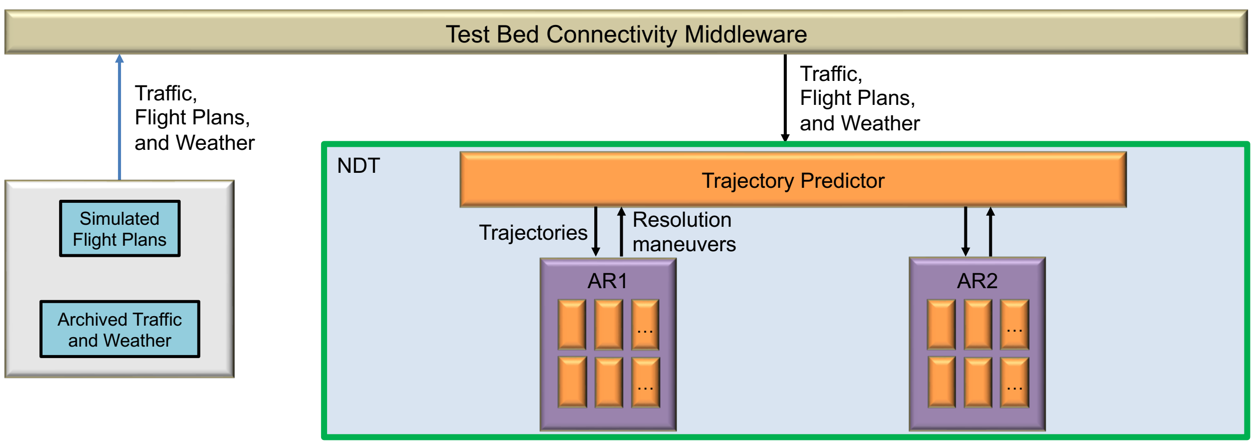


**Fig. 3 Simulation Test Apparatus with Federated Conflict Management for Digital Operations.**

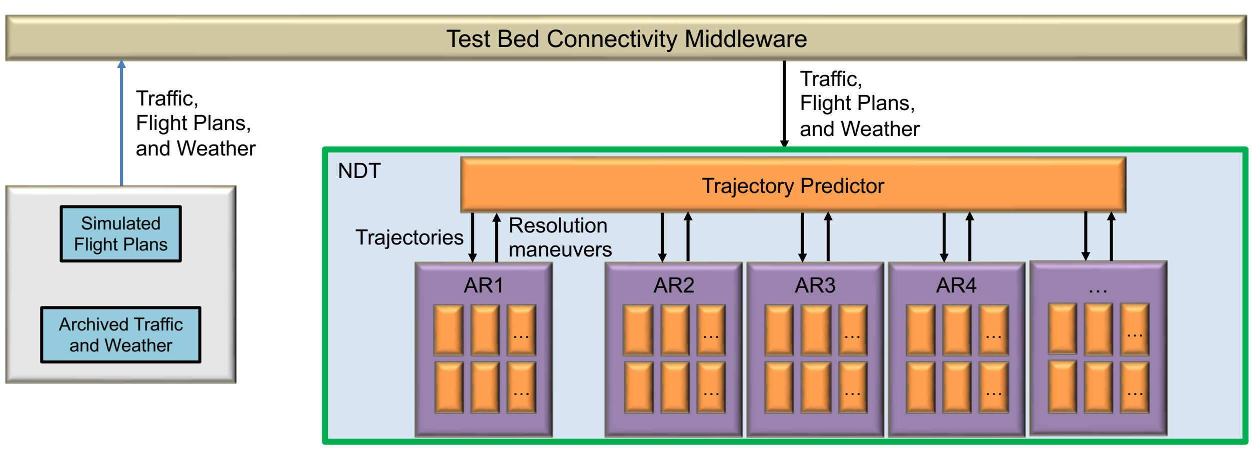


**Fig. 4 Simulation Test Apparatus with Fully Distributed Conflict Management for Digital Operations.**

Prior to departure, the conflict management service utilizes the trajectory predictor to perform conflict detection and holds the simulated digital operation on the ground as needed to resolve conflicts. As the digital operation proceeds through the airspace, the conflict management service continues to perform conflict detection and issue conflict resolution maneuvers for the digital operation as needed. At the freeze horizon, which was set to be 20 minutes prior to the arrival meter fix in this study, the conflict management service performs operator-based self-scheduling by calculating an arrival meter fix scheduled time of arrival (STA) and a runway threshold STA for the digital operation to meet. After the digital operation crosses the freeze horizon, the conflict management service continues to perform conflict detection and issue conflict resolution maneuvers for the digital operation as needed to ensure separation and conformance to its arrival meter fix STA. In general, when large delays (of more than five minutes) are required, the conflict management service attempts to maneuver the digital operation when it is in Center airspace where there is generally more available airspace. Then, after the digital operation crosses the arrival meter fix, the conflict management service continues to perform conflict detection and issue conflict resolution maneuvers as needed to ensure separation and conformance to its arrival runway threshold STA.

## III. Methodology

A set of nine fast-time simulations was conducted to analyze the integration of digital operations with VFR and IFR operations in Class D terminal airspace, assess technical feasibility, and substantiate and refine the digital operations conceptual framework and its attributes. These simulations (Table 1) were combinations of three simulated traffic scenarios of digital operations arriving at KAFW and three conflict management configurations for digital operations.

Regarding the three traffic scenarios, in simulations 1 through 3, digital operations were simulated to nominally arrive at KAFW (given no conflict resolution maneuvers) once every 20 minutes. This was based on discussions with industry about the expected initial tempo of one new type of operation (regional air cargo with UA) [10]. In addition, more challenging simulated traffic scenarios were run to evaluate scaled-up, higher-tempo operations. In simulations 4 through 6, digital operations were simulated to nominally arrive at KAFW once every 10 minutes. In simulations 7 through 9, digital operations were simulated to nominally arrive at KAFW once every 5 minutes.

Regarding the three conflict management configurations, in simulations 1, 4, and 7, the conflict management service was utilized in a centralized configuration to model a scenario with only one fleet operator conducting digital operations or all fleet operators utilizing the same service. In simulations 2, 5, and 8, it was utilized in a federated configuration with two different instances operating sequentially at different times to model a scenario with two different fleet operators conducting digital operations. (If desired, more than two and fewer than *n* instances can be utilized in alternative federated conflict management configurations, where *n* is the number of digital operations.) In simulations 3, 6, and 9, it was utilized in a fully distributed configuration with a different instance for each digital operation.

**Table 1 Simulation Configurations**

| Simulation Configuration | Simulated Traffic Scenario (nominal time between digital operations arriving at KAFW) | Conflict Management Configuration for Digital Operations |
|---|---|---|
| 1 | 20 minutes | Centralized |
| 2 | 20 minutes | Federated |
| 3 | 20 minutes | Fully distributed |
| 4 | 10 minutes | Centralized |
| 5 | 10 minutes | Federated |
| 6 | 10 minutes | Fully distributed |
| 7 | 5 minutes | Centralized |
| 8 | 5 minutes | Federated |
| 9 | 5 minutes | Fully distributed |

### A. Traffic Scenarios

In the baseline simulated traffic scenario, five digital operations were simulated to nominally arrive at KAFW in Texas at intervals of 20 minutes. They were based on recorded Cessna 208 Caravan (C208) flights into KAFW on January 18, 2022—three flights from Austin airport (KAUS) in Texas, followed by one flight from Lubbock airport (KLBB) in Texas, and one flight from Wichita airport (KICT) in Kansas. This date was selected due to having minimal convective weather in Fort Worth Center as indicated in the NASA Sherlock Data Warehouse. The higher-tempo simulated traffic scenarios were created by duplicating the five original digital operations, with the duplicates assigned different departure times between those in the baseline simulated traffic scenario. The highest-tempo simulated traffic scenario with a nominal time between digital operations arriving at KAFW of 5 minutes was particularly challenging due to greater airspace congestion and conflict complexity that resulted from the increase in the number of digital operations, especially in the constrained terminal area environment.

KAFW was selected as the airport of focus because it has complex operations as a Class D airport underneath a Class B shelf of Dallas-Fort Worth airport (KDFW) in Texas and Dallas Love Field airport (KDAL) in Texas [34]. In addition, it is a cargo carrier hub for FedEx Express and Amazon Air. It has various features, such as a continuously operating control tower and two 11,000-ft runways with Instrument Landing System (ILS) approaches (including one with a Category II/III approach) that can enable new types of operations with new types of aircraft.

In each simulation, recorded tracks for about 3800 flights in Fort Worth Center (ZFW), adjacent Centers, and their respective TRACONs on January 18, 2022 from around 1430 to 1730 UTC (0830 to 1130 local time) were played back as background traffic that the conflict management service needed to maneuver the simulated digital operations away from to maintain safe separation. This period was selected due to the high density of departing and arriving flights in 2022 [10].

### B. Conflict Management Parameters

In all simulations in this initial analysis, all instances of the conflict management service were provided zero-error flight information and ran once per simulation minute. In the simulations with the federated conflict management configuration, the two instances of the conflict management service ran sequentially at different times within any given one-minute simulation timespan to model the asynchronous nature of real-world operations with two different fleet operators utilizing different conflict management services. Similarly, in the simulations with the fully distributed conflict management configuration, each instance of the conflict management service ran sequentially at different times within any given one-minute simulation timespan. At any given time, only one instance of the conflict management service performs conflict detection and resolution, with every conflict resolution maneuver immediately known by every other instance of the conflict management service.

As summarized in Table 2, in each simulation, the conflict management service identified conflicts in terminal airspace with less than 3.0 nmi of horizontal separation (HorzSep) and less than 1000 ft of vertical separation (VertSep) and, when the predicted time to LOS was 8 minutes or less, the conflict management service developed conflict resolution maneuvers for the simulated digital operations to maintain HorzSep ≥ 4.0 nmi and/or VertSep ≥ 1000 ft for at least 10 minutes. In addition, the conflict management service identified conflicts in Center airspace with HorzSep < 5.0 nmi and VertSep < 1000 ft and, when the predicted time to LOS was 8 minutes or less, the conflict management service developed conflict resolution maneuvers for the simulated digital operations to maintain HorzSep ≥ 7.0 nmi and/or VertSep ≥ 1000 ft for at least 12 minutes.

**Table 2 Conflict Management Parameters**

| Conflict Management Service Airspace | Horizontal Separation for Detection [nmi] | Horizontal Separation for Resolution [nmi] | Vertical Separation for Detection [ft] | Vertical Separation for Resolution [ft] | Time to LOS to Start Conflict Resolution Process [minutes] | Required Conflict-Free Duration for Conflict Resolution [minutes] |
|---|---|---|---|---|---|---|
| Terminal | < 3.0 | ≥ 4.0 | < 1000 | ≥ 1000 | ≤ 8 | ≥ 10 |
| Center | < 5.0 | ≥ 7.0 | < 1000 | ≥ 1000 | ≤ 8 | ≥ 12 |

## IV. Results

This section presents the metrics that were calculated in this initial analysis of integrating digital operations with VFR and IFR operations in Class D terminal airspace, specifically around KAFW. Safety-related metrics and notable corresponding conflict situations were the primary focus. LOS were identified by calculating the distances between pairs of flights at each simulation time step and recording: 1) instances with HorzSep < 3.0 nmi and VertSep < 1000 ft in terminal airspace, and 2) instances with HorzSep < 5.0 nmi and VertSep < 1000 ft in Center airspace.

## A. Losses of Separation (LOS)

Figure 5 illustrates the number of LOS that involved one or more simulated digital operations in each of the nine simulation configurations, excluding LOS that involved a digital operation on final approach. These LOS were excluded because it is reasonable to expect ATC to clear the final approach path for arrival flights, which have limited maneuver options. It is particularly challenging to maintain separation when other flights are in the immediate area around the arrival airport for long periods of time (Section IV.A.1).

The number of LOS was generally similar among the simulation configurations with the same simulated traffic scenario. In the simulations of the traffic scenario with a nominal time between digital operations arriving at KAFW of 20 minutes, there were zero or one LOS (left-most group of three bars). This was also the result in the simulations of the traffic scenario with a nominal time between digital operations arriving at KAFW of 10 minutes (middle group).

By comparison, there was more variation in the number of LOS among the simulations of the highest-tempo traffic scenario with a nominal time between digital operations arriving at KAFW of 5 minutes (right-most group). This was the eventual result of different instances of the conflict management service operating sequentially at different times within any given one-minute simulation timespan to model the asynchronous nature of real-world operations (Section III.B). Although every conflict resolution maneuver made by one instance of the conflict management service is immediately known by every other instance of the conflict management service, the resulting differences in the conflict situations and the flights that can be maneuvered at the different times at which each instance ran resulted in different conflict resolution maneuvers being issued at different times to the simulated digital operations. The collective ripple effect of these differences eventually resulted in specific clusters of LOS that resulted in more LOS in the simulations with federated conflict management (Section VI.A.2) and fully distributed conflict management (Section VI.A.3) within this group.

The higher number of LOS in the simulations of the highest-tempo simulated traffic scenario highlights the need for follow-on research to investigate the extent to which additional capabilities for digital operations, such as complexity management and/or flow organization, could be needed. The greater variation in the number of LOS across this latter group of simulations was due to different clusters of LOS in the federated and fully distributed simulations (Section IV.A.2 and Section IV.A.3).

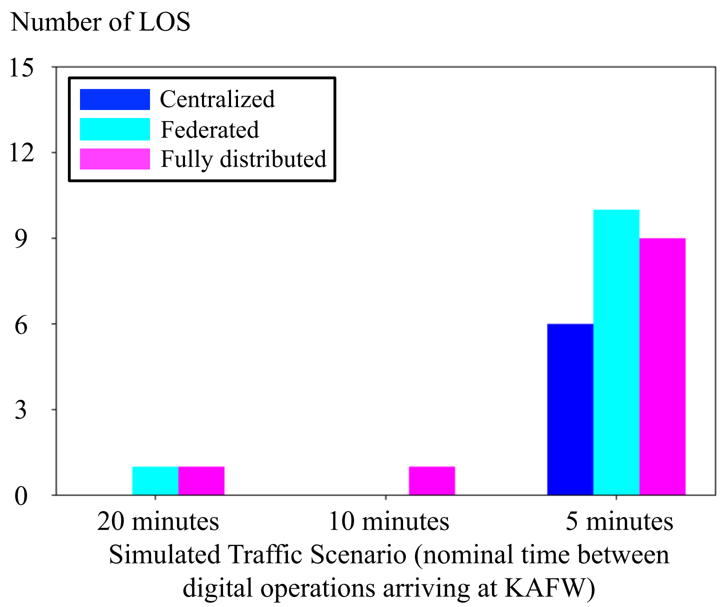


**Fig. 5 Number of Losses of Separation (LOS).**

*1. Example LOS Excluded: VFR circling around KAFW with digital operation on final approach*

Figure 6 illustrates an example from simulation configuration 8 of a common situation that substantiates the exclusion of LOS that involved a digital operation on final approach. The dashed blue curve illustrates the horizontal path of the simulated digital operation that was on final approach into KAFW. The solid black curve illustrates the horizontal path of the recorded VFR flight that was performing touch-and-go maneuvers around KAFW around the same time. LOS like this were excluded from the analysis results because it is reasonable to expect ATC to clear the final approach path for arrival flights, which have limited maneuver options, especially when other flights are in the immediate area around the arrival airport for long periods of time.

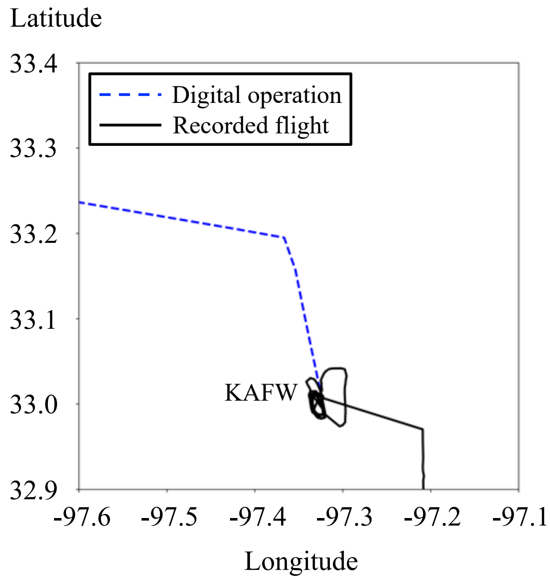


**Fig. 6 LOS involving VFR Flight Circling around KAFW.**

2. *Example Cluster of LOS: High-speed IFR flight arriving from behind multiple digital operations*

Figure 7 illustrates the cluster of LOS that occurred around the same time and area in simulation 8. This cluster of LOS was directly or indirectly caused by a high-speed IFR recorded flight (solid black curve) arriving at nearby KDFW from behind multiple digital operations arriving at KAFW (dashed cyan, magenta, green, and blue curves). Other recorded flights at or below 7000 ft altitude in the vicinity around the same time (black dots) contributed to the inability of the conflict management service to find conflict-free resolution maneuvers for the digital operations in this example.

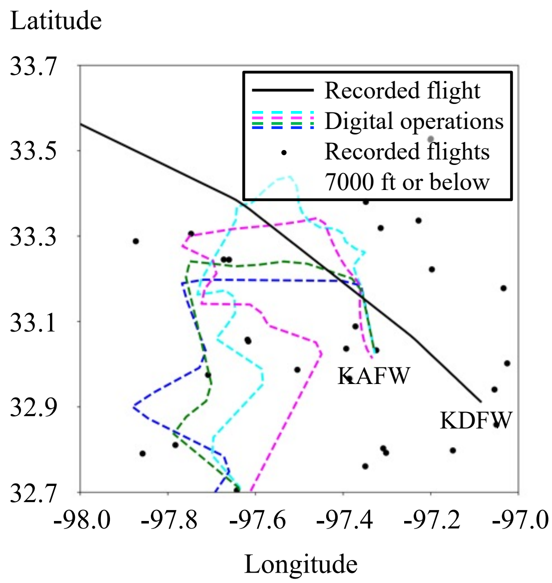


**Fig. 7 Cluster of LOS due to High-Speed IFR Flight Arriving at KDFW.**

*3. Example Cluster of LOS: Meandering VFR flight around digital operations prior to final approach*

Figure 8 illustrates the cluster of LOS that occurred around the same time and area in simulation 9. This cluster of LOS was directly or indirectly caused by a meandering VFR recorded flight (solid black curve) around the digital operations arriving at KAFW (dashed cyan, magenta, and green curves). As in the prior example, other recorded flights at or below 7000 ft altitude in the vicinity around the same time (black dots) contributed to the inability of the conflict management service to find conflict-free resolution maneuvers for the digital operations in this example.

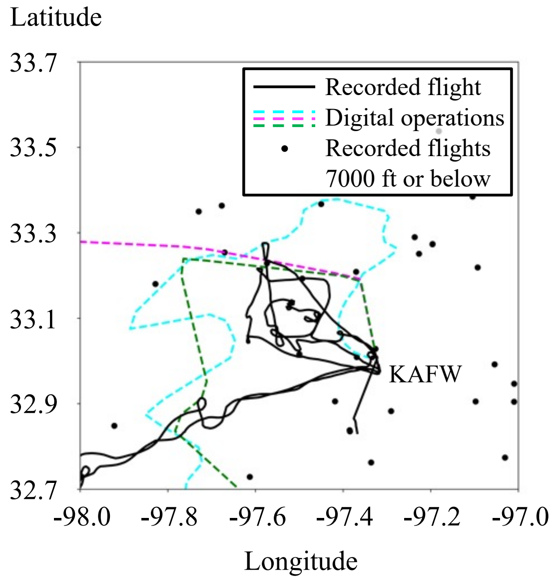


**Fig. 8 Cluster of LOS due to Meandering VFR Flight around KAFW.**

## B. Conflict Resolutions

Figure 9 illustrates the number of conflict resolutions in each of the nine simulation configurations. As the number of simulated digital operations doubled between the different traffic scenarios, the number of conflict resolutions grew exponentially.

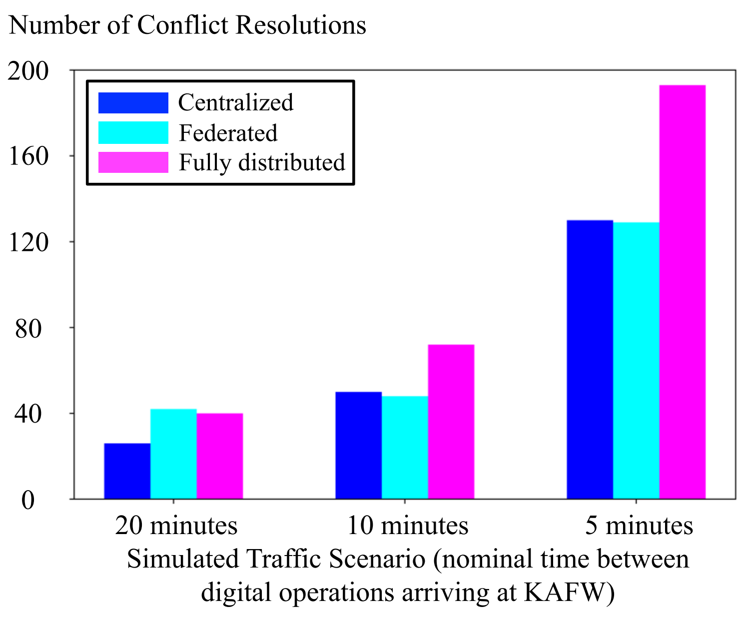


**Fig. 9 Number of Conflict Resolutions.**

In addition, there are noticeable differences between the number of conflict resolutions issued among the simulation configurations with the same simulated traffic scenario (i.e., within each group). This was the result of the different conflict situations that occurred due to different instances of the conflict management service operating sequentially at different times in the simulations that utilized a non-centralized conflict management configuration (i.e., federated or fully distributed).

*1. Example Conflict Resolution: Path Stretch*

Figure 10 illustrates the modified path of a digital operation (dashed blue curve) relative to its initial planned path (dotted blue curve) that was the result of performing a path stretch conflict resolution maneuver developed by an instance of the conflict management service for a conflict with a recorded flight (solid black curve) in simulation configuration 8. This was one of only two conflict resolution maneuvers performed by this digital operation, which was the second to enter the simulation before other digital operations entered and increased the congestion of the airspace and complexity of subsequent conflicts.

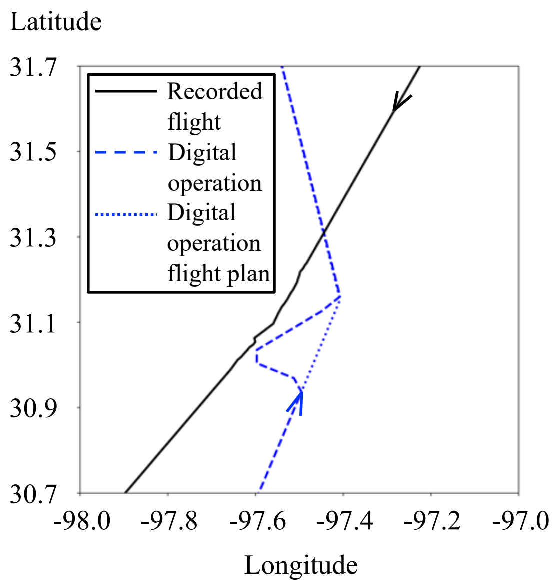


**Fig. 10 Path Stretch Conflict Resolution Maneuver Performed by Digital Operation (arrows indicate the locations and directions of the flights at the time the conflict resolution was issued).**

*2. Example Conflict Resolutions: Multiple Path Stretches*

Figure 11 illustrates the modified flight path of a different digital operation (dashed blue curve) relative to its initial planned path (dotted blue curve) that was the result of performing multiple path stretch conflict resolution maneuvers in simulation configuration 8. This flight departed KAUS 31 minutes after the flight illustrated in Figure 10 departed KAUS. The flight in Figure 11 encountered greater airspace congestion and conflict complexity, especially in the constrained terminal area environment, due to being in the middle of the set of simulated digital operations in the highest-tempo simulated traffic scenario.

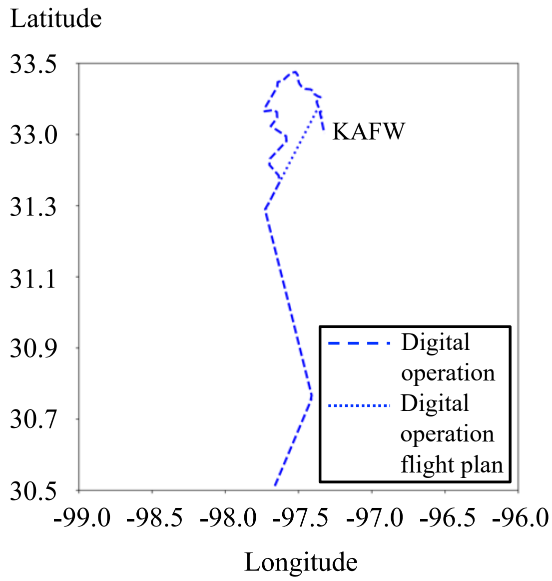


**Fig. 11 Multiple Path Stretch Conflict Resolution Maneuvers Performed by Digital Operation.**

## V. Discussion

The results of this initial analysis indicate that there are challenges for digital operations to integrate with VFR and IFR operations in Class D terminal airspace. Solutions could include additional capabilities for complexity mitigation and/or flow organization. It would be valuable to run follow-on studies with these capabilities, variations of different aspects of the simulations that were conducted in this initial analysis, and/or trajectory prediction uncertainties.

### A. Variations of Simulation Aspects

*1. Different Airspaces*

In addition to KAFW that was the focus of this initial analysis, it would be valuable to study additional Class D terminal airspaces. Follow-on studies could also focus on Class B terminal airspaces, such as: 1) Newark airport (KEWR) in New Jersey, which was the subject of prior studies that utilized the same software platform, simulation environment, and conflict management service as in the present study [17]-[19], and/or 2) KDFW, which is adjacent to KAFW that was the subject of the present study.

*2. Different Flight Phases*

It would also be valuable to study departures in addition to arrivals. It would be particularly interesting to study this in a busy metroplex environment with digital operations going into and out of multiple nearby airports (e.g., the D10 metroplex that includes KAFW and KDFW).

*3. Different Aircraft Types*

In addition, it would be valuable to study digital operations conducted with a representative range of aircraft types beyond the C208 that was simulated in this initial analysis. A methodical step-by-step approach in which each aircraft type is first modeled separately in different simulations and then together in different combinations would maximize the identification, understanding, and mitigation of the complexities and challenges of integrating digital operations with VFR and IFR operations.

*4. Different Conflict Management Configurations*

Regarding conflict management, it would be valuable to conduct and analyze simulations in which the conflict management service(s) for digital operations run more frequently than once per minute as in this initial analysis. This would enable more opportunities to find conflict-free resolutions for the dynamic and complex conflict situations that can occur in digital operations, especially in terminal airspace. It would also be valuable to model and analyze different coordination schemes for conflict management in addition to the sequential process that was simulated for all conflict management configurations in this initial analysis.

*5. Different Conflict Management Parameter Values*

It would also be valuable to study using different conflict management parameter values for different combinations of digital operations, VFR operations, and IFR operations involved in a conflict. For example, conflicts involving two digital operations could have the smallest separation criteria due to sharing performance information and having more capable 4D navigational performance. It would also be interesting to study the use of conflict management parameter values that vary depending on the situation (e.g., nominal operations or contingency management situations).

*6. Different Traffic Scenarios*

Related to conflict management, it would also be interesting and valuable to conduct and analyze simulations of different traffic scenarios. This could lead to the identification, understanding, and mitigation of additional challenges towards further refining the digital operations concept and framework. This could include analyzing a wide range of days and time periods beyond what was simulated in this initial analysis. This could also include simulations in which some or all of the VFR and/or IFR flights are simulated instead of only being played back, with some or all of them being simulated as digital operations.

### B. Integrated Multi-Point Resource Scheduling

The present study explored the integration of digital operations with VFR and IFR operations around and into a Class D airport without an integrated multi-point resource scheduling service that computes and coordinates STAs across arrival meter fixes and runway thresholds to meet resource rate constraints. Adding an integrated multi-point resource scheduling service like Time-Based Flow Management (TBFM) [35] may be necessary to reduce traffic and conflict complexity to enable conflict management to be performed more effectively. This was seen in prior studies that utilized the same software platform, simulation environment, and conflict management service as in the present study. In these prior studies, the inclusion of an integrated multi-point resource scheduling service helped establish a more manageable flow into the terminal area environment [17]-[19].

## VI. Conclusion

The primary contribution of this paper is an initial analysis of integrating digital operations with VFR and IFR operations in the terminal airspace around a Class D airport, specifically around KAFW. It is the first investigation to identify feasibility challenges for digital operations at a capacity-constrained airport, characterize the scope and magnitude of these challenges, and propose potential mitigations and extensions to explore in follow-on studies. The insights gained through the present study would have been challenging to uncover without the fast-time simulations that were conducted due to the myriad of concurrent and ensuing complex interactions and outcomes involved in conducting digital operations in constrained airspace.

In the present study, three conflict management configurations were analyzed: 1) centralized with a single instance of a conflict management service for all digital operations, 2) federated with two different instances for different subsets of digital operations, and 3) fully distributed with a different instance for each digital operation. Simulations were run in which recorded tracks for VFR and IFR operations were played back and different tempos of digital operations were modeled.

Challenging situations were identified, including VFR flights operating around the arrival airport and high-speed IFR arrival flights coming from behind digital operations on arrival, that will need to be addressed to integrate digital operations with VFR and IFR operations in Class D terminal airspace. Follow-on study is needed to investigate the extent to which additional capabilities for digital operations, such as complexity management and/or flow organization, may be needed. In addition, it would be valuable to study different airspaces, flight phases, aircraft types, conflict management configurations, conflict management parameter values, and/or traffic scenarios to further assess technical feasibility and substantiate and refine the digital operations concept and framework.

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