Second US-Europe Air Transportation Research and Development Symposium (ATRDS2026)

Uncrewed Aircraft System Lost Command and Control Link Arrival Procedures with Simulated Air Traffic Control Resolution Maneuvers

Jordan Sakakeeny†, David P. Thipphavong, Todd A. Lauderdale
Aviation Systems Division,
NASA Ames Research Center
Moffett Field, CA, USA
jordan.a.sakakeeny, david.p.thipphavong, todd.a.lauderdale@nasa.gov

Nadezhda Dimitrova⋆, Vishwanath Bulusu×, James D. Phillips×
⋆*Metis Technology Solutions, Inc.*, ×*Crown Innovations Inc.*
NASA Ames Research Center
Moffett Field, CA, USA
nadezhda.d.dimitrova, vishwanath.bulusu, james.d.phillips@nasa.gov

Abstract*—This paper presents an analysis of Uncrewed Aircraft Systems (UAS) contingency management procedures, focusing on the loss of command-control link off-nominal scenario. The impact on interaction with other traffic in the airspace from navigating the uncrewed aircraft is analyzed in the Fort Worth Alliance terminal airspace. This work is the first known series of simulations of Lost Command and Control (C2) Link (LC2L) UAS procedures in a simulated realistic airspace environment with Air Traffic Control (ATC) conflict resolution maneuvers. 72 unique scenarios, in which a UAS undergoes a LC2L event, are simulated and simulated ATC resolutions are enacted using Autoresolver. Metrics including the number of unique Loss of Separation (LOS), the number of conversions, and the locations of conversions are evaluated. Scenarios with up to eight unique LOS events, up to five simulated ATC resolutions, and up to 15 additional ATC communications were observed. Critically, the path between the end of the Standard Terminal Arrival Route (STAR) and the beginning of the final approach was identified as a key issue area for the LC2L procedures. Across ten scenarios in the 9am hour, 18 predicted LOS were observed across the scenarios within this area. In summary, this work identifies challenges and their scope, tests solutions (such as LC2L procedures), and proposes potential (and realistic) mitigation(s).

***Index Terms*—Uncrewed aircraft systems, unmanned aircraft systems, lost command and control link, air traffic control resolution, LC2L, simulation**

I. Introduction

Increasingly automated and autonomous UAS are rapidly developing and being introduced into the airspace [1]. These UAS range from small, hobbyist multi-rotor aircraft less than 55 lbs. (25 kg) (termed small UAS (sUAS)) to large fixed-wing aircraft capable of carrying cargo or passengers. Despite increasing utilization, none of the extant UAS operations are routinely and seamlessly integrated into the United States National Airspace System (NAS) - a key hurdle to the widespread commercialization of such operations. sUAS are typically permitted to operate below 400 ft (122 m) above ground level within visual line of sight, which keeps them largely separate from conventional (i.e., crewed) traffic.

The focus of this work, however, is on the routine operation of large, fixed-wing UAS – those heavier than 1,320 lbs. ($\sim$ 600 kg) – intended to operate out of existing conventional airports. At present, the only operations of this type are large military UAS, which are able to operate in the NAS under a Certificate of Waiver or Authorization (COA) from the Federal Aviation Agency (FAA) [2]. To enable more widespread and scalable operations, however, large, fixed-wing UAS will need to be able to routinely integrate into the NAS without the need for individual COAs. These UAS are expected to be remotely operated under Instrument Flight Rules (IFR) and will initially perform missions such as carrying cargo (without passengers on board) on regional routes. For more information specific to the regional air cargo use case, the reader is referred to previous work [3], [4], [5], [6]. The Remote Pilot (RP) will operate the aircraft and, because the operation is utilizing IFR, will vocally interact with ATC – executing any instructions – as well as with other conventionally crewed traffic. It is important to clarify that these operations are *not* assumed to operate under any novel flight rules (e.g., digital flight rules [7], U-Space [8]) in this work. Therefore, the RP needs means to operate the UAS and convey voice to integrate into the NAS.

The means by which a RP commands and controls a UAS are called the "C2 link" system. This C2 link allows the RP to uplink command and control instructions to the UAS as well as receive downlinked telemetry about the state of the aircraft.

† Corresponding author.

It is also through this system that the RP communicates with ATC and other crewed traffic over Very High Frequency (VHF) radio, which is routed through the Uncrewed Aircraft (UA) in most architectures. The specific implementation of the C2 link is not considered in this work.

The C2 link is a critical piece of the UAS architecture. What happens when the link is degraded, or even fails? Although there are different types and severities of degradation (e.g., loss of uplink, loss of downlink, loss of radio), this work will only consider the worst case scenario: a total severance of the C2 link. In this LC2L state, the RP is unable to uplink data to or downlink data from the UA. Additionally, the RP cannot relay VHF data through the UA, meaning a critical function of communication in the current NAS is gone.

In the event of an LC2L, it is assumed that the UA, after internal on board systems confirm the loss of link, will automatically execute an LC2L procedure. An LC2L procedure is a set of rules and/or route(s) that are programmed into the UA. The procedure can range from remaining on the filed IFR route to returning to the departure airport via a set of waypoints. The LC2L procedure needs to be predictable. An Air Traffic Controller (ATCO) needs to be able to predict potential conflicts with sufficient time to resolve them, thus it can be said that a UAS LC2L procedure should not differ drastically from a "typical" IFR filed routing and/or the prevailing traffic flow of the operational area. Additionally, any pilots operating under Visual Flight Rules (VFR) need to be able to see and avoid the UAS, though said pilots may not know the UAS does not have a pilot on board. The LC2L procedure also needs to be robust. It should be flexible to account for externalities such as weather, yet not be so prescriptive that the aircraft is placed in dangerous situations. Finally, the LC2L procedure should be survivable. The UAS must be able to safely land, even if not at the original destination. The impact these LC2L procedures may have on ATC and on surrounding traffic can, in certain situations, be significant. It is important to classify the impact.

This paper focuses on LC2L procedures for the arrival and approach phases of flight. The absence of a pilot on board the aircraft and the lack of VHF communication capabilities in an LC2L state is especially apparent in these time-sensitive phases of flight. In the current NAS, in busy terminal areas, procedures known as STAR are used to funnel in arriving traffic from the Air Route Traffic Control Center (ARTCC) to the Terminal Radar Approach Control (TRACON) (i.e., from en route ATC to terminal ATC). Instrument Approach Procedure (IAP) are used to guide aircraft down to specific runways. However, STARs do not always connect directly to an IAP. In such scenarios, it is common for ATCOs to utilize vectored control instructions (vectors) to maneuver IFR aircraft to the IAP in a safe, orderly, and expeditious manner. This process typically involves ATCOs sending frequent vectors over VHF with the expectation that the pilot on the receiving end of the instruction will respond and comply quickly. In nominal UAS operations, assuming no issues with transmission latency, it is expected that the communication and control approach should be similar to those for conventionally crewed operations.

In the event that a UAS is in an LC2L state during the arrival and approach phases of flight, conflicts and disruptions could occur. Normally, when two IFR aircraft are predicted to be in conflict, the ATCO has two aircraft to which they can issue a resolution to resolve the conflict. However, an LC2L UAS is unable to execute any ATCO instruction, meaning the ATCO effectively only has one aircraft to which they can issue control instructions to resolve the conflict. To resolve the predicted conflict without undue workload impact, the ATCO needs to be sufficiently aware of the path the UAS will follow under its LC2L procedure in addition to maintaining their other responsibilities.

This work directly builds off a previous fast-time simulation effort, published in 2024 [9]. In that work, several gaps and issues related to LC2L UAS arrivals were discovered, namely that numerous losses of separation do occur between an LC2L UAS and other IFR traffic when conflict resolution does not occur. The goal of fast-time simulation is to take a concept (such as the introduction of a novel aircraft type like large, fixed-wing UAS) and accurately model that concept in a representative airspace environment to identify challenges and their scope, test solutions (such as LC2L procedures), and propose potential (and realistic) mitigation(s). A key difference with this work is the inclusion of conflict resolution capabilities to the simulations. These differences are expounded upon in Section III.

Additional background on LC2L procedures is presented in Section II. The fast-time simulation setup, including differences with the previous work, is described in Section III. Results of the simulations are presented and explained in Section IV. Lastly, the Conclusions from this work are summarized in Section V.

II. Lost C2 Link Procedures

To begin, the definition of a "lost" link must be stated. The C2 link is not purely binary; rather, it has a temporal aspect. In other words, the link can degrade without fully failing (i.e., being "lost"). The link can be lost via technical means (a "dropped" link) or via the operator (a "severed" link). However, in this work, the exact means of degradation and loss are not considered; the link is simply lost, meaning no data or voice can be transmitted over it. To put this statement in context, consider the Cavan Solutions decomposition of the LC2L event, redrawn in Fig. 1 [10]. Within this decomposition, there are several key definitions, namely:

- LC2L Decision Time: The maximum amount of time permitted before an LC2L state is declared.
- T0: The time at which an LC2L state is declared.
- T1: The time at which Segment 2 is begun.
- T2: The time at which the link is re-established.
- T3: The time at which the LC2L event is over.

Beginning at the left side of Fig. 1, the C2 link begins to degrade. This section prior to T_0 is known as the "LC2L Decision Time" and can be thought of as the call quality becoming spotty. At time T_0, either via technical or operator means, the C2 link is considered "lost". The UAS then enters into an "LC2L State" wherein no data or voice can be relayed over the link. At T_0, the UA will squawk (i.e., change the transponder code to) 7400. In doing so, other airspace users

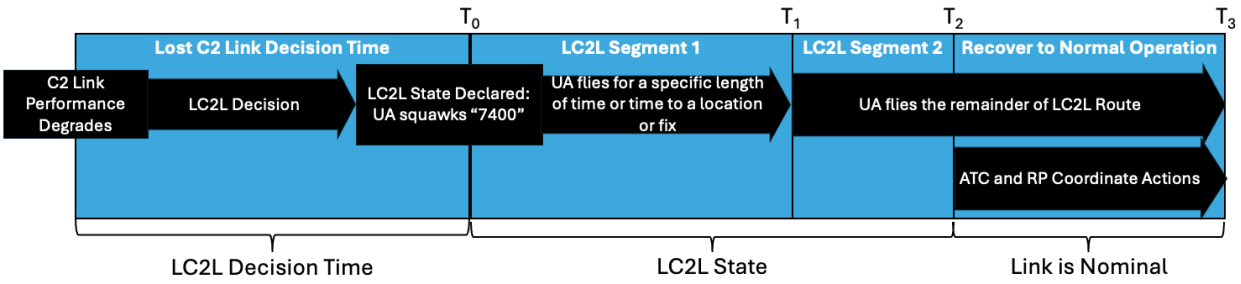


Figure 1. Decomposition of an LC2L event

are able to recognize that the UAS is in an LC2L state. To facilitate this knowledge acquisition process and allow for appropriate response, the UAS will, from time T_0 to T_1, fly for a specific length of time or a time to a location or fix – in general, it is likely that this Segment 1 will be the UAS continuing on its current assigned control instruction. This approach will be followed in this work, though other implementations are possible.

After Segment 1 is finished, Segment 2 begins at T_1. In Segment 2, the UAS executes the "LC2L Procedure". This procedure is the focus of this work and can vary based on location of the UAS, what stage of flight the UAS is in, or other factors. The LC2L Procedure can range from remaining on the filed IFR flight plan, going direct to a fix or waypoint, to flying a specified distance away from the departure airport, holding, and returning to the departure airport. In the case where the C2 link is reestablished, that will occur at time T_2. From T_2 to T_3, the RP, ATC, and any other appropriate parties will work together to regain the filed flight plan (or other option, as appropriate). At T_3, nominal UAS operation is regained and the LC2L event can be considered finished.

In this work, the worst case scenario – in which the link is permanently lost – is considered, meaning that time T_2 to T_3 is irrelevant. Throughout the course of an LC2L event, the UAS will need to avoid traffic. ATC will maneuver other IFR traffic, as appropriate, to maintain separation. Pilots of traffic operating under VFR will need to "see and avoid" the UAS. The UAS is assumed to have an onboard, Detect and Avoid (DAA) system, perhaps one that could automatically execute a resolution maneuver (i.e., a so-called auto-DAA) [11]. The specifications and execution of the DAA system are outside the scope of this work. The maneuvering of other IFR traffic will be modeled in this work (more on that below). Conflicts between the UAS and VFR traffic are not modeled, but will be counted. It is assumed that, in real operations, the VFR aircraft will maneuver to maintain separation.

Two standards bodies have published documents regarding LC2L procedures, International Civil Aviation Organization (ICAO) and Radio Technical Commission for Aeronautics (RTCA). An example procedure of an LC2L in the arrival phase of flight will be presented from each document.

A. ICAO RPSASP-16/WP-15

In 2020, a working paper was presented at the 16th meeting of the ICAO Remotely Piloted Aircraft Systems Panel (RPASP) [12]. This document begins from the assumption that a loss of C2 link is akin to the loss of radio (commonly called "NORDO" or "no radio") and thus the behavior of the UAS should be similar to the expected behavior of a NORDO crewed aircraft. By modeling the LC2L procedure off of NORDO procedures, it is assumed that the behavior of the UAS will be predictable; the controllers and other pilots have training on how to respond to NORDO aircraft.

In this document, two domains are defined: the terminal area and the en route area. The terminal area is defined as the area within 30 NM of either the departure or arrival airport. In the en route area, the LC2L Decision Time (see Fig. 1) is specified as 240 seconds (4 minutes), whereas in the more time-critical terminal area, it is specified as 30 seconds. During an arrival within the terminal area, the LC2L procedure is similar to the procedure found in the second document and will be elaborated upon in Section II-B.

B. RTCA DO-400

In 2023, the RTCA, Inc. Special Committee 228 (SC-228) published "Guidance Material: Standardized Lost C2 Link Procedures for Uncrewed Aircraft Systems", or "DO-400" [13]. DO-400 represents the first guidance specifically for the United States NAS. This document builds off of the ICAO document and FAA policy and regulations regarding UAS till 2023. For assumptions and restrictions, the reader is referred to the work itself.

DO-400 provides discrete guidance for UAS operations across eight phases of flight: preflight, taxi, takeoff, climb out/departure, transit/extended UA operations, arrival/approach, landing, and post-flight. In each phase, guidance is proposed in the form of actions for the UA itself, the RP, and the ATCO, as all three must work together to ensure safe operations. Additionally, where applicable, differentiation in the guidance is presented for towered and non-towered environments (i.e., airports with/without an operational air traffic control tower). Finally, several gaps are identified in areas that require further discussion and research.

The arrival and approach subphases of flight are distinctly defined in DO-400. The arrival subphase of flight consists of the descent from level flight (i.e., starting at the top of descent) to the Initial Approach Fix (IAF). The approach subphase of flight then begins at the IAF and ends at the Final Approach Fix (FAF) of a published approach procedure (as the UAS is assumed to be flying under IFR and utilizing an IAP). Unless otherwise stated, this work will use definitions consistent with DO-400.

For the arrival phase (assuming that the UA is arriving from another airport), DO-400's paraphrased guidelines for UA actions are as follows:

1) The UA should continue flying in conformance with its most recent clearance (T_1 in Fig. 1). After reaching its last clearance, the UA should either:
   a) If the UA is not established on a STAR, the UA should proceed to the IAF of the published approach listed in its flight plan; or
   b) If the UA is established on a STAR, the UA should complete the STAR, then proceed to the IAF of the published approach listed in its flight plan.
2) After reaching the IAF, the UA should execute the published approach. The approach guidance then states that the UA should execute the published approach and land.

III. Methodology

This work presents a set of fast-time simulations testing DO-400 LC2L procedures in a representative airspace environment with simulated air traffic control resolutions. Specifically, a UAS, the simulated Cessna 208 is simulated flying to an airport, Fort Worth Alliance Airport (KAFW), located in the Dallas-Fort Worth metroplex. This work utilizes the NAS Digital Twin simulation environment, which will be explained further below. To best understand the impact these DO-400 LC2L procedures might have on surrounding traffic, it is vital to model the airspace environment as accurately as possible, especially in the terminal airspace. To that end, NAS Digital Twin (NDT) utilizes real FAA air traffic structures (e.g., STARs, IAPs) and allows for the playback of historical aircraft tracks. Thus, the simulated UAS is able to fly with historical recorded traffic that is flying exactly it they did in real life, increasing the fidelity of the simulation and allowing for better impact classification.

A. NAS Digital Twin

NDT is, at a high level, a simulation environment used to create diverse, realistic simulations of current and future airspace operations, whether in fast- or real-time operating mode [14]. The environment leverages decades of work at the NASA Ames Research Center, including the Airspace Concept Evaluation System (ACES) [15] and the Center TRACON Automation System (CTAS) [16]. Additionally, the NDT leverages the work of the NASA Air Traffic Management (ATM) TestBed (or simply "TestBed") software platform [17], [18], [19], [20]. Recent example uses of NDT to study operations in increasingly complex airspace with increasingly diverse aircraft and increasingly autonomous operations from the present day through the far term include [21], [22], [23], [24], [25], [26], [27], [28], [29]. For further information about the NDT, the reader is referred to [14].

B. Autoresolver

A key distinction between this work and the previous work [9] is the inclusion of conflict detection *and* resolution functions, made possible by the inclusion of Autoresolver. Autoresolver is a NASA-developed software tool to model air traffic control services such as separation, spacing, and sequencing, and can be utilized to ensure appropriate separation between aircraft, to avoid regions of airspace (e.g., for weather avoidance), and perform arrival management for both en route and terminal operations using control strategies that are modeled upon those employed by controllers in real operations [30]. The use of Autoresolver allows for simulated ATC resolutions to be enacted; more on this point below.

C. Point Mass Trajectory Generator

Another change from previous work is the use of a new trajectory generator, the Point Mass Trajectory Generator (PMTG) [31], within NDT. PMTG accurately integrates the point mass equations using energy methods. PMTG uses energy methods to support a special type of vertical segment, termed a controlled throttle segment, where the throttle varies to meet altitude and/or speed equality constraints at a specified point in the route. Within limits, controlled throttle segments allow following a desired three-dimensional profile in a wind field without numerical iteration of the vertical profile.

As a consequence, this new trajectory generator is significantly more accurate than legacy trajectory generators used in NDT (see [14]) at hitting prescribed points that are at low altitude (below 10,000 ft) and low speed (below 250 kts). This is crucial for the Cessna 208 (a smaller turboprop aircraft) being simulated as the UAS in this work. The use of this new trajectory generator allowed the LC2L procedures for the UAS to be exactly prescribed in alignment with DO-400 and flown accordingly.

D. Adaptations and Extensions

To enable the current research, several adaptations and extensions were made to the NDT simulation environment. Arrival procedures into the Dallas-Fort Worth D10 TRACON, especially for KAFW, were modified to better reflect reality. By default, NDT uses actual published FAA procedures (e.g., STARs, IAPs). However, in some cases, a STAR is not directly connected to an IAP, which is the case for south-flow arrivals into KAFW. In these cases, the default behavior of NDT is to simply connect the end of the STAR with the beginning of the IAP using a direct path, which is not always realistic. Researchers analyzed historical flight paths to manually stich together the procedures, yielding higher fidelity to the simulations. The ability to fly waypoint-to-waypoint trajectories with appropriate speed and altitude restrictions enabled precise implementation of the DO-400 procedures. The UAS's DO-400 LC2L procedure may be different than arrival procedures, therefore it was critical to accurately implement the ability for a simulated UAS to 1) Fly a STAR to completion, then fly direct to the IAF and 2) Fly an IAP, whether that be an Instrument Landing System (ILS) or GPS Area Navigation (RNAV) procedure.

E. Enabling Conflict Resolution

The key change from previous work is the ability to perform conflict resolution (i.e., simulated ATC resolution). At the beginning of each simulation run, there are two types

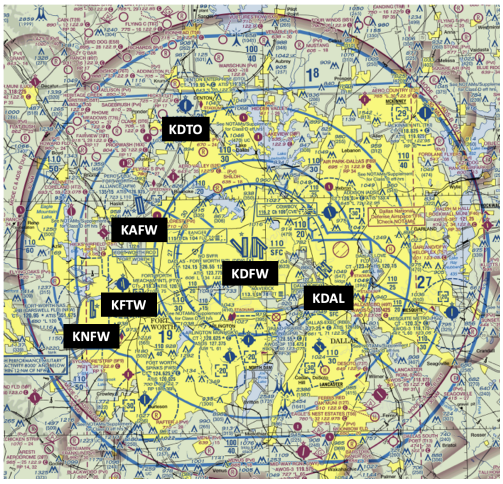


Figure 2. The Dallas-Fort Worth Terminal Area [32]

of aircraft: the simulated UAS and the historical air traffic. Autoresolver can be configured to issue conflict resolutions to certain aircraft and not to others. Because the UAS is in an LC2L state, there will be no resolutions issued to it, mimicking the inability of the RP in an LC2L scenario to issue any commands to the UAS. Additionally, Autoresolver will not issue any resolutions to the historical traffic, which simply fly the exact flight path the real aircraft did. If (and when) a loss of separation between the UAS and any historical IFR aircraft is predicted, a converted digital twin of the historical IFR aircraft is created. This converted aircraft is now a simulated aircraft to which simulated ATC resolutions can be issued by Autoresolver. Additionally, should that converted IFR aircraft be predicted to lose separation with a different historical IFR aircraft, the latter IFR can be converted, enabling simulated ATC resolutions to be applied to either simulated aircraft, just like in real life.

By enabling this capability to convert historical aircraft, an estimate of the additional number of ATC resolutions the ATCO needs to make as a result of the LC2L UAS can be identified. This number is especially important in any "domino effect" scenarios, wherein control resolutions are issued to several non-UAS IFR aircraft as a direct result of a UAS flying its LC2L procedure. For example, if the LC2L procedure has the UAS fly at low altitude directly through the initial departure or final approach areas near a major airport, such as Dallas-Fort Worth International Airport (KDFW), it likely will lead to significant disruptions of the surrounding historical traffic, necessitating a high number of simulated ATC resolutions to maintain separation (if even feasible). Such a scenario is obviously problematic for ATC and should be avoided. This work aims to help uncover such scenarios to better inform the LC2L procedure development and refinement process.

F. Traffic Scenario

KAFW was chosen as a representative cargo airport for this series of fast-time simulations. Located in the northwest corner of the Dallas-Fort Worht metroplex, KAFW is a busy cargo hub, serving FedEx and Amazon Air, as well as many non-commercial operators. Previous research has identified KAFW as a prime candidate for initial regional air cargo operations using UAS [3], [4]. As seen in Fig. 2, KAFW is a Class D environment, located underneath the Class B shelf of KDFW and Dallas Love Field (KDAL). Other nearby airports include Fort Worth Meacham (KFTW), Denton Enterprise (KDTO), and Naval Air Station Joint Reserve Base Fort Worth (KNFW), all of which are Class D environments. At KAFW, there are two 11,000 ft runways, one of which (16L/34R) hosts an ILS Category II-III ILS approach on the 16L end.

The busy Dallas-Fort Worth TRACON (D10), in which KAFW is situtated, is a large square with its corners cut off, as shown in Fig. 3. In most situations, departing IFR flights exit the TRACON through the "sides" of the square (north, east, south, and west) whereas arriving traffic is directed through the "corner posts" (northeast, southeast, southwest, and northwest) along one of several STARs. Aircraft intending to land at KAFW have seven STARs to utilize. These STARs provide a published manner in which aircraft can transition from ARTCC control to TRACON control. Typically, this handover will occur at a known point, called the "arrival fix" (i.e., a defined waypoint on or just inside the boundary of the TRACON). From there, unless the STAR directly connects to the intended IAP, the ATCO will provide vectored control instructions to IFR aircraft from the completion of the STAR until they are established on the appropriate IAP.

For simplicity, a single runway end, Runway 16L, was chosen as the arrival runway for LC2L UAS in these simulations. For KAFW, none of the published STARs directly connect to either the RNAV or ILS IAP for runway 16L and flight vectoring is not modeled in NDT. Thus, it was necessary to fabricate flight plans for the UAS that would connect the end of the STAR with an appropriate point on the IAP. These "nominal" routes, see Fig. 3, were informed by historical flight paths as well as subject matter expert input. These routes can be thought of as a "do-nothing" scenario. That is, if the UAS loses link and continues on its filed flight plan, it would follow these paths. To contrast with the remain-on-flight-plan approach, DO-400-compliant LC2L routes were also created. For both the nominal and LC2L scenarios, a route for the RNAV and ILS Runway 16L IAP were created.

Four airports, Lubbock (KLBB), Little Rock (KLIT), Shreveport (KSHV), and Austin (KAUS) were chosen as departure airports to align with the northwest, northeast, southeast, and southwest arrival corner posts, respectively. Such procedures were then vetted with D10 TRACON ATC subject matter experts to ensure they were feasible [1]. Thus, 16 different routes are tested, though it should be noted that four of the routes are exact duplicates of another route (underlined in Fig. 3). Therefore, 12 unique routes are shown in Fig. 3.

[1]The use of the DODJE STAR from the southeast was deemed infeasible by subject matter experts for UAS as a DO-400-compliant route from DODJE would take the UAS directly across the departure path of KDFW, resulting in a ground stop at the airport. Instead, the REEKO STAR was used.

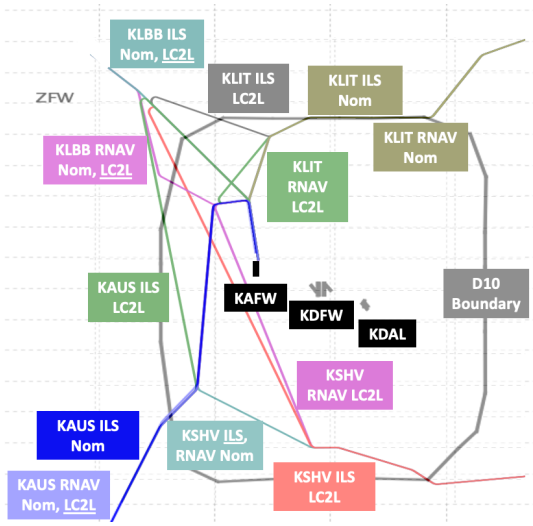


Figure 3. Each of the sixteen arrival routes used in the simulations are shown. Note that four arrival routes are duplicative and are underlined.

G. Date and Aircraft Selection

January 18, 2022, was selected as the date from which the historical data were taken, due to having minimal convective weather in the Fort Worth Center as indicated by the Weather-Impacted Traffic Index [33] and delay statistics in the Sherlock ATM Data Warehouse [34]. In each simulation, around 4,700 recorded flights (both IFR and VFR) from Fort Worth Center, adjacent Centers (Albuquerque, Kansas City, Memphis, and Houston), and their respective major TRACONs (D10, ABQ, MCI, T75, and I90) on that day from 1500 to 2000 UTC (0900-1400 local time) were played back as background traffic, meaning that these aircraft in the simulation flew exactly what the corresponding real aircraft flew on January 18, 2022.

For each simulation, a representative UAS, the Cessna C208B Grand Caravan (C208), was simulated. This simulated UAS was injected into the historical traffic described in the previous paragraph and flew one of the 12 arrival routes in Fig. 3. Each simulated UAS had a cruise speed of 160 kt and a speed of 150 kt after the arrival fix was reached. To mitigate time- and scenario-specific effects, the same 12 routes were repeated with the UAS arriving at six different hours of the day: 0900 to 1400 local time. A total of 72 scenarios were simulated (i.e., 12 different routes x 6 arrival times). The simulated UAS flew exactly its prescribed flight plan, including altitude and speed constraints at waypoints, to emulate an LC2L scenario.

IV. Results

For each of the 72 scenarios a simulation with a single UAS was performed. The simulated UAS flew exactly as prescribed in the scenario file, including altitude and speed constraints at waypoints. The simulated UAS flew among historical traffic from January 18, 2022 as if it were flying on the actual day. If (and when) a conflict[2] between a historical aircraft and the simulated UAS was predicted, one additional flight is created. The historical aircraft, also called the shadow flight, is renamed and follows the trajectory of the historical aircraft exactly as that historical aircraft had flown originally, without regard for conflict resolution (i.e., it remains in the simulation but it is not visible to other aircraft). Additionally, a simulated aircraft called the converted flight, is instantiated with a new trajectory, linking its position at conversion to the destination airport. The conversion process is intended to enable the conflict resolution process for the historical flight and the UAS. Additionally, this converted aircraft is subject to Autoresolver conflict resolution maneuvers (see Section III-E). Note: historical aircraft operating under VFR are *not* converted.

This work aims to measure the impact a UAS LC2L procedure has on the surrounding airspace, including any potential impact on air traffic controllers. To measure these impacts, several metrics were captured, including:

- Number of aircraft converted: The minimum number of additional conflict resolution maneuvers an air traffic controller would enact to maintain separation as a result of the LC2L UAS.
- Number of unique LOS events: The number of unique historical aircraft, including VFR aircraft, that lose separation with the LC2L UAS.
- Number of executed ATC conflict resolution maneuvers: The number of conflict resolution maneuvers issued by Autoresolver. This number provides an example of an ATCO surrogate[3].
- Number of inferred communications: The number of inferred communications that the surrogate ATCO would have had to make to manage the converted aircraft beyond the baseline communications in the historical flight version. Communications to historical aircraft in the scenario are excluded; only communications to the converted aircraft are counted to isolate the change in ATC engagement resulting from the flight conversion[4]. This metric serves as an observable proxy for ATC engagement required during LC2L events, representing the number of additional radio communications a sample controller would need to transmit.

These metrics are intentionally conservative estimates. As such, the metrics could be understating the severity of each scenario. This point will be elaborated upon in the following paragraphs.

[2]Here a loss of separation means the aircraft came within 3 or 5 nmi horizontally within the TRACON or ARTCC, respectively, and 1,000 ft vertically of one another. A conflict is a predicted loss of separation.

[3]It is important to note that Autoresolver, the conflict detection and resolution tool used in these simulations is an *example* ATCO surrogate. No claim is made that Autoresolver perfectly mimics the varied decisions human ATCOs would make in the same scenarios.

[4]Communications are inferred from maneuvering events identified in the trajectory data. Only communications for altitude and heading changes are inferred using thresholds of 3.3 ft/sec and 2 deg/sec respectively, informed by subject matter expertise. Speed changes are excluded due to noisy data. Each inferred communication represents a discrete ATC instruction.

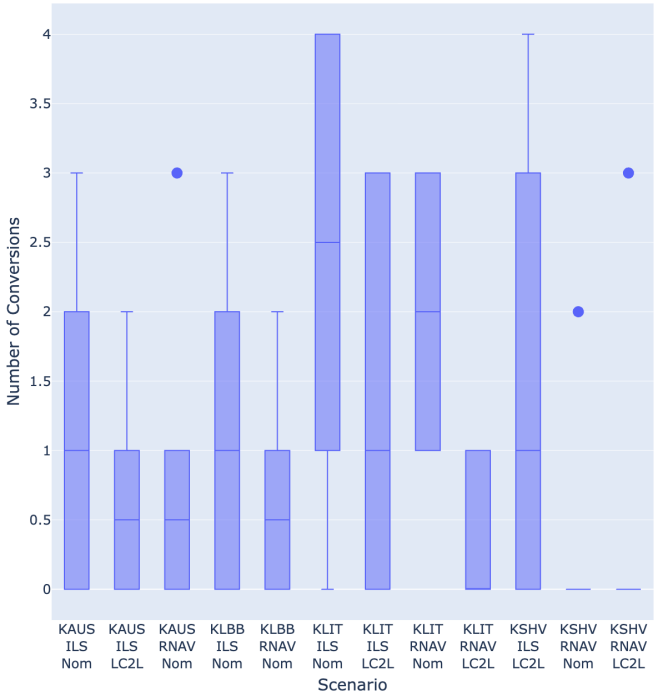


Figure 4. Number of converted aircraft per scenario across all times.

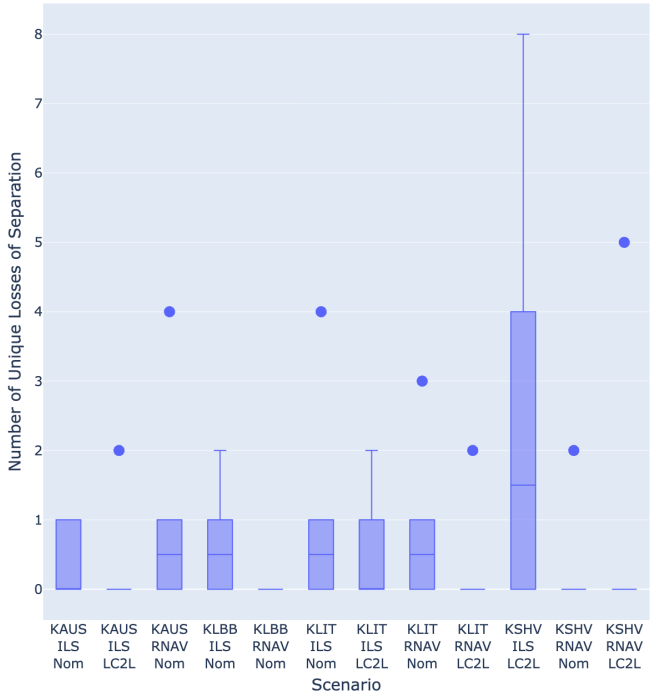


Figure 5. Number of unique LOS events per scenario across all times.

Fig. 4 showcases the number of converted aircraft across all 72 scenarios. That is, the number of converted aircraft in the KAUS ILS Nom scenario for 9am, 10am, ..., 2pm simulations are aggregated in a box plot labeled "KAUS ILS Nom". The largest number of converted aircraft observed in a single scenario is four. The scenario with the highest median number of conversions (i.e., predicted LOS between a historical IFR aircraft and the simulated UAS) is the KLIT ILS Nom scenario, with a median of 2.5 conversions across the six different time frames. The route takes the LC2L UAS through the northeast corner of D10 and across the arrival flow into KDFW, both very busy sections of the TRACON. These conversions – which each necessitate the simulated ATCO issuing a conflict resolution maneuver to prevent a LOS – indicate a clear impact on the ATCO as a result of an LC2L UAS. Further clarification of this impact will be discussed below.

The number of unique LOS events is shown in Fig. 5. This number primarily denotes VFR aircraft that have not been converted in the simulation[5]. In real life, the VFR aircraft would need to "see and avoid" the UAS or, depending on the airspace, could imply situations in which the ATCO would be making radio calls to inform the VFR pilot of the UAS. LOS events that occur when the UAS is on final approach are *not* counted in this metric. In such a situation, the LOS occurs with either a departing aircraft or with a VFR aircraft that is close to the destination airport (e.g., doing pattern work). In the former scenario, an ATCO may simply hold the departing aircraft on the ground. In the latter, the varied nature of VFR operations makes accurate modeling difficult in fast-time simulation. During the busier 9am hour, the majority of the unique LOS are observed, with the worst-case scenario of eight unique LOS events occurring in the 9am KSHV ILS LC2L scenario.

The number of simulated ATC conflict resolution maneuvers enacted by Autoresolver is shown in Fig. 6. This metric counts each conversion of a historical aircraft as a conflict resolution maneuver, in addition to any additional conflict resolution maneuvers (e.g., a path stretch) given to the converted aircraft after it was converted. This metric indicates the minimum number of communications the simulated ATCO would have to convey as a direct result of the LC2L UAS. For example, in the 9am KAUS ILS Nom scenario, the simulated ATCO had five conflict resolution maneuvers, indicating that the ATCO would have issued at least five radio calls.

As the final aggregate metric, the number of inferred additional communications is displayed in Fig. 7. This metric infers communication from the flight track of the converted aircraft and compares it to the corresponding shadow aircraft track. Each track is analyzed for heading or altitude changes above a subject matter expert-informed threshold. This metric captures the delta between those two inferred values, in addition to a communication for each conversion, assuming that the conversion process itself is a communication. This metric serves as a proxy for controller workload. Additional communication burdens the controller and can indicate scenarios in which controller overload is feasible. For example, the 9am KLIT ILS LC2L scenario has an additional 15 inferred communications relative to a scenario without the single LC2L UAS. Such a high number of additional inferred communications could be an indication that the planned UAS

[5]Some small number of historical aircraft that actually flew IFR may have been erroneously counted as VFR aircraft, especially business jets that use their tail number as a call sign. This minor error is a known data quality issue.

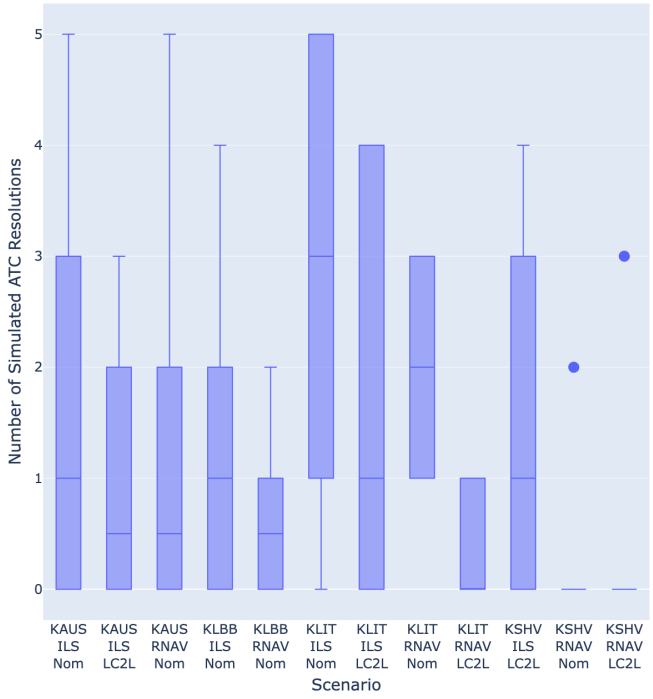


Figure 6. Number of simulated ATC resolutions per scenario across all times.

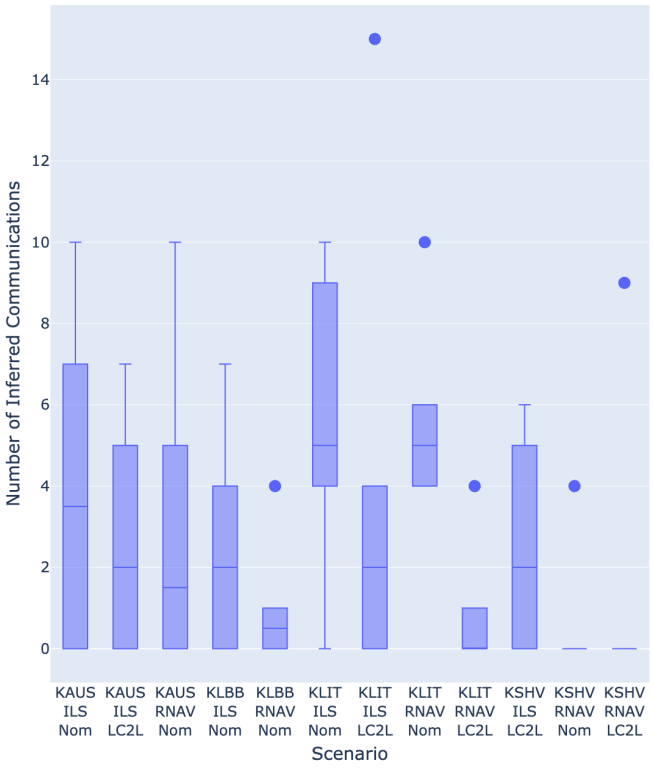


Figure 7. Number of inferred additional heading and altitude changes, including conversions, per scenario across all times.

route at that time needs to be amended to mitigate impact. Additionally, it is clear that the inclusion of additional UAS could present a serious situation, should those UAS also be in an LC2L state.

Let us next focus on the 9am scenarios. This time frame exhibited the highest number of additional inferred communications and simulated ATC resolutions. Fig. 8 aggregates 27 conversions across ten different simulations (two of the 9am simulations had zero conversions). The locations of the UAS and the corresponding historical aircraft that were predicted to lose separation with the UAS and thus needed to be converted are shown using color-coordinated square and circle markers, respectively, with some visual overlap. Using these data, the phase of flight the UAS is in when a conflict detection event occurs can be determined. Recalling that the DO-400 procedure states a UAS established on a STAR should complete the STAR in the event of an LC2L, it can be seen that 9 of 27 conversions occur when the UAS is still on the STAR (i.e., before UKW, TRUUK, LIKES, and SCOPS). 18 of the 27 conversions occur once the UAS has completed the STAR and is either going direct to the IAF or is heading to an Intermediate Fix along the IAP. Crucially, these 18 conversions as a result of a detected conflict occur in situations when the ATCO would normally be providing vectored control instructions to IFR aircraft to bridge them between the end of the STAR to the IAP. A simplified version of Fig. 8 is shown in Fig. 9, with just the KSHV ILS LC2L scenario shown. As discussed in the Introduction, this phase is especially problematic for LC2L UAS.

Looking next at the historical aircraft that are converted in Fig. 8, it can be clearly seen that the majority are clustered around the northwest and northeast corners of D10 and correspond to arriving aircraft. These arriving aircraft are converted when the historical aircraft is further away from the arrival airport (typically KDFW) than the UAS, due to the significant speed differential between a C208 (the UAS) and most commercial jets. Another critical aspect with these conversions is that many take place just outside TRACON airspace (denoted by the gray box) in ARTCC airspace, while the UAS is located *within* the TRACON. This distinction could imply that additional communication and coordination between TRACON and ARTCC controllers is necessary, heightening the complexity of the situation. Finally, a few departure aircraft had conflict detection events with the UAS, though these were primarily mitigated by the procedural deconfliction of STARs from Standard Instrument Departure (SID)s present in the real Dallas-Forth Worth airspace.

V. Conclusions

Using the NDT simulation environment, 72 unique scenarios in which a UAS undergoes an LC2L event were simulated, and simulated ATC resolutions were enacted using Autoresolver. Several metrics, including the number of unique LOS, the number of conversions, and the locations of conversions were identified. Scenarios with up to eight unique LOS events, up to five simulated ATC resolutions, and up to 15 additional ATC communications were observed.

It is clear from the simulation results that, at least in the busy Dallas-Fort Worth metroplex environment, the path between the end of the STAR and the final approach is a key issue area for the LC2L procedures. 18 predicted conflicts were observed across the 9am scenarios within this area,

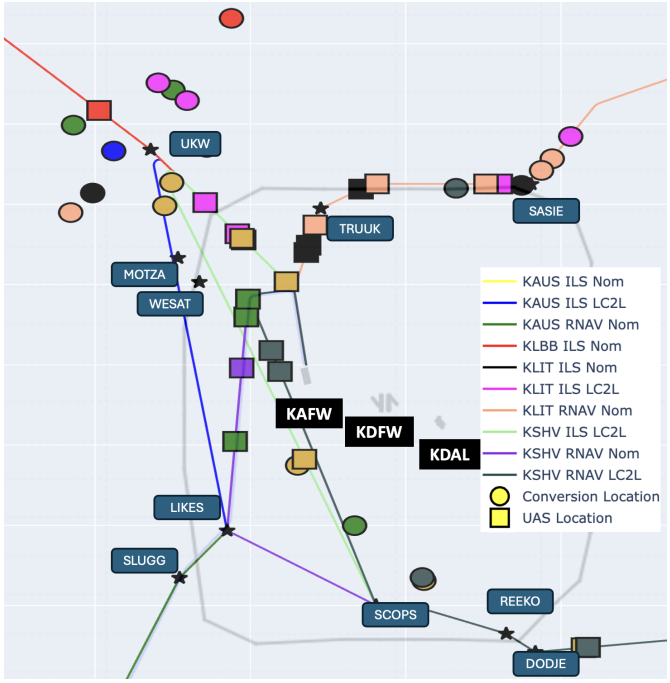


Figure 8. Ten simulations from the 9am scenarios. The route of the UAS is shown. The location of both the UAS (square marker) and the corresponding historical aircraft (circle marker) at the time of the conversion of the historical aircraft (due to a predicted conflict with the UAS) is shown. Each color corresponds to a unique scenario. Three key airports (KAFW, KDFW, and KDAL) for the D10 TRACON are shown, as is the boundary of the TRACON. Additionally, key waypoints for the STARs for KAFW are denoted.

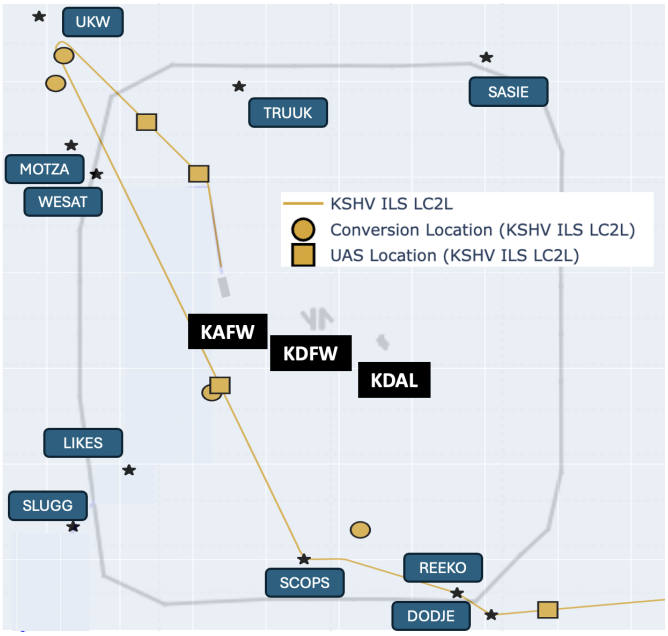


Figure 9. A simplified version of Fig. 8 with just the KSHV ILS LC2L scenario shown. Four predicted conflicts between the UAS and an IFR aircraft were observed, yielding four conversions. The location of the UAS and the respective IFR aircraft at the point of conversion are denoted with a square and circle, respectively.

meaning that simulated ATC resolution maneuverss needed to be enacted to maintain proper separation. In other words, additional ATC communications would have been needed to handle LC2L UAS in many of the scenarios. This additional communication load must be considered when LC2L procedures are designed. Additionally, there were situations in which the UAS was inside the TRACON when the conflict was observed with an IFR aircraft that was outside the TRACON, potentially necessitating additional coordination between ARTCC and TRACON controllers, adding to complexity. The methodology and results presented in this paper can be used to better inform LC2L procedure development. Consideration for ATC communication load, existing traffic, and the risk of losing link are critical to the safe and successful integration of UAS into the NAS.

Acknowledgments

The authors sincerely thank the many individuals and groups who contributed and are continuing to contribute to this research. We are grateful for the insightful discussions from our colleagues in the Aviation Systems Division at NASA Ames Research Center. We thank Richard Coppenbarger, Todd Farley, Aastha Acharya, and Anahita Jain. Our gratitude also extends to Subject Matter Experts Scott Howe, Wayne Bridges, and Michael Sanders for their crucial expertise on operational procedures and metric interpretation. The teams managing the NASA Sherlock Data Warehouse and the NAS Digital Twin environment provided essential support; we specifically thank Robert Windhorst, Christian Plaunt, and Chok Fung Lai.

References

[1] J. Andrews et al., "Lmi automated air cargo operations market research and forecast," *NASA Contractor Report - 20210015228*, 2021.

[2] U.S. Department of Defense, *Unmanned aircraft systems (uas)*, https://dod.defense.gov/UAS/, Accessed: 2025-09-29.

[3] J. Sakakeeny, N. Dimitrova, and H. R. Idris, "Preliminary characterization of unmanned air cargo routes using current cargo operations survey," in *AIAA Aviation 2022 Forum*, 2022.

[4] J. Sakakeeny, T. F. Sievers, and H. Idris, "Potential of united states and european regional air cargo operations for uncrewed aircraft systems," in *15th USA/Europe Air Traffic Management Research and Development Seminar (ATM2023)*, 2023.

[5] T. F. Sievers, J. Sakakeeny, N. Dimitrova, and H. Idris, "Comparative analysis of airspace system accessibility for uncrewed aircraft systems for regional operations," in *2023 IEEE/AIAA 42nd Digital Avionics Systems Conference (DASC)*, IEEE, 2023, pp. 1–10.

[6] M. Hayashi, H. Idris, J. Sakakeeny, and D. Jack, "Paav concept document," *NASA Technical Memorandum*, 2022.

[7] D. Wing et al., "Digital flight: A new cooperative operating mode to complement vfr and ifr," *NASA Technical Memorandum*, 2022, NASA/TM-20220013225.

[8] T. F. Sievers et al., "Dlr blueprint - intitial conops of u-space flight rules (ufr))," *DLR Institute of Flight Guidance*, 2024.

[9] J. Sakakeeny, D. Thipphavong, T. Lauderdale, and H. Idris, "Initial assessment of lost command and control link procedures," in *43rd Digital Avionics Systems Conference (DASC)*, 2024.

[10] Cavan Solutions, "Uas nas integration: Lost link procedures concept document," *Prepared for the FAA New Entrants Division (ANG-C2)*, 2020.

[11] C. L. Smith, R. C. Rorie, M. Chandarana, T. L. Tyson, J. Keeler, and V. Tran, "Helicopter pilot assessments of the airborne collision avoidance system xr with automated maneuvering," in *AIAA AVIATION 2023 Forum*, 2023.

[12] I. C. A. Organization, "Progress of lost c2 link and detect and avoid (daa) procedures (rpasp/16-wp/15)," 2023.

[13] RTCA, "Do-400: Standardized lost c2 link procedures for uncrewed aircraft systems," 2023.

[14] T. A. Lauderdale, R. D. Windhorst, R. Coppenbarger, D. P. Thipphavong, and H. Erzberger, "The national airspace system (nas) digital twin simulation environment," in *AIAA AVIATION FORUM AND ASCEND 2024*, 2024, p. 4011.

[15] S. George et al., "Build 8 of the airspace concept evaluation system," in *AIAA Modeling and Simulation Technologies Conference*, 2011.

[16] H. Erzberger, T. J. David, and S. Green, "Design of center-tracon automation suystem," *AGARD, Machine Intelligence in Air Traffic Management*, 1993.

[17] K. Palopo, G. B. Chatterji, M. D. Guminsky, and P. C. Glaab, "Shadow mode assessment using realistic technologies for the national airspace system (smart nas) test bed development," in *AIAA Modeling and Simulation Technologies Conference*, 2015, p. 2794.

[18] J. E. Robinson III, A. Lee, and C. F. Lai, "Development of a high-fidelity simulation environment for shadow-mode assessments of air traffic concepts," in *Aeronautical Society Modeling and Simulation in Air Traffic Management Conference*, 2017.

[19] C.-F. Lai, "Air traffic management testbed traffic viewer: Developer's guide," *NASA Technical Memorandum*, 2020, NASA/TM-20200002188.

[20] C.-F. Lai, "Air traffic management testbed data exchange model," *NASA Technical Memorandum*, 2020, NASA/TM-20205001252.

[21] V. Bulusu, G. B. Chatterji, T. A. Lauderdale, J. Sakakeeny, and H. R. Idris, "Impact of latency and reliability on separation assurance with remotely piloted aircraft in terminal operations," in *AIAA Aviation 2022 Forum*, 2022, p. 3704.

[22] R. D. Windhorst et al., "Initial validation of a simulation system for studying interoperability in future air traffic management systems," in *AIAA Aviation 2021 Forum*, 2021, p. 2352.

[23] R. D. Windhorst, T. A. Lauderdale, A. V. Sadovsky, J. Phillips, and Y.-C. Chu, "Strategic and tactical functions in an autonomous air traffic management system," in *AIAA Aviation 2021 Forum*, 2021, p. 2355.

[24] T. Lauderdale, P Pradeep, K. Edholm, and C. Bosson, *Separation at crossing waypoints under wind uncertainty in urban air mobility, 2021*.

[25] R. D. Windhorst, T. A. Lauderdale, R. A. Coppenbarger, and H. Erzberger, "Validation of an automated system for arrival traffic management," in *AIAA Aviation 2022 Forum*, 2022, p. 3828.

[26] R. A. Coppenbarger, A. Aweiss, and H. Erzberger, "Flight demonstration of the tailored arrival manager," in *AIAA Aviation 2021 Forum*, 2021, p. 2373.

[27] D. P. Thipphavong et al., "Initial study of tailored trajectory management for multi-vehicle uncrewed regional air cargo operations," in *2023 IEEE/AIAA 42nd Digital Avionics Systems Conference (DASC)*, IEEE, 2023, pp. 1–10.

[28] D. P. Thipphavong and T. A. Lauderdale, "Initial analysis of digitally-enabled cooperative operations in class d terminal airspace," in *AIAA AVIATION 2024*, 2024.

[29] V. Bulusu, N. Dimitrova, J. Sakakeeny, and H. Idris, "Risk-aware routing for uncrewed aircraft contingency management," in *AIAA AVIATION FORUM AND ASCEND 2025*, 2025.

[30] H. Erzberger, T. A. Lauderdale, and Y.-C. Chu, "Automated conflict resolution, arrival management, and weather avoidance for air traffic management," *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of aerospace engineering*, vol. 226, no. 8, pp. 930–949, 2012.

[31] J. D. Phillips, "Point mass trajectory generator for flying conceptual designs in air traffic management simulations," *NASA Technical Memorandum*, 2026, NASA/TM-number pending.

[32] *Faa sectional chart for dallas-fort worth area*, https: / / www . faa . gov / air_traffic / flight_info / aeronav / productcatalog / VFRCharts / Sectional/, Images produced by the U.S. Government and in the public domain., 2023.

[33] D. J. C. A. G. J. M.-M. D. Callaham M. and G. Solomos, "Assessing nas performance: Normalizing for the effects of weather," in *4'b USA/Europe Air Traffic Management RD Symposium, Santa Fe, NM*, 2001.

[34] H. M. Arneson, P. Hegde, M. E. La Scola, A. D. Evans, R. M. Keller, and J. E. Schade, "Sherlock data warehouse," NASA Ames Research Center, Tech. Rep. ARC-E-DAA-TN67994, 2019. [Online]. Available: https://ntrs.nasa.gov/citations/20190025090.