# Initial Assessment of Lost Command and Control Link Procedures


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***Abstract*—This paper presents an initial assessment of lost command and control (LC2L) procedures for large Uncrewed Aircraft Systems (UAS) in a simulated representative airspace environment using real airspace procedures. The experiment matrix consists of nine different flight routes: four nominal, four following current LC2L procedures, and one that routes the UAS more conservatively through less-busy airspace. For each route, eleven simulated UAS flights – in ten-minute increments – were flown into Fort Worth Alliance Airport following a real Instrument Approach Procedure. The simulated UAS flew amongst real recorded tracks of approximately 4,700 flights on January 18, 2022. The analysis focused primarily on the number of aircraft with which each UAS lost separation and where the losses occurred. This work presents a significant increase in testing capability and provides the foundation for further verification and validation of LC2L procedures using additional analysis metrics.**



***Keywords*—*uncrewed aircraft, lost link, lost command and control link, fast-time simulation, regional air cargo.***


## I. Introduction

Uncrewed Aircraft (UA) Systems (UAS) [1] have grown increasingly popular in recent years [1]. The current trade space for UAS is broad and well-established, ranging from hobbyist small multirotor aircraft less than 55 lb. (sUAS) to large, long-endurance surveillance aircraft for the military. However, none of the extant UAS operations have routinely and seamlessly integrated into the National Airspace System (NAS). sUAS are only permitted to operate below 400 ft, separate from conventional crewed air traffic [2]. Limited package delivery by drone has occurred via Part 135, with adaptations as necessary [3] Large military UAS do fly in the NAS, albeit under Certificate of Waiver or Authorization (COA) from the Federal Aviation Administration (FAA) [4].

Industry is seeking to utilize UAS for routine commercial operations. One of the likely initial operations will be the use of remotely-piloted large, fixed-wing UAS for regional air cargo operations [1]. It is expected that a remote pilot (RP), operating out of a ground station, will operate a UA from conventional airport to conventional airport under Instrument Flight Rules (IFR). Operating under IFR and at conventional airports necessitates the interaction of the RP/UAS with air traffic control (ATC) services, as well as other conventionally crewed air traffic. For more information on the regional air cargo use case, see [5]-[8].

The means by which the RP operates the UA is called a command and control (C2) link system [9][2]. This C2 link is also expected to be used by the RP to communicate, via voice routed through the UA, with ATC. C2 links are generally provided over either a ground-based network or a satellite-based network. The specific implementation of a C2 link is not considered in this work.

A key barrier to entry is the ability of UAS and the NAS to handle the loss of the C2 link (LC2L). Although there are levels of severity to the loss of C2 link (e.g., loss of radio, uplink, and/or downlink), for simplicity, and to evaluate the "worst case scenario", the LC2L event in this work will refer to the total severance of the C2 link system and the link will not be regained. In a LC2L state, the RP will be unable to upload data to or receive data from the UA.

In the event of a LC2L, it is assumed that the UA, after internal systems confirm the loss of link, will automatically execute a LC2L procedure. These procedures, in their simplest form, are a set of rules and/or route(s) that would be programmed into the UA. There are numerous aspects that need to be considered when creating LC2L procedures. The first, given that UA will operate under IFR, is the need to be predictable. Air traffic controllers (ATCOs) are trained to constantly look ahead and predict potential conflicts, so that they can avoid them. UA LC2L procedures that are drastically different from "typical" IFR operations could be unpredictable and unsafe. Further, the UA need to be predictable to other traffic, especially if the other traffic is operating under Visual Flight Rules (VFR) and may not have ATC separation support. The second aspect is robustness. The LC2L procedures need to be flexible enough that they can be executed in a variety of situations – yet also without being over-prescriptive. Finally, the third aspect is survivability. The LC2L procedures must ensure that the UA safely lands, even in situations where unexpected changes, such as weather, occur. The impact these procedures have on the workload of ATC and on surrounding traffic (both IFR and VFR), is important to classify.

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[1] In this work, "UA" is used to refer to the aircraft itself, whereas "UAS" refers to the system, inclusive of the aircraft, the ground station, and all associated elements.

[2] In this work, for brevity, "C2 link" will be used in place of "C2 link system".

In many busy terminal areas, the STARs are designed to funnel IFR aircraft from the Air Route Traffic Control Center (ARTCC or "center") into the Terminal Radar Approach Control (TRACON or "terminal") area. However, the STARs do not typically connect directly to a published instrument approach procedure (IAP). Especially in metroplex environments, where there are multiple airports with IAPs in the same TRACON, it is common for air traffic controllers to bridge the gap between a Standard Terminal Arrival Route (STAR) and an IAP by providing an IFR aircraft with vectored control instructions (i.e., "vectors") during this arrival phase of flight. This process involves TRACON ATCOs constantly communicating with conventionally crewed aircraft pilots over voice. In a nominal situation for a UAS in the arrival phase, assuming no significant transmission latency between the RP and the ATCO, this communication and control approach should be similar to conventionally crewed operations.

In a LC2L situation, however, the LC2L UA could be extremely disruptive to ATC operations. Unlike other IFR aircraft in the TRACON, ATC would be unable to instruct the LC2L UA to maneuver. Instead, ATC would necessarily have to maneuver other IFR aircraft around the path of the LC2L UA. This maneuvering requires that ATC be sufficiently aware of the intended path of a UA in a LC2L state, have the workload capacity to maneuver other aircraft, and have the workload capacity to recover from possible LC2L UA-induced disruptions to the TRACON operations.

This work aims to quantify an initial impact assessment of a well-defined set of LC2L procedures in a representative airspace environment. By understanding better the impact these procedures might have, an iterative process of improving the procedures to reduce impact, while balancing the three previously mentioned aspects, can occur.

Additional background on LC2L procedures will be presented in Section II. Section III will describe the fast-time simulation environment and setup that is used to provide this initial impact assessment. Results of the simulations will be presented in Section IV and conclusions and future work provided in Section V.

## II. Lost C2 Link Procedures

The degradation of a C2 link is a temporal process. The "loss" of the link can be difficult to determine. An analogy can be thought of as follows: Imagine one is riding on a train through the mountains while on a cell phone call. The train enters a long tunnel and the audio quality of the call begins to degrade, though bits and pieces of audio are able to be exchanged, but not enough for active conversation. Is the call lost at this point? The degraded conversation continues for a time. Eventually, the call drops. At this point, the call can safely be considered lost.

Cavan Solutions presented a concept for a decomposition of the LC2L event, which is redrawn in Fig. 1 [10]. Within this decomposition, there are several key definitions, namely:

**LC2L Decision Time:** The maximum amount of time permitted before a LC2L state is declared.

**$T_0$:** The time at which a LC2L state is declared.

**$T_1$:** The time at which Segment 2 is begun.

**$T_2$:** The time at which the link is re-established.

**$T_3$:** The time at which the LC2L event is over.

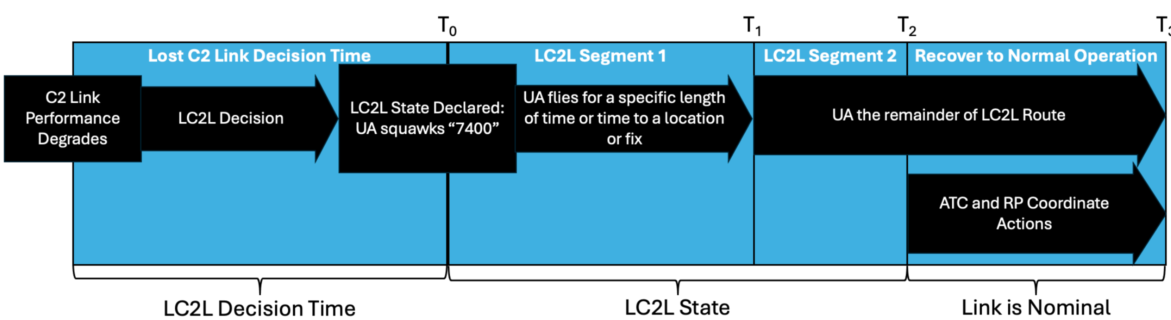


Fig. 1. LC2L event while UA is airborne (redrawn from [10]).

Moving left to right in Fig. 1, the C2 link performance begins to degrade. After the link has been degraded for a given LC2L Decision Time, a LC2L state will be declared at $T_0$. The UA will squawk (i.e., change the transponder code to) 7400[3]. At this point, the RP is unable to uplink any commands to the UA. The UA will then execute LC2L Segment 1 for a set period of time (until $T_1$). In general, Segment 1 is a continuation of the current flight route, though implementations of this Segment can vary and are described later in the paper. Segment 1 is intended to provide time for ATC and other air traffic to acknowledge the LC2L UA and plan/react appropriately (e.g., maneuvering traffic out of the way of the UA's path). After Segment 1 is finished, Segment 2 begins at $T_1$. Segment 2 could be a continuation of the nominal flight route, a diversion to an alternate airport, a hold at a designated fix, or any other number of routes. Assuming the C2 link is re-established, that occurs at $T_2$. From $T_2$ to $T_3$, there is a need to recover to normal operations. During this stretch of time, the RP and ATC need to coordinate

[3] For more information about the use of transponder code 7400 for LC2L procedures, see [SOURCE-ICAO WP.17]

actions to return the UA to its nominal flight plan (or other route, as needed). Once normal operations are recovered, the LC2L event is deemed over ($T_3$). Throughout the course of the LC2L event, ATC will need to maneuver other IFR traffic away from the UA and other crewed aircraft operating under Visual Flight Rules (VFR) will need to see and avoid the UA. It is expected that the UA itself with be equipped with 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 DAA implementation and execution is, however, outside the scope of this work.

There have been two standards bodies that have published procedures for what the UA should do and what rules it should follow during a LC2L event. In the following subsections, the example procedures will be described for the arrival procedures in a LC2L state.

### A. *ICAO RPASP-16/WP-15*

In 2020, a working paper was presented at the sixteenth meeting of the International Civil Aviation Organization (ICAO) Remotely Piloted Aircraft Systems Panel (RPASP) [12]. This paper built off of existing radio communication failure (commonly called "NORDO") procedures to develop procedures for UAS in a LC2L state. The intention of building off of NORDO procedures is so that LC2L procedures are predictable to air traffic controllers and the controllers can maneuver other traffic appropriately.

The ICAO paper distinguishes between terminal and en route airspace, where the former is defined as within 30 NM of either the departure or arrival airport. Unless otherwise specified, the ICAO paper defines the LC2L Decision Time as 30 seconds in terminal airspace and 240 seconds (4 minutes) in en route airspace. For the arrival phase (i.e., within 30 NM of the arrival airport), the LC2L procedure is described in Section X.4.3.3. Because the ICAO procedure is similar to the RTCA procedure that is listed below, it will not be described here.

Within the ICAO document, it is acknowledged that, in certain airspaces, factors such as traffic density and/or airspace complexity may necessitate additional predictability. Increased predictability could also be desired by ATC to help them perform their job safely and efficiently. The default procedure mentioned above may be especially unsuitable for busy terminal environments, leading to the creation of airspace-specific procedures. This work will focus on one such busy terminal environment to attempt to quantify the suitability of a default procedure might be on a typical day.

### 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", also referred to as "DO-400" [13]. This document builds off of previous work, including the above ICAO work, as well as current Federal Aviation Administration (FAA) policy and regulations surrounding UAS. Specifically, DO-400 applies to the NAS in the U.S. Further assumptions and application restrictions can be found in the document itself.

DO-400 utilizes the Cavan Solutions decomposition (Fig. 1) to provide step-by-step guidance material across eight phases of flight: preflight, taxi, takeoff, climb out/departure, transit/extended UA operations, arrival/approach, landing, and post-flight. DO-400 provides guidance material in each of these phases in the form of actions. These actions are prescribed not only for the UA itself, but also for the RP and ATC. Additionally, in each phase of flight, DO-400 identifies differences for non-towered airports (i.e., airports without an operational air traffic control tower) and gaps to address.

The DO-400 definition of arrival is distinct from that of approach. The arrival subphase is defined as the descent from level flight (i.e., it begins at the top of descent) to the IAF. The approach subphase is defined as from the IAF to the final approach fix (FAF) along a published approach. Unless otherwise noted, definitions in this work will adhere to the DO-400 definitions.

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 to its last clearance. 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

The present study, a set of fast-time simulations, utilizes a variety of NASA research simulation platforms, which are described below. The fast-time simulations are set up to enable testing of LC2L procedures in a representative airspace environment. Accurately simulating the representative airspace environment as close to real world operations as possible is a key factor in determining the impact UAS LC2L procedures will have. To this end, there was a need to identify challenges with implementing these novel operations into the simulation platforms, characterize the magnitude and scope of those challenges, propose potential (and realistic) mitigations, and implement those mitigations into the representative airspace environment, while identifying areas of future improvements. The simulation platforms allow for simulated aircraft to fly amongst playback of recorded traffic, have been used for verifying and validating numerous airspace integration technologies and concepts, and are especially useful for identifying unintended risks and/or consequences and quantifying benefits of introducing technologies into the NAS [14], [15].

### A. ATM TestBed

The NASA Air Traffic Management (ATM) TestBed (or simply "TestBed") is a robust and flexible air traffic management software platform used in the current study [16], [17]. TestBed provides a foundational environment that enables multi-fidelity, real- and fast-time, human- and automation-in-the-loop simulations of current and proposed future air traffic and airspace integration concepts. TestBed includes a configuration panel, traffic viewer, interfaces for input data (e.g., airspace and airport models, including arrival and departure procedures; flight tracks and plans, both recorded and live), and other capabilities. TestBed is an integration middleware that connects aircraft simulators, ATM services (e.g., conflict detection and resolution), and other technologies.

### B. NAS Digital Twin

The NAS Digital Twin (NDT) simulation environment [18] is used in the present study. Built off of the NASA ATM TestBed software platform, NDT has been employed to verify and validate new concepts and technologies, simulate changes to the NAS, and uncover unintended consequences and risks of introducing new concepts and technologies. NDT leverages decades of research and development within the NASA Ames Aviation Systems Division [18] to provide a Live, Virtual, and Constructive (LVC) simulation environment that can contain recorded, simulated, and/or live airspace service providers, fleet operators, aircraft, and weather. NDT is composed of a modular architecture that allows the LVC simulation environment to be tailored to the needs of the current research effort, including the integration and testing of new algorithms and services in a common environment. NDT has been employed to study operations in increasingly complex airspace with increasingly diverse aircraft and increasingly autonomous operations from the present day through the far term [19]-[24].

### C. Adaptations and Extensions

For the current research effort, NDT was enhanced to enable simulated flights to perform LC2L procedures at airports with a TRACON model. By default, for these types of airports (including Fort Worth Alliance Airport (KAFW)), NDT simulates arrival flights on a default STAR based on the direction of origin. This approach works well for conventional flights conducting nominal operations. However, to model LC2L procedures in NDT, the TRACON model was overridden to allow for waypoint-to-waypoint (with altitude and speed constraints) trajectories. This change: 1) enabled the simulated UA to fly a STAR and then deviate from that STAR to fly to an IAF as in an LC2L procedure, and 2) allowed the simulated UA to fly an ILS CAT III approach to runway 16L at KAFW. These changes improved the realism of the simulation and facilitated the modeling and analysis of LC2L procedures against recorded background traffic in simulations that were representative of actual operations, which was not previously possible. The flexibility added to NDT means that additional LC2L procedures can easily be tested in representative airspace environments.

### D. Traffic Scenario

Fort Worth Alliance Airport (KAFW) was chosen as a representative cargo airport for this series of fast-time simulations. KAFW is located in the northwest of the Dallas-Fort Worth metroplex and is a busy cargo hub, serving as a focus airport for both FedEx and Amazon Air. Previous research has identified KAFW as a prime candidate for initial regional air cargo operations using UAS [5]-[7]. As seen in Fig. 2, KAFW is a Class D environment, located underneath the Class B shelf of Dallas-Fort Worth International (KDFW) and Dallas Love Field (KDAL). Several other Class D environments are located nearby KAFW, including two general aviation airports (Fort Worth Meacham (KFTW), Denton Enterprise (KDTO)) and a military airbase (Naval Air Station Joint Reserve Base Fort Worth (KNFW)). KAFW also hosts a continuously operating control tower and two 11,000 ft runways. One of these runways, 16L/34R hosts an Instrument Landing System (ILS) approach on both ends, including a Category (CAT) II-III ILS approach on the 16L end.

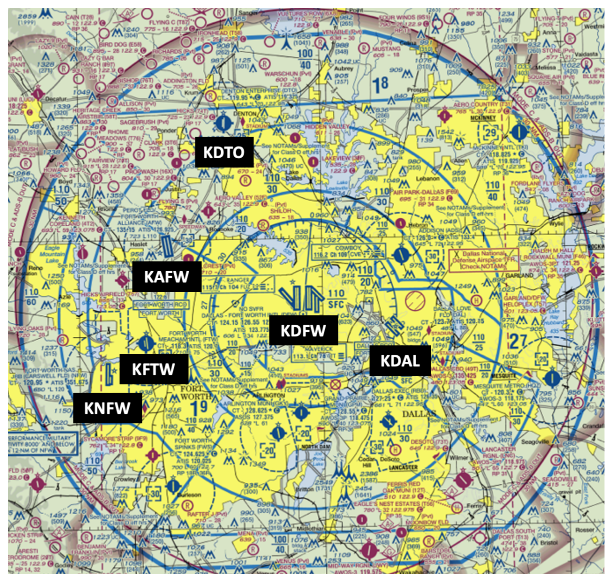


Fig. 2. The Dallas-Fort Worth Terminal Area [25].

The Dallas-Fort Worth TRACON area ("D10") surrounds the busy metroplex environment. The TRACON is a large square with its corners cut off, shown in light gray in Fig. 3. Generally, IFR flights will depart the TRACON along the flat edges of the square (to the north, east, south, or west). Arriving flights will be ushered through the four "corner posts" of D10 (i.e., northeast, southeast, southwest, and northwest). Aircraft arriving into KAFW will typically utilize one of seven STARs. These STARs provide a fixed route for an IFR aircraft to transition from ARTCC control to TRACON control. The handover typically, though not always, occurs at an "arrival fix" (i.e., a defined waypoint on the boundary of the TRACON). Unless the STAR contains further waypoints within the TRACON (which is possible), the IFR aircraft will then typically receive vectors to their assigned/scheduled approach procedure from the ATCO. If the STAR does contain further waypoints, the aircraft will receive vectors after completion of the STAR.

According to the ICAO and RTCA procedures described in Section II, the procedure for a departing UAS returning to its origin airport in a LC2L state and an arriving UAS approaching its destination airport in a LC2L state have many overlaps. For this initial analysis, this work will focus solely on the arrival procedures. To further simplify, proper landing system selection must occur. Categories of landing systems, CAT I, II, and III, are classified based on the decision height (DH; the height at which the pilot must decide to either continue the approach or execute a missed approach) and a runway visual range (RVR; the range over which the pilot can see the runway surface markings), with CAT III being the most stringent. In crewed operations, the pilot onboard must visually identify the runway by the decision altitude or execute a missed approach [26]. The lack of an onboard pilot presents a dilemma for a UAS: there is no ability to visually identify the runway. Although alternative means of landing (e.g., computer vision, GPS) are being considered, the most stringent currently certified landing system is the CAT III ILS (and it is only certified for crewed operations; no landing systems are currently certified for routine uncrewed use). CAT III ILS is the only system that can enable “0/0” operations (i.e., a 0 ft DH, 0 ft RVR). Under current regulations, since there is no pilot to provide visual acceptance on board the UAS, it is likely that “0/0” operations will be used. As such, it is assumed in this work that the UAS will need to utilize the CAT III ILS instrument approach procedure in all cases. Given that only one runway end at KAFW has a CAT III ILS, it then follows that all UAS in the study will utilize the ILS RWY 16L (CAT III) approach (hereafter referred to simply as “ILS 16L”), which is shown in Fig. 4.

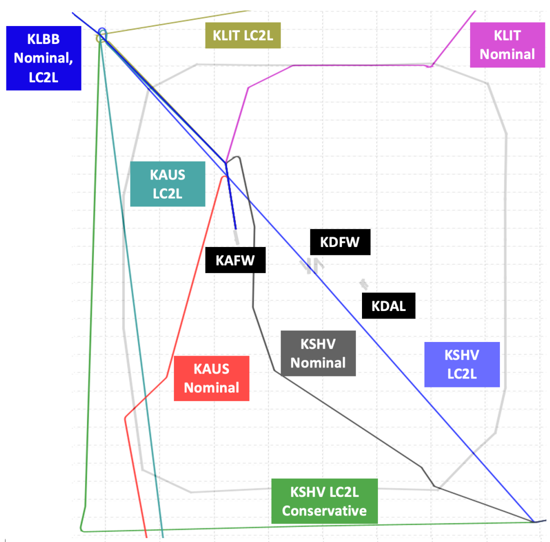


Fig. 3. D10 TRACON (black rectangle with cutoff corners) and airports of interest (black) along with the nine different nominal and LC2L routes used in this study (various colors), described in Section III.F and III.G. D10 is approximately 70 nmi x 70 nmi in size.

## E. Date and Aircraft Selection

January 18, 2022, was selected as the simulation date due to having minimal convective weather in the Fort Worth Center as indicated by the Weather-Impacted Traffic Index and delay statistics in the Sherlock ATM Data Warehouse [SOURCE]. 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 around 1400 to 1800 UTC (0800-1200 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.

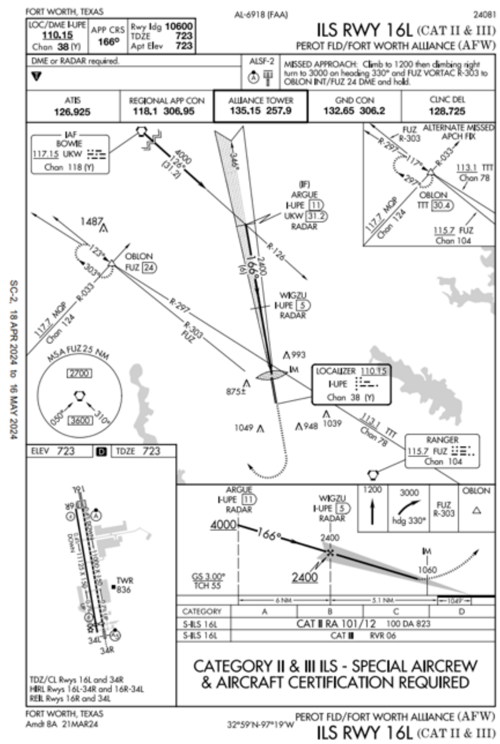


Fig. 4. ILS RWY 16L (CAT II & III) instrument approach procedure for KAFW [27].

A representative aircraft, the Cessna 208B Grand Caravan (C208), was simulated as the UAS. This aircraft is the most used aircraft in regional air cargo in the United States [6]. In each simulation, eleven UAS, spaced in 10-minute increments, were flown along the nominal route with no conflict resolution active. Each simulated UAS had a cruise speed of 160 kts and a speed of 150 kts after the arrival fix is reached. The four baseline scenarios were designed to gather information about losses of separation in a “do nothing” scenario with different background traffic. In all routes, the departure times of the simulated flights were adjusted so that the first aircraft of the eleven departed at 14:23:30 UTC (08:23:30 local time), with the next ten aircraft following in 10-minute intervals.

Fig. 5 shows arrivals for KAFW throughout the year 2022. The red dots represent C208 flights, the yellow dots represent ATR 72 flights (another common regional air cargo aircraft), the orange dots are flights that squawked 1200 (i.e., were flying under VFR), and the blue dots are other flights in the area (e.g., large jet cargo aircraft). As can be seen in the black box in Fig. 5, the arrivals occur during a consistently busy morning rush to investigate a “worst case scenario” wherein the arrival airspace was at its busiest. Additional times can also be investigated in future work.

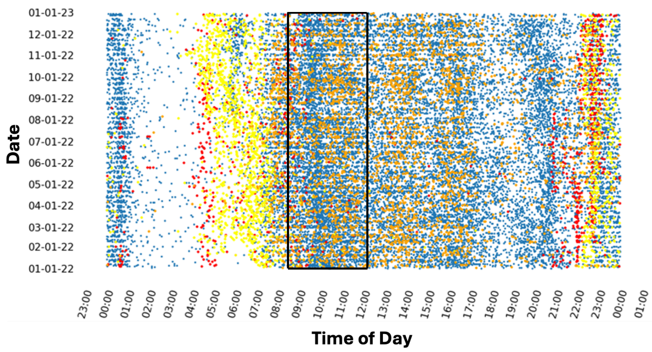


Fig. 5. Arriving flights by time of day into KAFW throughout 2022. The simuation occurred in the time denoted by the black box on January 18, 2022.

### *F. Nominal Routes*

Starting from the assumption that all routes must utilize the ILS 16L approach, and working back to the arrival phase of flight, routes for four different origin airports were chosen to highlight entry into each of the four D10 "corner posts". These routes mirror, as closely as possible, real recorded flights of regional cargo aircraft between the two airports. These baseline, "nominal" routes assume that the aircraft loses C2 link and continues to execute the waypoints initially inputted into the flight plan. In other words, the baseline scenario investigates a "do nothing" scenario, where no LC2L procedure beyond simply continuing the flight plan as defined. Routes are shown in Fig. 3.

TABLE I. NOMINAL UAS ROUTES

| Origin Airport | Flight Plan | | |
|---|---|---|---|
| | ***Flight Route***[a] | ***Corner Post*** | ***STAR*** |
| KLBB | KLBB..SPS..UKW..KAFW | NW | MOTZA1[b] |
| SKAUS | KAUS..TPL..SLUGG..LIKES.. KAFW | SW | LIKES3 |
| KLIT | KLIT..LESME..PONYY.. RIDDE..MELTE..CAINE.. SASIE..BLECO..TRUUK.. KAFW | NE | TRUUK2 |
| KSHV | KSHV..CQY..DODJE.. CABBY..STURN..FIRMN.. MARSN..UNYUK..KAFW[c] | SE | DODJE6 |

a. The last two waypoints before KAFW are always ARGUE and WIGZU and are not included.

b. If the IAF (in this case, UKW) for the IAP is reached prior to completion of the STAR, it is assumed that the UAS will follow the IAP instead of completing the STAR.

c. To better mimic the recorded route via vectors, fixes STURN through UNYUK were added.

Note that, in three of the four routes, the IAF (UKW) is not included in the nominal route, breaking slightly with the "full" IAP. Per input from internal NASA pilot subject matter experts, it is common for an aircraft to go direct to the Intermediate Fix (IF), which in this case is ARGUE, if routing first to the IAF would be out of the way. For more information, including limitations on this method, see [28].

The routes are shown below in Table I. The first route, from Lubbock (KLBB), fully executes the ILS 16L IAP through the northwest corner post. This route utilizes the MOTZA1 STAR, though cuts the STAR short before reaching its final waypoint because the STAR intersects the IAP at UKW. The second route, from Austin-Bergstrom (KAUS), routes through the southwest corner using the LIKES3 STAR. The third route enters the northeast corner post via the TRUUK2 STAR from Little Rock (KLIT). The final route, from Shreveport (KSHV), utilizes the southeast corner DODJE6 STAR. This route had four additional waypoints added within the TRACON area to mimic the routing that an ATCO would give, via vectors, to a flight using the DODJE6 STAR to land on 16L at KAFW.

### *G. LC2L Routes*

The LC2L scenarios are designed with the assumption that the UA is not established on a STAR when it loses link. Per DO-400 procedures and like the ICAO procedures, if the UA is not established on a STAR, the UA should procedure direct to the IAF, and, once it reaches the IAF, should continue on the IAP. Note that no holding pattern, as prescribed in the ICAO procedures, is implemented in these scenarios. In all cases, due to the assumption of utilizing ILS 16L approach, this procedure dictates that the UA must pass through the UKW IAF prior to continuing the 16L approach. Routes are shown in Fig. 3.

Table II shows the LC2L procedure routes for each corner post of the TRACON. The northwest corner post route from KLBB is the same as the nominal case, as that route already passes directly through UKW. The southwest route from KAUS bypasses much of the LIKE3 STAR, largely staying west of the D10 TRACON. The northeast route from KLIT largely remains north of the D10 TRACON, bypassing the TRUUK2 STAR. In these three routings, the procedure has the UA staying clear of the busy TRACON environment. It is anticipated that, given the en route environment is less busy than the TRACON, the UA should encounter fewer aircraft with which it could conflict. The fourth routing, coming from KSHV and entering through the southeast corner post, goes directly from the SE corner to the IAF UKW. This routing takes the UA straight across the D10 TRACON (including directly over KDFW, a major airport).

TABLE II. LC2L PROCEDURE UAS ROUTES

| Origin Airport | Flight Plan | | |
|---|---|---|---|
| | ***Flight Route***[a] | ***Corner Post*** | ***STAR*** |
| KLBB | KLBB..SPS..UKW..KAFW | NW | N/A |
| KAUS | KAUS..UKW..KAFW | SW | N/A |
| KLIT | KLIT..UKW..KAFW | NE | N/A |
| KSHV | KSHV..CQY..UKW..KAFW | SE | N/A |
| KSHV | KSHV..CQY..JEN..UKW.. KAFW | N/A | N/A |

a. The last two waypoints before KAFW are always ARGUE and WIGZU and are not included.

Although the LC2L procedure cutting directly across the TRACON is predictable, insofar as the UA routing is straightforward, the routing is also highly likely to be disruptive to TRACON operations. This routing points at the need to balance predictability of LC2L procedures to ATC with the safety of avoiding other aircraft and minimizing ATC workload of having to maneuver multiple different aircraft out of the way of the LC2L UA. To test the hypothesis that a more conservative routing through the en route airspace would reduce the number of conflicts the UA might encounter, a second LC2L procedure for the flight from KSHV was created. This routing, shown as the fifth route in Table II, stays south of D10 until JEN, a waypoint to the southwest of the TRACON, then routes north to UKW.

## IV. Results

Each simulation run contained eleven simulated C208. With nine different routes (four nominal "do nothing" routes, four LC2L routes that follow existing procedures, and one LC2L procedure that flies more conservatively), there were a total of 99 simulated UA flights investigated. For each simulated flight, several values were calculated. Any instance where the simulated UA lost separation with a recorded background aircraft was recorded. A loss of separation is defined as a UA and another aircraft being within 1000 ft vertically and 3 or 5 nmi horizontally in the terminal area (defined as being within 30 nmi of the arrival airport) or en route area, respectively. A loss of separation indicates a situation in which either ATC would need to maneuver the other aircraft (if appropriate, e.g., for an IFR aircraft) or the other pilot of that aircraft (e.g., for a VFR aircraft) would need to maneuver to avoid the UA. By counting the number of unique aircraft with which the losses of separation (with respect to each UA) occurred, a first-order approximation of the impact on additional workload an air traffic controller or other pilot might face when handling/interacting with a LC2L aircraft can be made.

### A. *Loss of Separation by Corner Post*

The distribution of the number of unique LOS per route is shown in Fig. 6. Each individual flight's number of unique LOS is shown by the markers to the left of the respective distribution. In blue are the nominal, "do nothing" routes. In red are the LC2L routes that follow existing procedures. Finally, the conservative LC2L route is in green. From left to right, the corner posts are the southeast (SE), southwest (SW), northwest (NW), and northeast (NE). The number of unique LOS across the entire flight (i.e., en route and terminal areas combined) is shown for a LOS criterion of 5 nmi (Fig. 6a) and 3 nmi (Fig. 6b). Across all routes, there is naturally a decrease in the median number of unique LOS when the separation criterion is reduced from 5 nmi to 3 nmi, as seen in Table III.

Looking at the NW corner, the exact same distribution of unique LOS is seen in both the nominal and LC2L routes. Given that the two routes are exactly the same, this distribution is expected. For the SW corner, a significant decrease in the median number of unique LOS for the nominal route is seen when reducing the separation criterion, indicating that many of the LOS recorded are between 3 and 5 nmi and would not be relevant in a terminal area. A similar decrease is seen of the NE nominal route. The SE corner is the most interesting; although there is again a decrease in the number of LOS recorded when the separation criterion is reduced, the LC2L route has the highest median value in both cases. This result indicates that there is a need for a refinement to the LC2L procedure in this situation. Shown in green is the conservative LC2L route, designed to loop around D10 instead of cut through it, with its fewer LOS. Fewer LOS may be a potential benefit to a more conservative routing that bypasses busier airspace.

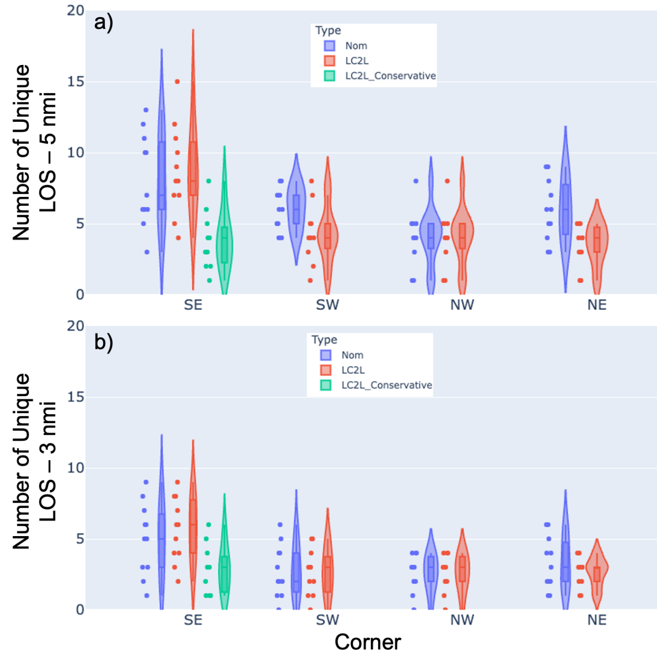


Fig. 6. Unique LOS by corner post with separation criterion of a) 5 nmi and b) 3 nmi.

TABLE III. Median Count of Unique LOS By UAS Routes

| Origin Airport | Flight Plan | | |
|---|---|---|---|
| | ***Flight Route*** | ***Corner Post*** | ***Unique LOS[a]*** |
| KLBB | Nominal | NW | 4/3 |
| KLBB | LC2L | NW | 4/3 |
| KAUS | Nominal | SW | 6/2 |
| KAUS | LC2L | SW | 4/3 |
| KLIT | Nominal | NE | 6/3 |
| KLIT | LC2L | NE | 4/3 |
| KSHV | Nominal | SE | 7/5 |
| KSHV | LC2L | SE | 8/6 |
| KSHV | LC2L (Conservative) | N/A | 4/3 |

a. The first and second numbers listed gives the count of unique LOS using 5 and 3 nmi as the separation criterion, respectively.

### B. *Loss of Separation by Flight Domain*

The LC2L routes for the SW and NE corner are, at first glance, not necessarily alike, nor do they look like the LC2L route for the NW corner. However, the portion of the routes that corresponds to the ILS 16L IAP aligns exactly (waypoints UKW, ARGUE, and WIGZU). UKW is roughly 43 nmi from KAFW, meaning that the path through the terminal area (i.e., within 30 nmi of KAFW) for these three different routes is identical. If it can be assumed that unique LOS are rare in the sparse en route environment, it follows then that all three routes should have similar median counts for unique LOS, as all unique LOS are assumed to happen in the terminal area and these routes have the same path through the terminal. Indeed, this conclusion holds true, as all three have 4/3 median counts for unique LOS. The conservative LC2L routing from KSHV that loops around the TRACON to avoid cutting through it also has the same path through the terminal (UKW, ARGUE, and WIGZU) and has 4/3 median unique LOS.

The routes through the SE corner, both nominal and LC2L, have the highest number of unique LOS. These routes both cut across the entirety of the busy D10 TRACON (i.e., within 30 nmi of KDFW). In fact, the LC2L route directly overflies KDFW, one of the busiest airports in the world. Intuitively, the longer an aircraft spends in an area with higher levels of traffic, the more like that aircraft is to lose separation with another aircraft. The fact that the conservative LC2L routing from KSHV (which routes around the D10 TRACON) has median counts unique LOS that are half that of the LC2L route that cuts directly across the TRACON (4/3 and 8/6, respectively) indicates that this intuition is supported by these initial simulation results.

To investigate the relationship between time spent in the terminal area versus the number of unique LOS, the first step is to classify each unique LOS as occurring in either the terminal area or in the en route area. An important point of clarification must be made regarding the airport referenced for the center of the terminal area. Given that the terminal area relative to an airport is described as a circle of radius 30 nmi and that the center of KAFW is roughly 15 nmi to the northwest of the center of KDFW, it can be shown that the KAFW terminal area has a roughly 70% overlap with the KDFW terminal area (i.e., the D10 TRACON). The other 30%, however, of the KAFW covers less busy areas to the northwest of the D10 TRACON (i.e., outside the Mode C veil of the KDFW Class B environment). To ensure clarity in the relationship between time spent in the terminal area versus the number of unique LOS, explicit reference to either the KAFW terminal area or the KDFW terminal area will be made.

Fig 7. shows the individual flight count (via markers) and the distribution of the counts of unique LOS (using 3 nmi separation criterion). The number of unique LOS in the nominal routes are shown for the terminal area (Fig. 7a) and en route area (Fig. 7b) relative to both KDFW (red) and KAFW (yellow). Figs. 7c and 7d show the same for the LC2L routes (excluding the conservative LC2L route) relative to both KDFW (purple) and KAFW (green). In blue are the total counts, irrespective of terminal or en route environment. Note that the sum of the terminal and en route counts cannot exceed the total count for a particular flight (blue). Across all routings, the count of unique LOS in the terminal area, whether the KAFW or KDFW terminal area, is higher than the respective en route area, in agreement with the earlier intuition.

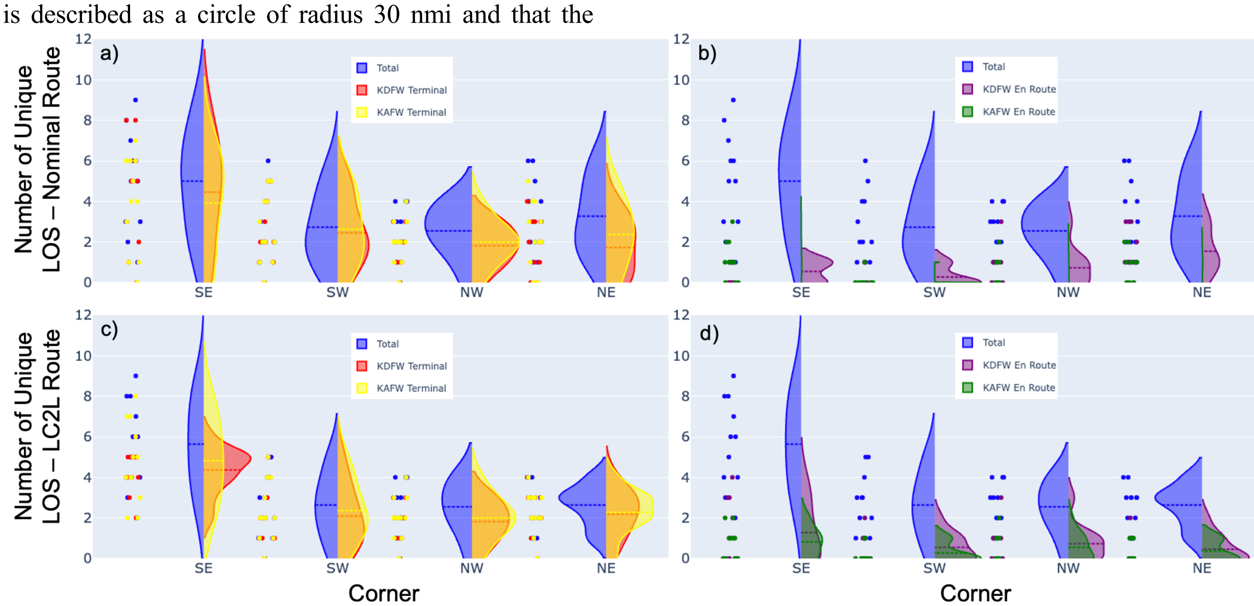


Fig. 7. Counts of unique LOS in terminal (a, c), en route (b,d) areas relative to KAFW (yellow, green), KDFW (red, purple) compared with overall counts of unique LOS using 3 nmi separation criterion (blue). Nominal routes are on top (a, b) and LC2L routes are on bottom (c,d).

### C. *Effect of Time in Terminal Area*

A possible influencing factor on the count of unique LOS overall might be the time spent in the air. However, as seen in Fig. 8, this supposition is not supported by the initial data assessment, as the trend line is essentially parallel to the x-axis.

Breaking down the flights into their en route and terminal components can help to isolate where the unique LOS are occurring. Fig. 9 shows the number of unique LOS in the KAFW en route Fig. (9a), KAFW terminal (Fig. 9b), KDFW en route (Fig. 9c), and KDFW (Fig. 9d) terminal regions relative to the amount of time the UA spent in the corresponding region. For example, in Fig. 9d, a flight spent 1600 seconds in the KDFW terminal and recorded 8 unique LOS. Figs. 9a and 9c show that, like the overall flight time trend, the amount of time spent in the en route environment has a minimal correlation with the count of unique LOS. Although the en route phase does not appear to be the most critical phase of flight (with respect to unique LOS), it is important to point out that many of the simulated flights did have at least one unique LOS in the en route environment, with one flight (the LC2L route from KSHV landing 80 minutes after the first flight) having 4 unique LOS just in the en route environment. LC2L can present a risk to the UA even in a "less busy" en route environment. This point will be discussed further in the Conclusions section.

Although the overall time in flight and the time in flight in the enroute environment do not have a clear impact on the count of unique LOS, the time spent flying in the terminal area might. To dig deeper into the relation between unique LOS and the terminal area, Table IV shows the number of unique LOS relative to the KAFW and KDFW terminal and en route areas, as well as how long (in seconds), the simulated aircraft spent in the respective terminal airspace.

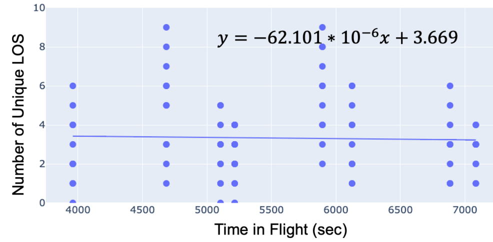


Fig. 8. Counts of unique LOS for each simulated flight versus the amount of time, in seconds, spent in flight.

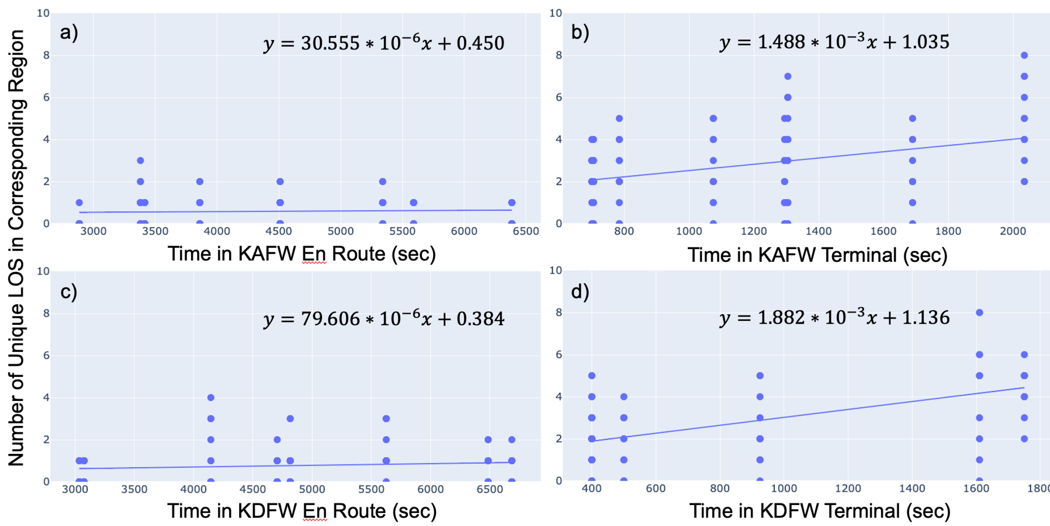


Fig. 9. Counts of unique LOS in the KAFW (top) and KDFW (bottom) en route environments versus the amount of time, in seconds, spent in the corresponding en route environment. A 3 nmi separation criterion is used.

TABLE IV. COUNT OF UNIQUE LOS

| **Origin Airport** | **Flight Plan** | | | | | |
|---|---|---|---|---|---|---|
| | ***Flight Route*** | ***C. Post*** | ***Unique LOS[a] (KAFW)*** | ***Unique LOS[a] (KDFW)*** | ***Time in KAFW[b] Terminal*** | ***Time in KDFW[b] Terminal*** |
| KLBB | Nom | NW | 2/0 | 2/1 | 705 | 400 |
| KLBB | LC2L | NW | 2/0 | 2/1 | 705 | 400 |
| KAUS | Nom | SW | 2/0 | 2/0 | 1075 | 925 |
| KAUS | LC2L | SW | 2/0 | 2/0 | 1690 | 400 |
| KLIT | Nom | NE | 2/1 | 2/1 | 785 | 500 |
| KLIT | LC2L | NE | 2/0 | 2/0 | 700 | 400 |
| KSHV | Nom | SE | 4/1 | 5/1 | 1305 | 1610 |
| KSHV | LC2L | SE | 5/1 | 5/1 | 2035 | 1750 |
| KSHV | LC2L (Con) | N/A | 2/1 | 2/1 | 1295 | 400 |

a. The first and second numbers listed gives the count of unique LOS in the terminal and en route environments relative to the listed airport, respectively, using a 3 nmi separation criterion.

b. The value listed in these columns is the time, in seconds, the simulated aircraft spent in the respective terminal area.

Because focusing solely on the median value can obscure trends, Fig. 9 shows the count of unique LOS in the KAFW (9b) and KDFW (9d) terminal areas for all 99 simulated aircraft. As expected, there is a positive correlation between the amount of time in the terminal area and the count of unique LOS. However, the datapoints themselves clearly indicate a wide spread of unique LOS, even within flights on the same route that spent the same amount of time in the terminal area. It would be erroneous to conclude that the time in the terminal area is the *only* factor influencing the count of unique LOS. Other factors will be discussed further in the Conclusions section.

## V. CONCLUSIONS AND FUTURE WORK

Significant alterations to the NDT simulation were made to enable testing of realistic LC2L procedures in a representative airspace environment. A total of 99 simulated UA C208 flights across nine total routes (four nominal routes, four routes that follow current LC2L procedures, and one route that flies more conservatively) were performed. The count of unique losses of separation were recorded for each flight. The total flight time and the flight time in the en route environment had minimal correlation with the count of unique LOS. The total flight time in the terminal environment (i.e., within 30 nmi of the arrival airport) did indicate a loose positive correlation with count unique LOS. However, the spread of the counts of unique LOS for the individual flights indicate that the flight time in the terminal area cannot be the only factor at play.

This result points to the need for more advanced metrics. These metrics will be used to provide the next level of clarity in the assessment of LC2L procedures and can eventually be coupled with path-planning capabilities to route UAS in an appropriate fashion, accounting for surrounding traffic, possibility of LC2L, prevailing ATC factors, and so forth. These advanced metrics should somehow quantify the background traffic complexity. In addition to the pure number of background traffic aircraft, the metrics should account for *where* the traffic is, both currently and where the traffic is likely to appear based on historic trends. Ultimately, it is likely that these metrics will need a temporal component as well. It can be seen from the current study that the exact same route can encounter vastly different counts of unique LOS (from zero to eight in the most extreme case). Ongoing work in developing these metrics, such as the development of maps of spatio-temporal distribution of traffic (operating under IFR and VFR) and predictive occupancy, can be found in [29] and on VFR trajectory forecasting using deep generative models can be found in [30].

Ultimately, there is a need to further assess the tradeoff between predictability, robustness, and survivability, as discussed in the Introduction. How the preemptive planning for and reactive response to LC2L contingencies affect the eventual operations of remotely piloted large UAS in the NAS is an area of ongoing research. One possibility is that LC2L events are rare enough that UAS can fly much the same as their conventional cousins. Another possibility is that, even if rare, the LC2L event impact is so severe that the possibility of the event itself must be mitigated (such as the "conservative LC2L route" presented in this paper or more stringent C2 performance requirements to reduce the occurrence of LC2L events). These possibilities will need to be further developed and tested in high fidelity fast-time and human-in-the-loop simulations.

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