ARTICLE INFO
Article ID: 01-16-03-0023

doi:10.4271/01-16-03-0023

Three Case Studies on Small Uncrewed Aerial Systems Near Midair Collisions with Aircraft: An Evidence-Based Approach for Using Objective Uncrewed Aerial Systems Detection Technology

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Abstract

Small uncrewed aircraft systems (sUAS) growth continues for recreational and commercial applications. By 2025, the Federal Aviation Administration (FAA) predicts the sUAS fleet to number nearly 2.4 million units. As sUAS operations expand within the National Airspace System (NAS), so too does the probability of near midair collisions (NMACs) between sUAS and aircraft. Currently, the primary means of recognizing sUAS NMACs rely on pilots to visually spot and evade conflicting sUAS. Pilots may report such encounters to the FAA as UAS Sighting Reports. Sighting reports are of limited value as they are highly subjective and dependent on the pilot to accurately estimate range and altitude information. Moreover, they do not account for NMACs that an aircrew member does not spot. The purpose of this study was to examine objective sUAS and aircraft telemetry data collected using a DJI Aeroscope sensor and Automatic Dependent Surveillance-Broadcast (ADS-B)/Mode S messages throughout 36 months near a major United States (U.S.) airport. This data offers objective insights into the interaction of sUAS and aircraft in the airspace surrounding this airport. Using the data, three NMAC case studies are presented based on three varying mission profiles: (a) commercial air carriers, (b) general aviation (GA) aircraft, and (c) helicopters. The findings inform on sUAS-aircraft encounter evolution and trends, including areas of encounter risk, lateral and vertical encounter separation distances, sUAS operator compliance with operational and altitude restrictions, and comparisons of objective detection data against sUAS sighting reports. Recommendations are provided to mitigate risks associated with encounter trends to further enhance safety within the NAS.

This article is part of a special Issue on Uncrewed Aircraft Systems (UAS) and Autonomy.

History

Received:	22 Dec 2022
Revised:	23 Apr 2023
Accepted:	19 May 2023
e-Available:	14 Jun 2023

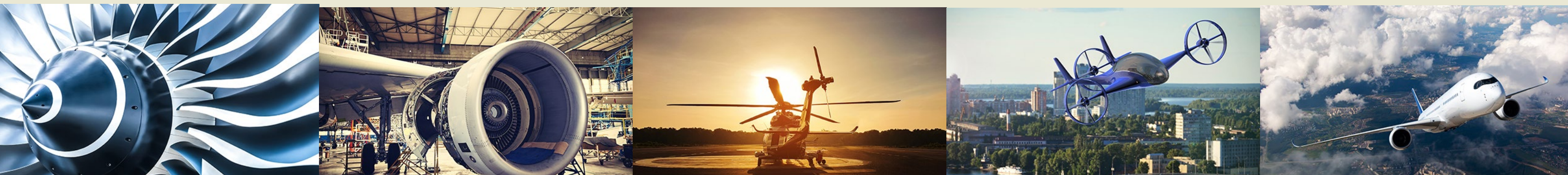
Keywords

Small uncrewed aircraft systems (sUAS), Near midair collisions (NMACs), Encounter mapping, Encounter distance, Case study

Citation

Wallace, R., Winter, S., Rice, S., Kovar, D. et al., "Three Case Studies on Small Uncrewed Aerial Systems Near Midair Collisions with Aircraft: An Evidence-Based Approach for Using Objective Uncrewed Aerial Systems Detection Technology," *SAE Int. J. Aerosp.* 16(3):263-278, 2023, doi:10.4271/01-16-03-0023.

ISSN: 1946-3855
e-ISSN: 1946-3901



1. Introduction

According to the Federal Aviation Administration (FAA) [1], as of 2020, an estimated 1,463,500 recreational and 488,000 commercial small uncrewed aerial systems (sUAS) were operating in the National Airspace System (NAS). Cumulatively, the agency expects the size of the sUAS fleet to grow to nearly 2.4 million units by 2025 [1]. As drone use becomes more common, experts worry about the potential for drone collisions with crewed aircraft. In comments at the 2020 Commercial UAV Expo, FAA Administrator Steve Dickson highlighted the importance of drone safety, stating, "…just one clueless, careless, or reckless drone pilot, in the wrong place at the wrong time could threaten others in the airspace or on the ground" [2, 1:33].

Administrator Dickson's comments are not without merit. Multiple reports of drone encounters with aircraft and collisions have occurred within the past several years. On September 18, 2020, a Los Angeles police helicopter supporting a burglary investigation struck a drone, prompting the pilot to initiate an emergency landing [3]. In another Los Angeles incident, nine months earlier, the National Transportation Safety Board (NTSB) concluded that an Airbus AS350B2 helicopter was likely struck by a drone while conducting a news flight near city hall. The collision resulted in minor damage to the airfoils and tail rotor [4].

It is important to note that not all reports of drone collisions or near misses are valid. For example, several news agencies reported an encounter between a drone and a commercial airline flight from Chicago O'Hare on August 22, 2021. According to one of these errant reports, the Embraer 175 aircraft struck a UAS while performing a climbing turn shortly after takeoff [5]. In a later clarification, the FAA announced the plane had likely struck a Mylar balloon and not a drone [6].

1.1. Problem Statement

Reports indicate that the proliferation of sUAS in the NAS is expected to continue [1]. As these vehicles increase operations, the chances of collision with crewed aircraft will also increase. There is currently limited data to accurately assess the encounter pathways between uncrewed and crewed aircraft. One of the primary sources of data is sighting reports. While these reports provide value, they are not without limitations. The subjective nature of these reports increases inconsistency, and these reports require the sUAS to be spotted by a pilot or crewmember. The lack of objective and complete data on sUAS and crewed aircraft encounters leaves significant gaps in understanding NAS operations with these vehicles. Without accurate, objective, and comprehensive methods to monitor and track encounters, it is impossible to make meaningful decisions related to the safe operations of integrated airspace between these types of aircraft and minimize the risks of midair collisions. The purpose of this study was to conduct a data-driven assessment of aircraft-sUAS encounters within the NAS. The researchers posed the following research question: To what extent are sUAS encounters with crewed aircraft occurring in the NAS?

1.2. Purpose

The purpose of this research was to collect empirical data about potentially-unsafe encounters that occur between crewed aircraft and uncrewed aircraft within the NAS.

1.3. Significance

The findings of this study serve to identify and evaluate the extent of potential collision hazards between crewed and uncrewed aircraft currently taking place within the NAS. The results of this study can inform the FAA about the effectiveness of existing regulations in preventing potentially hazardous encounter situations. Additionally, this study serves as an initial resource to aircraft pilots, remote pilots, airport operators, and other aviation stakeholders to identify common characteristics about where and how dangerous encounters evolve within the NAS. It is recognized that further research will help to expand the generalizability of these findings through the use of analyzing additional data and making comparisons at various locations, such as urban and rural. Finally, study data can be used as a more objective measure of the sUAS encounter risk over less reliable and subjective UAS Sightings Reports.

2. Literature Review

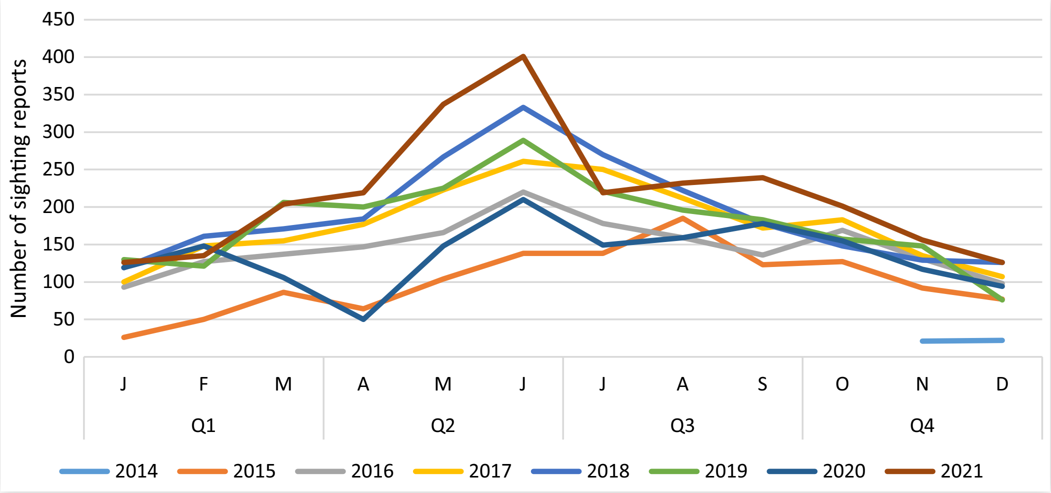
2.1. UAS Sighting Reports

The FAA uses several metrics to evaluate potential risks posed by uncrewed aircraft. One medium of data includes UAS Sightings Reports—reports from pilots and other stakeholders involving potentially unsafe UAS flights around airplanes, helicopters, and airports [7]. The number of sUAS sightings has risen sharply since the FAA first began tracking sUAS sighting incidents in late 2014. In 2021, the agency received more than 2,595 sighting reports—more than double the 1,210 reports received in the first full calendar year of tracking in 2015 (see Figure 1).

It is important to note that sighting reports are a *proxy measurement* of the potential hazards of drones within the NAS. In the absence of a nationwide system of drone detection technology, it is not possible to directly observe and assess UAS incidents. UAS sighting reports provide an *indirect measurement* of the state of safety within the NAS that is assumed to be strongly correlated with the results of direct observation. Sighting reports are also subjective, which can lead to questions about the accuracy of the reports.

Perhaps not surprisingly, the validity of sighting reports has come under intense scrutiny by several organizations. In

FIGURE 1 UAS Sightings Reports (November 2014–December 2021).



Data taken from Ref. [7]. © Embry-Riddle Aeronautical University

a 2015 analysis of sUAS Sightings Reports, the Academy of Model Aeronautics (AMA) reported that only a small percentage of cases were accurately reported as close calls or near misses. Several reports included spurious data such as compliant sUAS operations, UFO sightings, and other activities not even involving UAS [8]. In a subsequent analysis of UAS sightings data, the AMA [9] reported that the preponderance of sighting reports were merely observations of UAS sharing the airspace. In a comprehensive study of UAS Sightings Reports amassed from 2015 to 2017 by the Unmanned Aircraft Safety Team (UAST) [10], the analysis team criticized the value of sightings data, stating:

> …ultimately the data set is too inconsistent and unstandardized to extract concrete conclusions. The current structure, inconsistency and unrefined nature of the sighting reports disproportionately exacerbate concerns about manned-unmanned interactions and do not provide industry or government with actionable data on which to base safety enhancements and regulatory or operational decision-making. (p. 2)

Even the FAA acknowledges the limitations associated with sighting reports, indicating that "reported sightings of unsafe UAS use are unreliable, because it cannot be verified whether the sighted object was a UAS, and if it was flying in compliance with current regulations" [11, p. 29]. In a separate Government Accountability Office (GAO) [12] report, the agency further highlighted that it generally does not assess the validity of UAS Sightings Reports. The investigation of some reports involving collisions resulted from birds, other flying objects, or unrelated issues not involving drones.

Validity issues aside, perhaps the most critical limitation of sightings report data is that it only identifies incidents where a pilot *becomes aware* of the encounter. Awareness of UAS encounters generally relies on pilots to visually spot the uncrewed aircraft. Extensive in-flight visibility studies by Kephart and Braasch [13], Maddocks and Griffitt [14], Loffi et al. [15], Wallace et al. [16], Wallace et al. [17], and Loffi et al. [18] would suggest that spotting an uncrewed aircraft in flight is highly problematic and by no means guaranteed to be accurate.

This is not to say that sighting reports do not provide any insight into potential safety issues. A thorough, systematic analysis of sighting report content has led to several unique findings that can be used to steer UAS policymaking. Gettinger and Michel [19] identified 17 problematic encounters between sUAS and crewed aircraft on the approach path to Los Angeles International Airport, demonstrating the extent of the problem. Their research also provides the first descriptive assessment of the conditions under which sUAS encounters occur. The AMA [20] study would further examine pilot responses to sUAS encounters, provide initial trending information, and highlight validity errors in the sightings report dataset. The UAST [10] analysis codified encounters within the context of the FAA's established near midair collision (NMAC) criteria of 500 ft [21]. Wang [22] performed substantial data cleaning of the UAS sightings database and provided a detailed overview of encounter development based on reported lateral and vertical estimates, aircraft types involved, proximity from aerodromes, relativistic encounter rates by airport traffic count, and other related incident details. A list of notable UAS Sightings Report studies is presented in Table 1.

Unfortunately, sighting reports alone fail to identify the crux of the sUAS-aircraft encounter problem—what is the real risk of a midair collision between a sUAS and crewed aircraft within the NAS and how often are these events occurring?

2.2. Lack of Available Data

One current challenge to assessing the risk of sUAS-aircraft encounters is the lack of available data to inform the problem. The Commercial Drone Alliance (CDA) [23] highlighted the lack of currently available data sources to assess low-level airspace risk adequately. In the open letter, the CDA [23] charged the FAA with being "exceptionally conservative" with rulemaking and waiver approvals and further warning that

TABLE 1 Summary of studies assessing UAS Sightings Reports.

Source/publication date	Start date	End date	No. reports	No. NMAC*	% NMAC
Gettinger and Michel (Dec 2015)**	12/17/2013	9/12/2015	921	327	35.5%
AMA (Aug 2015)	11/13/2014	8/20/2015	764	27	3.5%
AMA (Mar 2016)	8/21/2015	1/31/2016	582	19	3.3%
AMA (Feb 2017)	2/1/2016	9/30/2016	1,270	44	3.5%
UAST (Dec 2017)	8/21/2015	3/31/2017	3,417	547	16.0%
Wang (Dec 2020)	9/1/2016	8/31/2019	6,551	210	3.2%

* Note: Studies varied in their definition of NMAC; caution should be used when comparing results.

** Note: Includes supplemental data sources in addition to UAS Sightings Reports.

the U.S. risks "falling behind [other nations]" in the UAS integration (p. 1). "Currently, the FAA routinely requires Part 107 waiver applicants to prove that planned operations below 400 feet AGL will not present any measurable risks to air traffic—even in uncontrolled airspace where risks of encountering a manned aircraft at such low altitude are exceedingly low" [23, p. 1]. The CDA recommended conducting a focused national study of operational risks for low-altitude UAS operations to address the deficiency.

The GAO [11] similarly concluded that the FAA might lack sufficient data to effectively provide oversight of UAS operations, stating:

> Without identifying existing or additional data and information necessary to evaluate the agency's efforts, FAA may be limited in its ability to effectively adjust oversight activities as needed. For example, FAA does not have reasonable assurances that it is positioned to make informed decisions about (a) targeting activities in locations identified as having increased noncompliant operations and (b) focusing oversight efforts to address identified trends in regulatory infractions. In particular, identifying and assessing necessary data could allow FAA to identify other trends that might help direct or target its ongoing compliance and enforcement efforts—such as analyzing potential trends in UAS occurrences, investigations, or compliance and enforcement actions based on certain locations, times of day, or types of regulatory violation (e.g., operating over people without permission) … (pp. 29–30)

These findings further echo the conclusions of an earlier National Academies of Sciences, Engineering, and Medicine (NASEM) [24] report:

> The current FAA process for considering and approving routine UAS operations continues to stifle needed industry investment in developing technical and operational risk mitigations. The lack of empirical data continues to be the driver for the agency's subjective approach to approvals. (p. 21)

NASEM [24] specifically identified the lack of UAS encounter statistics, low-altitude environmental data, and performance data for UAS detect-and-avoid technologies as contributory to the problem. It is notable that the FAA has been responsive to these findings and commissioned several studies to address these issues through the FAA's Center of Excellence for UAS Research—the Alliance for System Safety of UAS through Research Excellence (ASSURE). These funded projects include the following studies: *sUAS Mid-Air Collision Likelihood*, *sUAS Traffic Analysis*, and *Verification and Validation of Low-Altitude Detect and Avoid Standards* [25]. As of the date of this publication, the results of these studies are still pending.

2.3. Remote Identification

One mechanism that may aid in reducing ambiguity and improving low-altitude source data for UAS operations in the NAS is a new requirement for UAS operators known as remote identification (RID). According to the FAA, *Remote Identification* "is the ability of a drone in flight to provide identification and location information that can be received by other parties" [26, p. 1]. The FAA anticipates that the implementation of RID will provide a means for identifying noncompliant or unsafe sUAS operators and enable more effective management of safety and security risks within the NAS [27]. Moreover, the RID capability is expected to provide "near real-time information regarding unmanned aircraft operations and increases situational awareness of unmanned aircraft to the public, operators of other aircraft, law enforcement, and security officials, and other related entities" [27, p. 4397]. The NTSB similarly sees positive potential for RID broadcast systems to improve midair collision avoidance with uncrewed aircraft [27]. "Manned aircraft, especially those operating at low altitudes where UAS operations are anticipated to be the most prevalent (such as helicopters and agricultural aircraft), could carry the necessary equipment to display the location of UAS operating nearby" [27, p. 4488]. While this technology may promise to shore up data limitations in the future, the mandatory implementation date articulated in 14 Code of Federal Regulations (CFR) §89.105 [September 16, 2023] promises that the agency will not benefit from available RID data for several years.

2.4. Current Study

Current means for assessing the risk of NMACs with uncrewed aircraft rely on observational reports from pilots, controllers, and other aviation stakeholders, which are prone to fallibility and human perceptual error. Accurately measuring the extent of

NMAC events between sUAS and crewed aircraft in the NAS is problematic due to the lack of accessible, reliable, and valid data. Combining data from UAS detection technology and aircraft-equipped tracking devices such as ADS-B, researchers can accurately assess sUAS and crewed aircraft telemetry for NMAC events. Using proprietary, cloud-based analytics software, this process can be applied to large datasets to establish a more complete picture of historical NMAC events over lengthy periods of time.

3. Methodology

This research project utilized an applied, exploratory methodology with selected case studies. Presented case studies represented the most egregious or hazardous examples of near encounters within the dataset.

3.1. Sampling

The authors partnered with Dallas-Fort Worth International Airport (DFW) operations personnel and collected sUAS data from a co-located DJI Aeroscope stationary unit with a G-16 antenna device mounted atop the 13th-floor Hyatt Regency Hotel on the airport's Terminal C concourse.

While DFW was a convenience sample, several reasons support this selection.

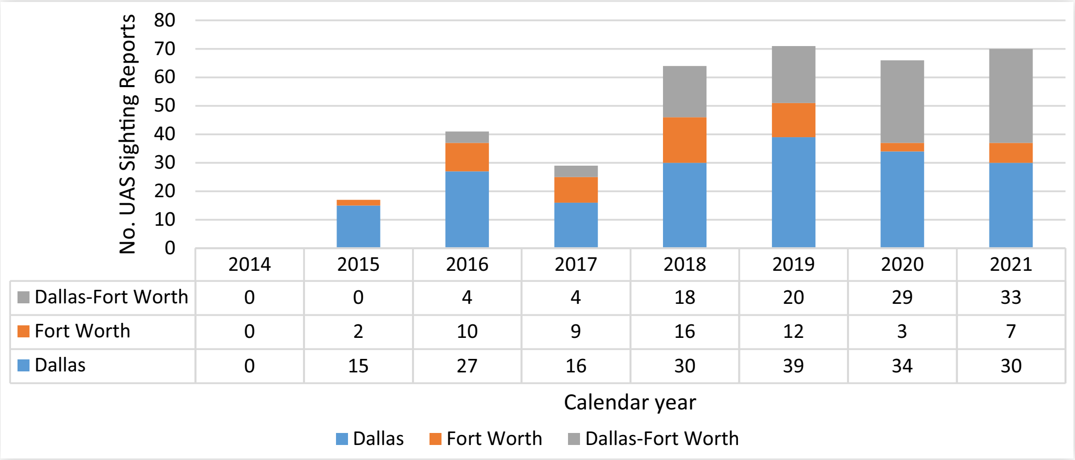
- **Longevity of sUAS Data Collection.** DFW was an early adopter of the UAS detection technology and established an agreement with a vendor to deploy a long-range G-16 Aeroscope sensor on airport property in late 2018 that remained in near-continuous operation until September 2021. The research team assessed that the long duration of available data collected was highly likely to contain several relatively rare NMAC events.
- **High Aircraft Operations Counts.** According to the FAA [28], during the sampling period, the DFW air traffic control facility handled 1,840,667 operations, comprising 86.7% air carrier, 12.4% air taxi, less than 0.1% general aviation (GA), and less than 0.001% military operations. Based on aircraft movements, DFW remained the third busiest airport in the world in 2019 and 2020 [29]. The quantity and density of aircraft operations in the sample area create highly favorable conditions for sUAS-aircraft encounters. An aggregation of historical UAS Sightings Reports collected in the area is provided in Figure 2.
- **Favorable Weather Conditions.** Weather conditions near the sample location are relatively favorable for nearly year-round sUAS operations, making the data more consistent and less susceptible to seasonal skewing. An overview of monthly climatological normal conditions is presented in Figure 3.

3.2. Data Collection Instrumentation

3.2.1. DJI Aeroscope The DJI Aeroscope detects sUAS by electronically identifying the characteristic communication links between the aerial vehicle and remote controller, while passively gathering information (sUAS serial number, telemetry, altitude, launch location, operator location, and other related information) [31, 32, 33]. The device only detects sUAS platforms manufactured by DJI and uses one of four proprietary datalink communications protocols, including Lightbridge, OcuSync, OcuSync 2, and WiFi [31, 34]. "The G-16 Aeroscope antenna can reliably detect drones [at ranges extending out to] between 20–30 miles" [32, p. 1]. There is some disagreement about the extent of DJI's market share in

FIGURE 2 Stacked bar chart of historical UAS Sightings Reports in the Dallas-Fort Worth Area.

Note: Data are based on the FAA [7] UAS Sightings Reports database, CY2014Q4–CY2021Q4, with entries listed as "Dallas," "Fort Worth," or "Dallas-Fort Worth."

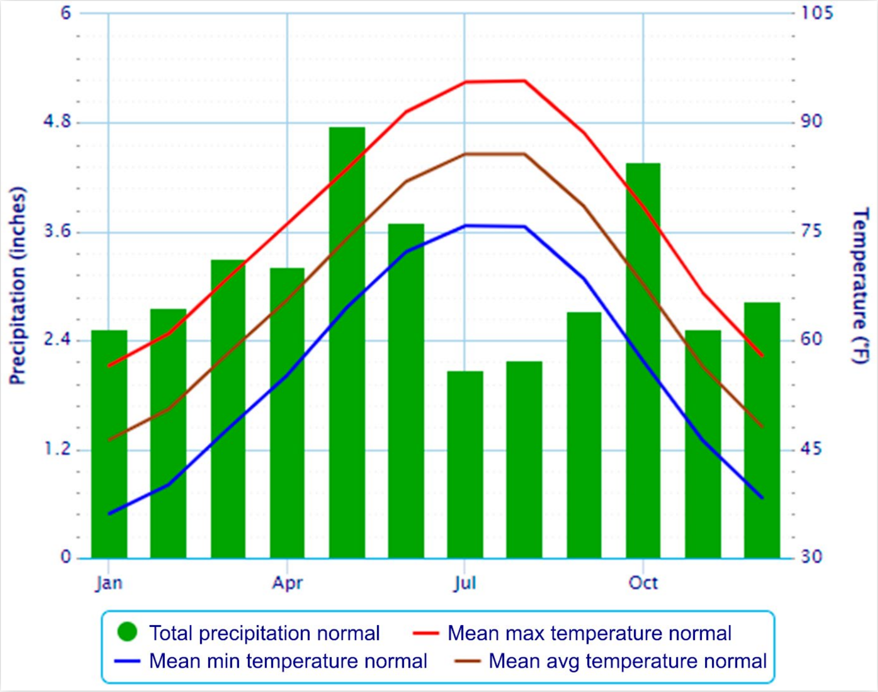


	2014	2015	2016	2017	2018	2019	2020	2021
▨ Dallas-Fort Worth	0	0	4	4	18	20	29	33
▨ Fort Worth	0	2	10	9	16	12	3	7
▨ Dallas	0	15	27	16	30	39	34	30

Data taken from Ref. [7]. © Embry-Riddle Aeronautical University

FIGURE 3 Monthly Climate Normals (1991–2020): Dallas-Fort Worth Area, TX.

Note: Based on 30-year averages [1991–2020].



Reprinted from Ref. [30]

2021. Drone Industry Insights assesses DJI as commanding a 70%–80% market share, while Drone Analyst suggests the Chinese manufacturer controls only about 54% of the commercial drone market [35, 36].

3.2.2. OpenSky Network

OpenSky Network (OSN) is a not-for-profit organization established to improve airspace reliability, efficiency, and security by providing open access to real-time and historical air traffic data [37]. OSN [37] operates a network of more than 4,300 receivers that track and record aircraft data via Automatic Dependent Surveillance-Broadcast (ADS-B) and Mode-S messages.

3.2.2.1. Automatic Dependent Surveillance-Broadcast. ADS-B is a generational alternative to radar technology in tracking aircraft. The system leverages ADS-B (Out) equipment on aircraft that transmits the vehicle location, altitude, ground speed, and other data to a satellite constellation and makes the data available to air traffic controllers and other stakeholders [38]. The technology automatically completes these transmissions for equipped vehicles while providing comprehensive surveillance of operations. ADS-B typically operates on either 978 MHz or 1090 MHz, and updates are completed once per second [39].

3.2.2.2. Mode S. Mode S transponders assign each aircraft with a unique code. These transponders serve as “secondary surveillance and communication systems” [40, n.p.]. The value of the unique code is the lack of ambiguity in transmissions to/from the aircraft. Mode S transponders can transmit position and altitude information [40].

3.3. Data Analysis Tools and Procedure

The UAS and Counter-UAS Analytics Platform (UCAP), a proprietary data analytics software suite designed by Unmanned Robotics Systems Analysis, was used to ingest, store, analyze, and visualize UAS detection and ADS-B/Mode S datasets. The UCAP system is designed to integrate multiple telemetry formats and geographical information systems (GIS) data and provide cloud-based processing of telemetry pathing, data interpolation, and other custom analytics. The web-based platform leverages cloud computing resources to store and process large datasets to identify generalized data trends and case-level analysis.

3.3.1. Data Cleaning and Datum Alignment

For UAS encounter analysis, the UCAP software ingested all historical sUAS and ADS-B telemetry and status data, preserving original data fields and units. The UCAP system performed a data cleaning process to remove duplicates, empty fields, spurious data (such as origin [0,0] location fields), and data points outside the region of interest. Validated data were converted to a common reference datum. Geolocation data utilized the World Geodetic System 1984 (WGS84) standards; all times were converted to Coordinated Universal

Time (UTC), distances were converted to imperial feet (ft), and all altitudes were derived from global positioning system (GPS) inputs and converted to mean sea level (MSL).

3.3.2. Data Interpolation A data interpolation and smoothing process was in place to correct for differences in sampling rates between telemetry datasets, ensure higher temporal fidelity for telemetry point correlation, and improve the positional accuracy of the GIS analysis. Additionally, this process plays a vital role in gap-filling missing data, which can occur when either aircraft or sUAS are operating at low altitudes or amid obstructions that prevent continuous electronic line of sight with either the ADS-B or Aeroscope collection sensor. However, upon evaluating the initial dataset, the research team elected not to utilize the interpolation process since that data were relatively consistent and generally do not contain large interval gaps.

3.3.3. Evaluation Criteria Selection A spherical, three-dimensional encounter envelope is selected within the evaluation software. For this analysis, the FAA NMAC criteria were used. According to the FAA [41], "A NMAC is an incident associated with the operation of an aircraft in which the possibility of a collision occurs as a result of a proximity of less than 500 feet to another aircraft …" (p. 1). An interaction time interval is selected. The system collectively analyzes all aircraft telemetry points against all sUAS telemetry points within the same time interval and conducts a haversine distance calculation. While a lower time interval would provide additional accuracy, the computing power required to support lower interval analysis is considerable. For this analysis, the research team assigned a 10-second time interval to provide an acceptable balance between needed processing power and analysis sensitivity. The aircraft and sUAS tracks associated with point pairs that fall inside the encounter envelope during the selected time interval are flagged. Flagged aircraft and sUAS tracks are reconstructed and depicted with a line connecting the point pair identifying the closest point of approach between the two tracks within the same time interval. Supplemental track data provides further context to each encounter, including date/time, aircraft ID, aircraft type, aircraft altitude, vertical/lateral separation, sUAS flight ID, sUAS model, and sUAS altitude. To protect the identity of individuals involved in NMAC encounters, the research team masked any data that provided identifying information or could be used in a derivative way to identify aircraft or sUAS involved in encounters.

3.4. Limitations and Assumptions

Several limitations and assumptions constrained the current study. A first limitation was that the Aeroscope instrument only detected DJI-manufactured sUAS platforms. However, this limitation was accepted due to the high level of prevalence of DJI systems in sUAS operations. Future research should work to incorporate other manufactured platforms to collect additional data points. Second, sUAS detection with Aeroscope may be compromised or degraded in signal-rich environments, where electronic signal interference is high [31, 42]. As with any electromagnetic signal, sUAS datalink communications signals are subject to signal interference, attenuation, and obstacle blockage. Third, since the Aeroscope is a passive system, the sUAS detection range is influenced by the data link equipment and protocols used by the sUAS (such as frequency, amplitude, and signal encoding). According to 911 Security [31], the transmission range of OcuSync protocols is 4.3 miles, Lightbridge platforms 3.1 miles, and WiFi-enabled platforms between 0.31 miles and 1.24 miles. In future studies, implementation of RID standards will likely make sUAS detection and tracking more consistent across most sUAS platforms since RID signals operate independently of sUAS datalink transmissions. Additionally, the use of Global Navigation Satellite Systems (GNSS) is subject to lateral and vertical errors that can induce minor inaccuracies in location position precision [43]. The research team assumed that GNSS errors were de minimis in nature and applied approximately equally to aircraft and sUAS.

The research team acknowledges that there are varying metrics by which to assess the risk of aircraft near encounters. An NMAC incident may apply to situations in which a report is received from a pilot or other flight crewmember stating that a collision hazard existed between two or more aircraft [41]. In a modeling and simulation study of encounters involving UAS, Weinert et al. [44] defined an NMAC as "a simultaneous loss of 500 feet of horizontal separation and 100 feet of vertical separation" (p. 2). Other encounter criteria can be derived from Terminal Collision Avoidance System or Detect-and-Avoid systems. For the purposes of this research project, the authors utilized the official FAA criteria of *less than 500 ft of separation* to define an NMAC. The authors further recognize that the utilization of different criteria or definitions of NMAC may adjust the quantity of NMACs discovered in this research.

The research team assumed, according to 14 CFR §91.131(d)(2), after January 1, 2020, ADS-B (Out) equipment is required to operate in Class B airspace in accordance with 14 CFR §91.225. The preponderance of the airspace within the sUAS detection range of the DFW Aeroscope sensor falls within the Class B surface area, with the exception of the area below the Class B airspace shelf starting at approximately 8 NM around the airfield. Since ADS-B use was not mandated before the January 1, 2020 implementation date, the research team acknowledges that not all aircraft operating in the DFW area were likely detected during those years.

The research team assessed sUAS altitudes relative to rules associated with 14 CFR §107, as well as Low Altitude Authorization and Notification Capability (LAANC) UAS Facility Map (UASFM) area altitude limits. The team did not have access to either LAANC approvals or FAA airspace approval data. The research team acknowledges that it may be possible that some detected sUAS reported as exceeding either Part 107 or UASFM altitude limits were operating in compliance with FAA waivers, airspace authorizations, or other means of compliance.

TABLE 2 Relative size of sUAS platforms involved in NMAC events.

	<0.55 lb	0.55 lb < 1 lb	1 lb < 2 lb	2 lb < 4 lb	≥4 lb	Unknown
No. of sUAS	1	2	13	4	3	1

The findings of this research were based on a convenience sample of a single, commercial hub airport in a singular region of the USA. They may not necessarily be representative of other locations. Moreover, NMAC encounters between crewed and uncrewed aircraft can be categorized as *rare events*—those that occur infrequently but incur the highest impact [45]. An additional implication of studying rare events is the *degrees of freedom problem*, in which the problem may have several probable causes. Still, because there are so few cases, it is difficult to isolate the effect of individual variables [46]. Similarly, rare events may also be subject to *combined causes*, in which the event does not occur unless multiple causal factors occur in succession or the event is the result of an interaction of multiple factors [46]. The exploratory methodology attempts to observe and record salient factors for the case studies and identify possible trends for further exploration. The research team asserts that this preliminary research should not be interpreted as inferential beyond the population or scope of the study.

4. Findings and Discussion

Aeroscope data were collected from August 22, 2018, to July 31, 2021 (35 months, 9 days). ADS-B and Mode S data for the same period were obtained from the OSN. During the sampling timeframe, the research team observed 459,549 drone flights from a population of 28,995 DJI-manufactured sUAS platforms. During the same period, DFW recorded a total of 1,840,667 aircraft operations, comprised of 86.7% air carrier flights, 12.4% air taxi flights, less than 0.1% GA flights, and less than 0.001% military flights [28]. The research team identified 24 cases of NMACs—cases in which an sUAS detected by the Aeroscope came within a 500-foot proximity of a crewed aircraft transmitting an ADS-B signal at the same point in time. Two NMACs were identified in 2018, one in 2019, 14 in 2020, and seven in 2021. Table 2 highlights the relative mass of the sUAS platforms involved in each NMAC. Figure 4 provides an overview of detected sUAS activity relative to recorded traffic activity at DFW during the sampling period. An overview of monthly UAS sighting reports for the Dallas-Fort Worth area and NMAC cases identified during this study are also presented.

The mean lateral separation distances for all detected NMACs was 214.9 ft ($M = 187$ ft), with a mean vertical separation distance of 287.5 ft ($M = 305$ ft) and mean total (slant) separation distance of 388.1 ft ($M = 413.5$ ft). Aircraft NMAC events were further separated into three operations categories: Air Carriers ($n = 11$), Helicopters ($n = 7$), and General Aviation ($n = 6$). Table 3 presents an overview of the mean and median lateral and vertical separation distances for each aircraft category. A scatterplot of lateral and vertical encounter distances for cases is presented in Figure 5.

The research team examined the location of each sUAS encounter to evaluate either the 400-foot maximum altitude compliance with both 14 CFR §107.51(b)(2) and 49 U.S. Code (U.S.C.) §44809(a)(6) or the LAANC UASFM altitude limit [47]. The results of this analysis are presented in Figure 6. In all encounters, the sUAS was below the aircraft altitude. In

FIGURE 4 DFW aircraft activity, detected DJI sUAS activity, UAS Sightings Reports, and confirmed NMACs (Aug 2018–Jul 2021).

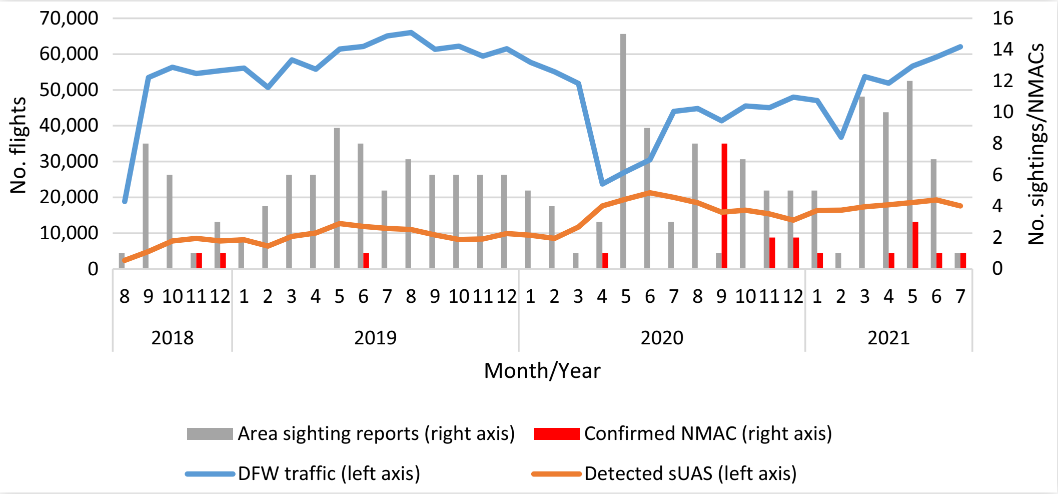


TABLE 3 NMAC encounter distances [mean/median] (ft).

Category	Lateral	Vertical	Total
General aviation	193.5/187.0	277.2/304.0	360.3/379.0
Helicopter	241.3/213.0	215.1/243.0	345.6/377.0
Air carrier	209.7/184.0	339.3/417.0	430.3/446.0
Cumulative	**214.9/187.0**	**287.5/305.0**	**388.1/413.5**

83.3% of cases (n = 20), the sUAS was operating within the lateral confines of the LAANC system. In 18 of those 20 cases, the UAS exceeded the maximum altitude prescribed by the UAS Facility Maps. In 55% of cases in which the encounter occurred within the confines of the LAANC system (n = 11), the sUAS was being operated in an LAANC grid in which the altitude ceiling is set at 0 ft—essentially an area that prohibits sUAS flight. For all four encounters that occurred outside the lateral confines of the LAANC system, the sUAS was flying well below the 400-foot regulatory limit. In two of the four cases that occurred outside the LAANC system, the crewed aircraft flight path penetrated below the UAS Facility Maps maximum prescribed altitude—in both cases, the aircraft was a helicopter.

Perhaps the most notable finding within the dataset is that of the 24 NMAC incidents, three sUAS were responsible for 54.2% (n = 13) of the encounters. A Matrice 200V2 encountered two helicopters and a GA aircraft on three successive days in 2020; A Mavic 2 was flown along the approach path to the DFW Runway 35C, resulting in successive NMAC counters with eight air carrier aircraft within an 84-minute period in 2020; A Phantom IV Pro 2.0 encountered two helicopters during a single flight operation in 2021.

Due to the unique nature of operations between the three categories of aircraft—air carriers, GA, and helicopters—the researchers assessed each category of aircraft encounters separately.

4.1. Case Study and Discussion: Air Carriers

In 91% of air carrier encounters (n = 10), sUAS encounters occurred when the aircraft was below 500 ft AGL. At least 91% of air carrier encounters (n = 10) occurred within 1.5 NM of a runway approach or departure corridor of DFW, with the remaining occurrence recorded near Dallas-Love Field (DAL). The data would suggest that commercial aircraft are particularly vulnerable to close encounters with uncrewed aircraft in the moments immediately after takeoff or proceeding landing. A sample of air carrier encounters that occurred along the approach path to DFW is presented in Figure 7.

The research team was somewhat surprised to discover sUAS operations along these approach and departure corridors. DJI [48] reported an update to its geofencing strategy. dubbed Geospatial Environment Online 2.0, a system is designed to provide improved protection to aircraft in the near airport environment [48]. According to DJI [48],

> DJI geofencing uses GPS and other navigational satellite signals to automatically help prevent drones from flying near sensitive locations such as airports, prisons, nuclear power plants and high-profile events. In certain locations, a DJI drone cannot take off or fly in a geofenced area without special authorization. Drone pilots with verified DJI accounts can unlock some areas if they have legitimate reasons and necessary approvals, but the most critical areas require special action from DJI to unlock them. DJI has streamlined the approval process so professional drone pilots with authorization to fly in sensitive locations can receive unlocking codes within 30 minutes. (p. 1)

Based on new guidance provided in the FAA Reauthorization Act and codified in 18 U.S.C. §39B, the regulatory guidance calls for the creation of a *runway exclusion zone* for airports in Class B, C, or D airspace that

FIGURE 5 Small UAS-aircraft encounters separation distance.

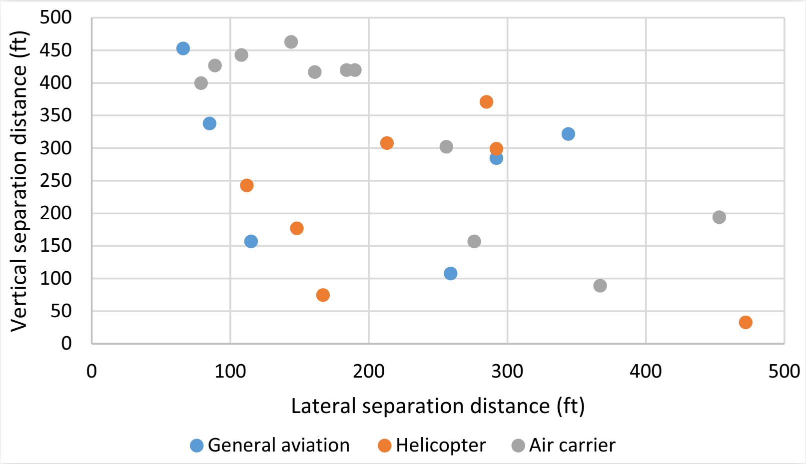
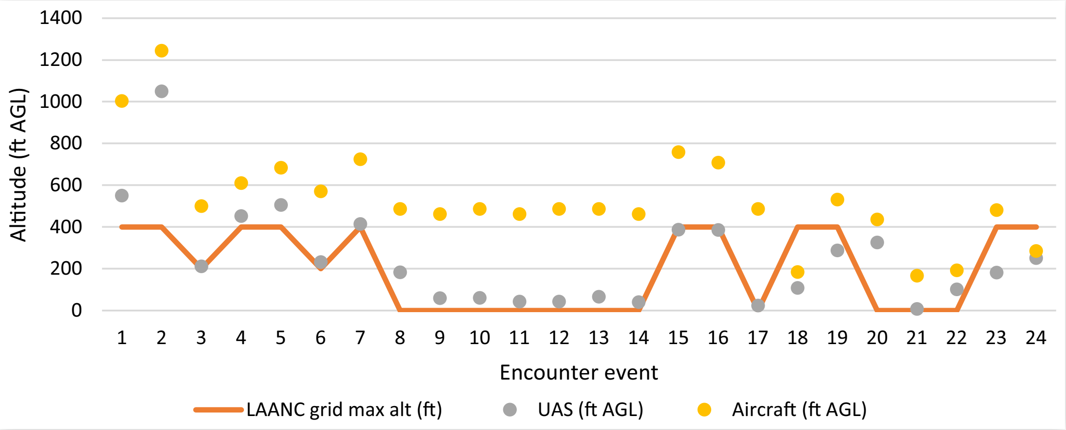


FIGURE 6 sUAS-aircraft vertical encounter distance versus maximum allowable altitude (ft).

Note: Events 18, 19, 23, and 24 occurred outside the UAS Facility Maps System; a maximum altitude of 400 ft above ground level (AGL) was assigned.



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encompasses a rectangular area oriented along each runway axis extending outward 1 SM from the runway end and 0.5 SM in width [49, 50]. DJI employs three different geofencing designs based on the risk level of the airport. The design used at the highest-risk airports, such as DFW, is presented in Figure 8. The exact configuration of geofencing protections around DFW is presented in Figure 9.

Brendan Schulman, DJI's Vice President of Policy and Legal Affairs, called the update "an enormous step forward for safely integrating drones into the airspace based on a more finely-tuned evaluation of risks associated with aircraft approaching and departing different types of airports" [48, p. 1]. DJI's new geofencing strategy includes five different zones, with each providing an increasing level of operator situational awareness or restriction [51]:

- **Restricted Zone**: In these zones, users will be prompted with a warning, and flight is prevented. Those with proper authorization can receive online unlocking of these areas.

FIGURE 7 Air carrier encounter with sUAS in the arrival/departure corridor at DFW.

Note: Aircraft ADS-B telemetry is presented in blue and sUAS telemetry in green. From left to right, each image provides an increasing granularity of the encounter development through the altitude and telemetry evolution of both aircraft.

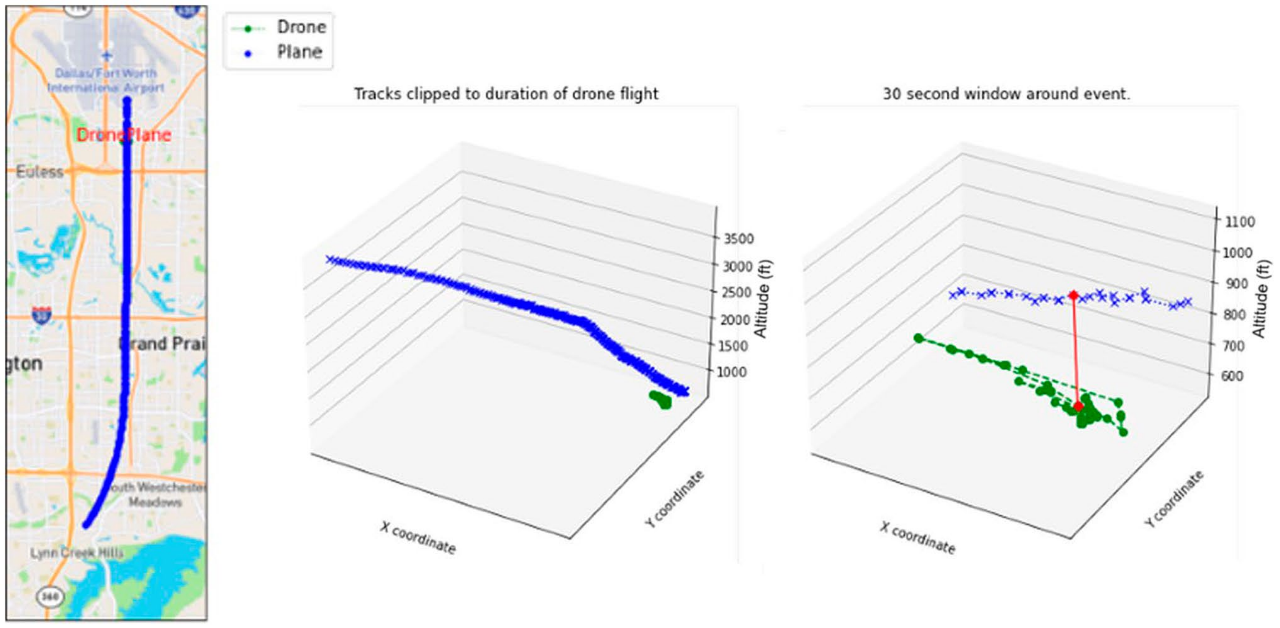

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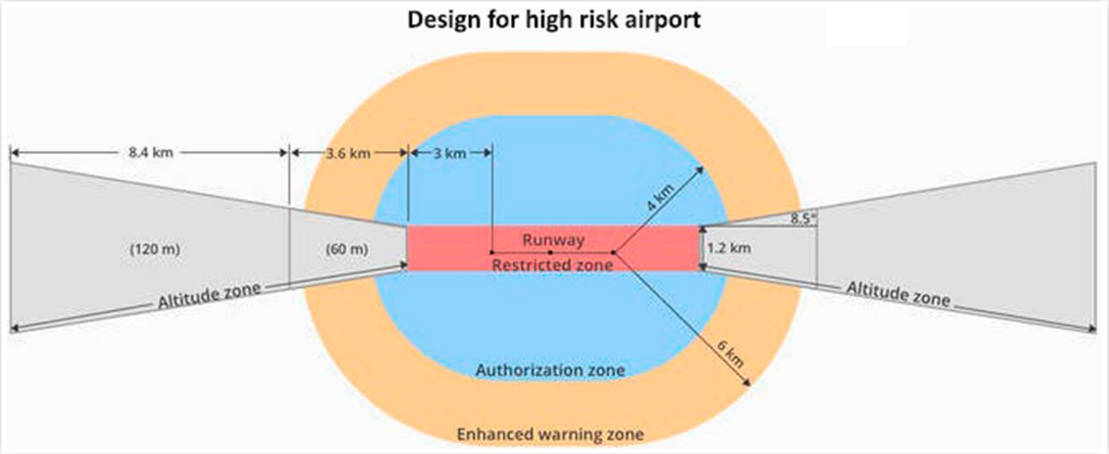
FIGURE 8 DJI geofencing design for high-risk airports (such as DFW).



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- **Authorization Zone**: In these zones, users will be prompted with a warning, and flight is limited by default. Authorization Zones may be unlocked by authorized users using a DJI-verified account.
- **Altitude Zone**: Users receive a warning and flight altitude is limited.
- **Warning Zone**: Users will be prompted with a warning message, but the flight is not restricted.
- **Enhanced Warning Zone**: Users are prompted to unlock the zone (similar process to Authorization Zones) but do not require a verified account or Internet connection at the time of flight.

The research team requested GIS data from DJI and received five KML files depicting the areas of each respective restriction. Based on the provided data, two of ten of the air carrier encounters that occurred within the DFW runway

FIGURE 9 DJI geofencing implementation surrounding DFW airport.

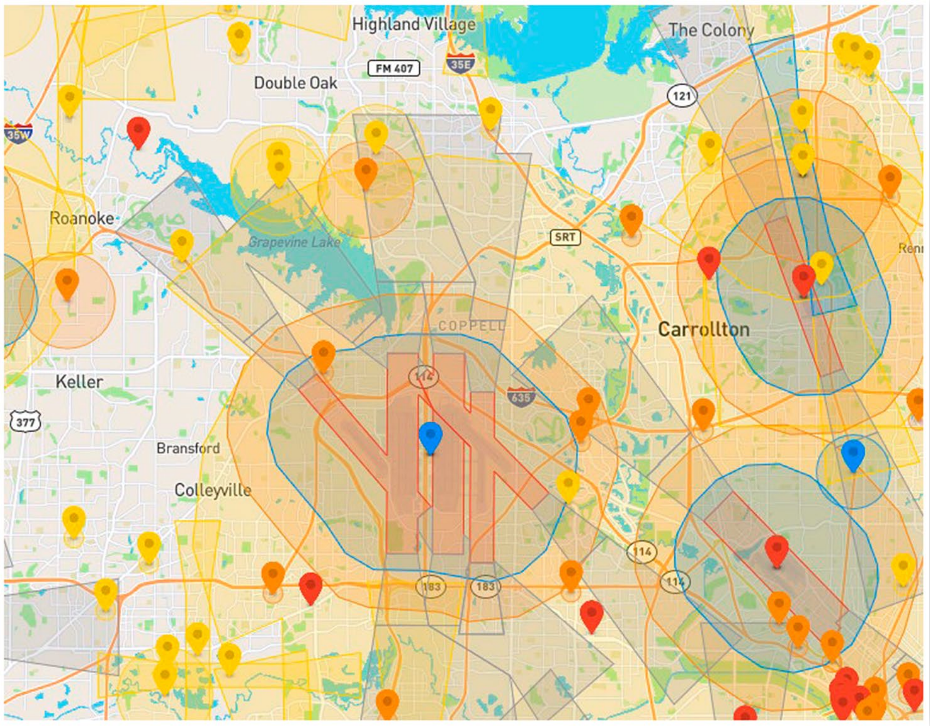

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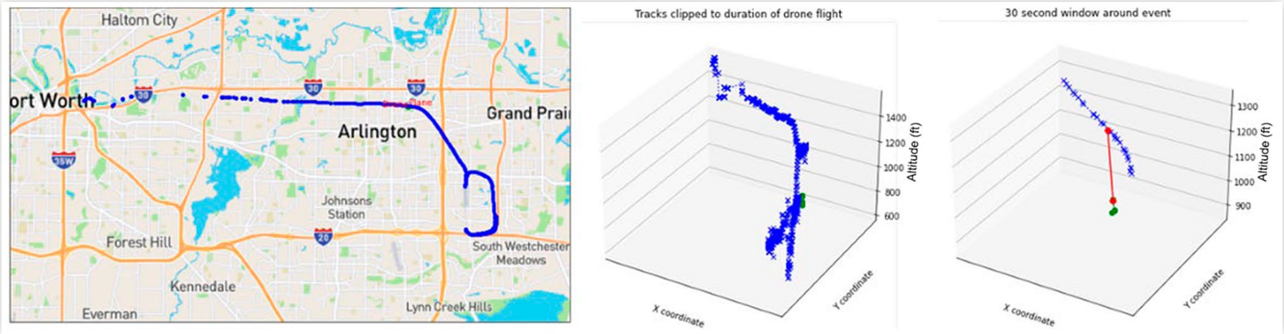
FIGURE 10 GA aircraft encounter with sUAS during cruise flight.



approach or departure corridors occurred inside *the runway exclusion zone*. The remaining eight air carrier encounters that occurred within the approach or departure corridors occurred outside the FAA-mandated runway exclusion zone, but did occur inside DJI's runway-restricted zone. Therefore, all ten air carrier encounters within the approach or departure corridors occurred in areas in which DJI geofencing flight restrictions were active. This implies that these sUAS operators had either sought Restricted Zone unlock permission from DJI or had otherwise bypassed the geofencing restrictions. According to DJI, unlocking restricted zones requires the submission of "authorization documents supplied by the controlling authorities in the areas where they wish to fly" [50, p. 1]. The research team could not ascertain under what authority these sUAS flights were conducted.

4.2. Case Study and Discussion: General Aviation

The research team did not detect clearly recognizable patterns or operational trends associated with GA encounters with sUAS. Of the six recorded GA encounters, the aircraft altitude varied from as high as 1,003 ft AGL to as low as 437 ft AGL. Of the six GA encounters, five occurred within the lateral confines of the LAANC system. The researchers further observed that GA encounters with sUAS, on average, tended to be approximately 19% closer than air carrier encounters. While there were no discernable trends for the locations in which GA aircraft encountered sUAS, all encounters occurred within relative proximity to an airport. At the time of the sUAS encounter, GA aircraft ranged from 1.32 NM to 5.97 NM away from the nearest airport reference point, with a mean distance of 3.6 NM. Unlike air carrier encounters that tended to occur primarily during approach and departure phases, GA encounters appeared to occur during the cruise portion of the flight, in which the aircraft altitude remains relatively constant. Figure 10 highlights a representative example of a GA encounter. It appears that in 83% (*n* = 5) of GA encounters that a low-altitude aircraft flew into the NMAC range of an sUAS that had exceeded the maximum permissible UASFM altitude threshold for the LAANC area.

4.3. Case Study and Discussion: Helicopters

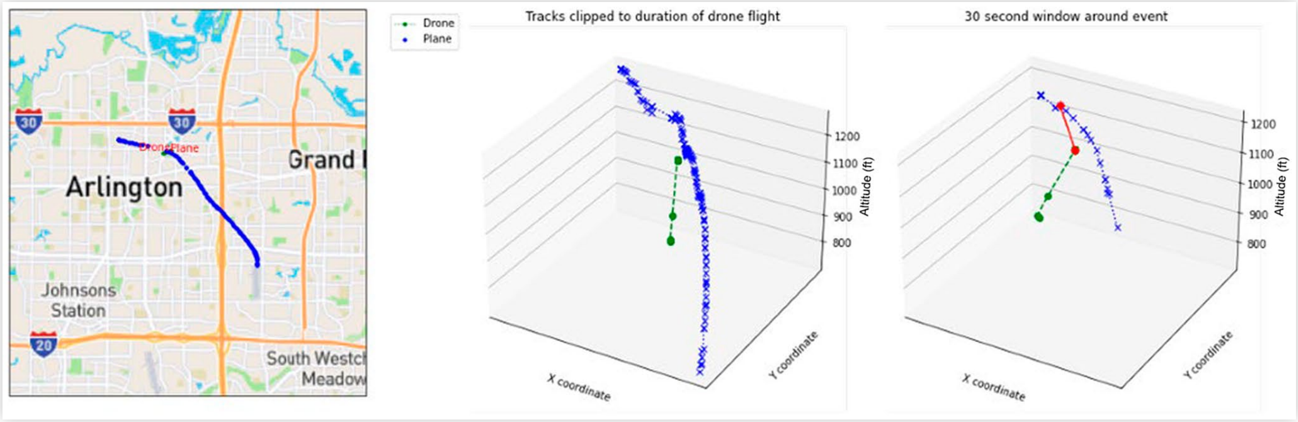
All of the seven helicopter encounters with sUAS occurred within 1.25 NM of a heliport. The mean distance between helicopters and the nearest heliport at the time of a drone encounter was 0.61 NM. DJI geofencing is also included around heliports in the DFW area, with most heliports appearing to be protected by Warning Zones, within a 500-meter radius (~0.27 NM) of the landing pad [33]. As previously indicated, DJI's geofencing *Warning Zones* do not restrict sUAS flight operations but provide the operator a warning message on the controller's user interface. The research team did not assess the location of the sUAS operator. Assuming that the sUAS operator was in a relative location to the helicopter-sUAS encounter, the operator would have received a warning message from a nearby heliport during only 29% (*n* = 2) of the helicopter encounters. Since the location of heliports is less obvious than airports or other aerodromes—as many heliport locations become hidden among the urban sprawl—this finding may provide justification for DJI to extend the radius of warning areas around heliports to enhance operator situational awareness of potential low-flying helicopter traffic. Moreover, helicopters are more likely to encounter sUAS operations as they are exempt from minimum safe altitude restrictions prescribed by 14 CFR §91.119(b) and (c) and ultimately share the same low-altitude airspace as sUAS operators [52].

In four of the seven encounters involving a helicopter (57.1%), the helicopter was being operated outside the area of the LAANC system. In all of those cases, the sUAS was being operated at an altitude well below the 400-foot AGL maximum, as required by 14 CFR §107.51(b) or 49 U.S.C. §44809(a)(6). Figure 11 highlights the closest encounter recorded between an sUAS and a helicopter, with a total separation of 230 ft.

5. Conclusions

From the available case study data, several clear trends emerged. In 96% of NMAC events (*n* = 23), the sUAS was operating in excess of the maximum permissible altitude for

FIGURE 11 Helicopter encounter with sUAS near The Ballpark in Arlington Heliport.



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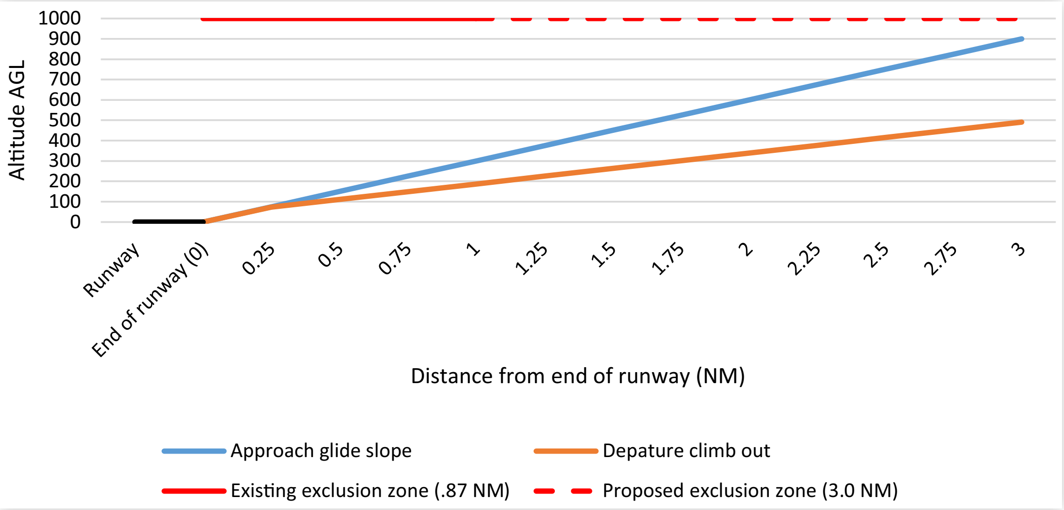
that area. This data suggests potential breaches of operator compliance with sUAS operational altitude limits codified in 14 CFR §107.51(b) and 49 USC §44809(a)(6), or in accordance with the LAANC UASFM airspace authorization restrictions. Successive encounters recorded between a single uncrewed aircraft and multiple air carrier aircraft in 2020 reveal the elevated potential risk posed by sUAS operations conducted along critical airport approach and departure corridors. Among the 10 NMAC events that occurred along an approach or departure corridor, all happened when the aircraft was operating at altitudes below 500 ft AGL.

5.1. Policy Implications and Recommendations

Due to the relatively high number of sequential NMAC events among air carriers along the final approach and departure paths, it may be prudent to provide additional protections to aircraft operating in these areas. During this study, 10 NMAC events involving air carrier aircraft occurred within 1.5 NM of a runway approach or departure corridor. Given these conditions, the research team suggests the FAA consider proposing regulatory guidance to extend runway exclusion zone protections from 1 SM from the runway end to 3.0 NM (~3.45 SM) from the runway end. According to FAA Order 8260.3, United States Standard for Terminal Instrument Procedures, "departure design criterion begins with the assumption of an initial climb of 200 ft/NM after crossing the Departure End of Runway at a height of at least 35 feet" [53, pp. 1–16]. This modification would provide extended protection of aircraft on a standard departure, allowing them to reach an altitude of at least 491 ft AGL before the end of runway exclusion zone protection. Based on a standard 3-degree glideslope, this change would also afford approaching aircraft protection beginning at approximately 900 ft AGL. These protections are displayed in Figure 12. Ultimately, these modifications would provide further

FIGURE 12 Proposed runway exclusion zone extension.



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protection for aircraft by prohibiting sUAS operations in approach or departure corridors where aircraft are operating at less than 500 ft AGL.

The research team further recommends that DJI consider extending the geofencing warning zone radius around heliports from 500 meters to 1.5 NM, which may provide sUAS operators further with situational awareness about nearby rotorcraft hazards. This recommendation is further reinforced because many heliport locations are not depicted on aeronautical sectional charts.

5.2. Recommendations for Future Research

The research team intends to conduct future sUAS-aircraft encounter studies at additional locations around the NAS to better understand contributing factors to NMAC events. These studies will be conducted in urban and rural areas, across various airspace and airport classes, and in regions of varied climate conditions.

Conflict of Interest

No conflicts with any of the authors exist.

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