ASSURE A45_A11L.UAS.87 – Shielded UAS Operations: Detect and Avoid (DAA) – Literature Review

October 1, 2021

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16. Abstract
The concept of shielded operations may serve as a mechanism for conducting certain Beyond Visual Line of Sight (BVLOS) operations that may be in close proximity to manned aircraft collision hazards. sUAS operations carried out near naturally occurring or man-made structures could serve as a mechanism to contain sUAS operations within a specific operational volume that essentially presents a shield to reduce the risk of a potential collision with a conventional aircraft. Title 14 of the Code of Federal Regulations (CFR) Part 91 requires aircraft operators to see and avoid other aircraft operating in the vicinity. Therefore, there may be a need to relax some DAA requirements to enable shielded operations. The purpose of this research is to investigate the concept of shielded operations and their associated risks. This research also aims to identify how shielded operations can be made safe; propose safe stand-off distances for carrying out shielded operations and explore whether shielded operations may allow DAA requirements to be relaxed.

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ABL	Atmospheric Boundary Layer
AGL	Above Ground Level
ALARP	As Low as Reasonably Practicable
AMOC	Alternate Method of Compliance
ANSI	American National Standard Institute
API	Application Programming Interface
ATP	Airline Transport Pilot
ATTCS	Automatic Takeoff Thrust Control System
BVLOS	Beyond Visual Line-of-Sight
C2	Command and Control
CFD	Computational Fluid Dynamics
CFI	Certified Flight Instructor
CFIT	Controlled Flight into Terrain
CFR	Code of Federal Regulations
CISA	Cybersecurity and Infrastructure Security Agency
CONOPs	Concept of Operations
COTS	Commercial Off-the-Shelf
CoW/A	Certificate of Waiver or Authorization
D&R	Durability and Reliability
DCP	Divert/Contingency Points
DE	Designated Examiners
DGO	Dynamic ground Object
DOC	Declaration of Compliance
FAA	Federal Aviation Administration
FTD	Flight Training Device
GCS	Ground Control Station
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HAA	Helicopter Air Ambulance
IFR	Instrument Flight Rules
IMU	Inertial Measurement Unit
JARUS	Joint Authorities for Rulemaking on Unmanned Systems
LAANC	Low Altitude Authorization and Notification Capability
LIDAR	Light Detection and Ranging
LPV	Localizer Performance with Vertical Guidance
LSA	Light Sport Aircraft
MAC	Mid-Air Collision
MHz	Megahertz
MOC	Means of Compliance
MOPS	Minimum Operational Performance Standards
NAA	National Aviation Authority
NAS	National Airspace System
NLSO	Non-Line-of-Sight

NMAC	Near Mid-Air Collision
NOA	Notice of Availability
NPRM	Notices of Proposed Rulemaking
OSO	Operational Safety Objectives
PIC	Pilot in Command
PPL	Private Pilot License
RPC	Remote Pilot Competency
RSL	Roughness Sub-Layer
RTCA	Radio Technical Commission for Aeronautics
RTK	Real Time Kinematics
SARP	Science and Research Panel
SDSP	Supplemental Data Service Provider
SGO	Static Ground Object
SLAM	Simultaneous Localization and Mapping
SMS	Safety Management System
SORA	Specific Operations Risk Assessment
SPS	Stand Positioning Service
sUAS	Small Unmanned Aircraft System
TC	Type Certificate
TCAS	Traffic Alert and Collision Avoidance System
TCO	Training Course Outlines
TFR	Temporary Flight Restriction
UA	Unmanned Aircraft
UAS	Unmanned Aircraft System
UBL	Urban Boundary Layer
UCL	Urban Canopy Layer
UOL	Urban Outer Layer
USC	United States Code
UTM	Unmanned Traffic Management
V2X	Vehicle-to-Everything
VFR	Visual Flight Rules
VLL	Very Low Level
VLOS	Visual Line-of-Sight
VO	Visual Observer

EXECUTIVE SUMMARY

Shielded operations present a potential avenue for conducting Beyond Visual Line of Sight (BVLOS) flight operations with unmanned aircraft systems (UAS) in a manner that reduces the likelihood of a traffic conflict with manned aircraft. However, the extent of the risk reduction offered through shielded operations is not well understood; leaving questions regarding what kind of Detect and Avoid (DAA) requirements may be needed as well as how close to an obstacle an UAS must operate to take advantage of shielding. This research seeks to address knowledge gaps that deter the successful implementation of shielded operations in certain BVLOS scenarios and inform the Federal Aviation Administration (FAA) of key aspects of operational risk and methods to take advantage of shielding as an operational risk mitigation. In addition, this research seeks to identify metrics for defining standoff distance from obstacles at which an unmanned aircraft (UA) must operate to take advantage of shielding.

This literature review serves as a foundational element of the ASSURE A45 research effort and provides a starting point for identifying key aspects of shielded operations, to include types of operations, an exploration of right of way rules, aircraft separation considerations, and more. To that effect, the literature review explores existing literature on shielded operations for the sake of identifying the current trends, definitions, and operational constructs. These trends, definitions, and operational constructs will drive further research while adding to the overall body of knowledge surrounding shielded operations.

One of the most significant findings was the scarce amount of literature surrounding shielded operations. The research team concluded that this was likely due to the novelty of the concept of shielded operations. However, the literature that was found identified several important elements of shielded operations that may influence general use cases, practical applications, operational constraints, and policy.

The researchers identified certain key elements affecting shielded operations. These elements consist of (1) wind and turbulence effects that may be detrimental to sUAS performance, particularly near buildings, (2) bird densities and behaviors near structures that may pose a collision risk, (3) GPS outages that may affect sUAS navigation, (4) electromagnetic interference may disrupt aircraft systems, (5) manned aircraft operations at low altitudes performing specific missions such as spraying, dusting and fish release, and (6) GPS navigation performance may be degraded by a combination of electromagnetic interference and GPS outages.

Shielded operations offer new avenues for approaching concepts surrounding liability and public perception. This is particularly true when considering the balance between potential safety gains and efficiencies from shielded operations when weighed against the liability that may be inherited when operating within close proximity to structures, particularly infrastructure elements that may be deemed critical. Finally, there are efforts by standards bodies to define performance requirements for DAA systems that could provide some level of mitigation for mid-air collisions in low-altitude airspace environments.

1 INTRODUCTION & BACKGROUND

The extensive growth of Unmanned Aircraft Systems (UAS) and unmanned aviation, in general, has groundbreaking implications for all associated stakeholders operating in the National Airspace System (NAS). Most notably, the existing rules and regulations that provide UAS operators with access to the NAS are grappling to withstand the demand generated by an increase in innovations and ever-widening applications in the sector.

The three key elements that contribute to the massive adoption of small Unmanned Aircraft Systems (sUAS) for commercial purposes have been: affordability, accessibility, and ease of operation (Kohler, 2017). Understanding the importance of this industry, the Federal Aviation Administration (FAA), in June of 2016, amended the Title 14 of the Code of Federal Regulations (CFR) to add Part 107, also called the sUAS rule, thereby opening the doors for commercial operations of sUAS weighing between 0.55 and 55 pounds. The introduction of the sUAS rule also made registration of UAS under Part 107 mandatory and required all Part 107 sUAS pilots to be remote pilot certified. The FAA has been following an "operations first" methodology to authorize UAS operations under the provisions of Part 107 and its associated exemptions (Federal Aviation Administration, 2020f). According to the Office of Aviation Policy and Plans – Federal Aviation Administration (2021a), the total number of commercial sUAS in the United States is forecasted to be around 835,000 by 2025.

With the ever-increasing number of sUAS flights in the NAS, most of which are concentrated in low-altitude airspace (400 feet above the ground), there is a need for the sUAS operating in such environments to exhibit a DAA capability to swiftly manage encounters with both manned aircraft and other sUAS. There is an industry-wide consensus among the stakeholders that the DAA capability has been one of the most important impediments in successfully implementing routine Beyond Visual Line of Sight (BVLOS) sUAS operations (Kopardekar et al., 2016).

Manned aircraft are constrained by regulation regarding their operation in close proximity to congested areas – e.g., cities, towns, and/or settlements, per 14 CFR §91.119. According to 14 CFR §91.119(b), manned aircraft are restricted to flying at no less than 1,000 feet above the highest obstacle and no less than 2,000 feet laterally from obstacles when over congested areas. Similarly, 14 CFR §91.119(c) requires manned aircraft to fly at no less than 500 feet above non-congested areas while remaining at least 500 feet from any person, vessel, vehicle, or structure. However, 14 CFR 91.119(d)(1) and (2) allow helicopters, powered parachutes and weight-shift aircraft to be operated at less than the prescribed altitudes of 14 CFR §91.119(a) and (b) if specific conditions are met, particularly the requirement to not create an undue hazard to persons and property on the surface. These regulatory constraints offer a potential segregation for sUAS from manned aircraft operations thereby reducing the likelihood of encountering manned aircraft. This helps to provide a conceptual foundation for shielded operations. While there has yet to be a widely accepted definition for shielded operations with quantitative metrics for its definition, the Civil Aviation Authority of New Zealand defines a shielded operation as one in which the "drone remains within 100 meters of, and below the top, of a natural or man-made object" (Civil Aviation Authority of New Zealand, 2019). Similarly, the FAA Drone Advisory Committee (DAC) qualitatively defines shielded operations as "flight within close proximity to existing obstacles and not to exceed the height of the obstacle" (Federal Aviation Administration, 2020c, pg. 31). To successfully help utilize shielded operations, to include BVLOS, this project aims to (1) determine the working balance between mitigating UAS hazards from low altitude manned aircraft, and (2) identify risks and methodologies to enable shielded operations in the NAS. To that end, this literature review endeavors to identify potential risks for operations in shielded environments and provide a comprehensive compilation of existing literature available for topics relating to shielded operations.

2 LITERATURE REVIEW

This literature review aims to provide a comprehensive foundation of research efforts that have been directed towards shielding operations. This report provides a consolidation of available literature to help better inform future tasks associated in this project which includes identifying shielding classes and analysis of DAA requirements. Additionally, this report summarizes the current state of research in related topics such as integration of UAS into NAS, right-of-way rules, and see and avoid requirements.

The literature review is comprised of the following sections:

- Types of Operations
- Right of Way Rules
- See and Avoid Requirements
- Integration of UAS into NAS
- Expanded and Non-Segregated Operations
- Aircraft Separation
- Low-Altitude Aircraft Operations
- Shielded UAS Operations
- Legal Ramifications

Before proceeding to these sections, a discussion of terminology is helpful. In a Command and Control (C2) context, the term masking can indicate communication disruption between the Ground Control Station (GCS) and the Unmanned Aircraft (UA) owing to either electronic interference or line-of-sight obstructions. This aligns with usage of this term for disruption of the global positioning system (GPS) signals in urban environments (Isik, Hong, Petrunun, & Tsourdous, 2020) and relates to the concept of electronic masking in military applications (Department of the Army, 2019). Additionally, in a C2 context, the term shadowing can indicate communications disruption owing to the airframe (Kerczewski, Griner, Bishop, Matolak, & Wilson, 2017). Such communication disruptions are expected to occur with relatively large UAS and are not expected with sUAS. Thus, the C2 context for the term shadowing may not apply for sUAS and creates significant complexities to derive common terminology that adequately captures operational nuances. Therefore, a recommended output of this research is to collectively derive definitions with the most appropriate meaning for the aforementioned terms based upon existing literature and FAA insight. The research team will compile this information into a standalone document for FAA and broader review. Such definitions would undoubtedly serve the FAA in terms of rulemaking and advancing UAS policy. The DAC definition may serve as a qualitative starting point, but further research is required to arrive at quantitative recommendations that will enable effective rulemaking and policy.

2.1 Types of Operations

Chapter 1 Title 14 of the CFR (herein 14 CFR) provides regulations for the FAA (eCFR, 2021). This is divided into the following subchapters, with some "Parts" identified for illustration:

- Subchapter A: Definitions and General Requirements
    - Part 5: Safety Management Systems
- Subchapter B: Procedural Rules
- Subchapter C: Aircraft
- Subchapter D: Airmen
    - Part 61: Certification: Pilots, Flight Instructors, and Ground Instructors
- Subchapter E: Airspace
- Subchapter F: Air Traffic and General Operating Rules
    - Part 91: General Operating and Flight Rules
    - Part 107: Small Unmanned Aircraft Systems
- Subchapter G: Air Carriers and Operators for Compensation or Hire: Certification and Operations
    - Part 119: Certification: Air Carriers and Commercial Operators
- Subchapter H: Schools and Other Certified Agencies
- Subchapter I: Airports
- Subchapter J: Navigational Facilities
- Subchapter K: Administrative Regulations
- Subchapters L-M: *Reserved*
- Subchapter N: War Risk Insurance

The relation of this research effort to Part 61 and Part 91 are discussed in the following subsections. From the above list, this research is expected to provide potential guidance for topics involving SMSs (Safety Management Systems; Part 5), Subchapter C (airworthiness) for required performance with shielded operations, Part 61 (Certification: Pilots, Flight Instructors, and Ground Instructors), Part 91 (General Operating and Flight Rules), Part 107 (Small Unmanned Aircraft Systems), and Part 119 (Certification: Air Carriers and Commercial Operators). It is not suggested that this research will impact these portions of the CFR. Rather, this simply identifies topical correspondence.

2.1.1 Part 61 – Certification: Pilots, Flight Instructors, and Ground Instructors

14 CFR Part 61 is described in detail by Waller et al. (2020). Part 61, along with Parts 121, 135, 141, and 142, defines the rules for manned aircraft pilot certification. Under Part 61, the categories are:

- Student Pilot Certificate
- Recreational Pilot Certificate
- Private Pilot Certificate
- Commercial Pilot Certificate
- Airline Transport Pilot Certificate
- Certified Flight Instructors Certificate
- Additional Ratings (added onto already-issued pilot certificates)

For shielded operations, certain proficiencies in addition to those outlined in Part 61 might be required. These include any associated with piloting a UAS and associated with operating supporting systems, such as DAA systems, geofencing systems, contingency procedures etc.

2.1.2 Part 91 – General Operating and Flight Rules

14 CFR Part 91 describes general operating and flight rules for aircraft that operate in the NAS. As such, 14 CFR Part 91 outlines the baseline regulatory requirements for aircraft operation, including provisions for general applicability, flight rules, equipment requirements, maintenance requirements, and more. Of particular interest to shielded operations are elements of 14 CFR Part 91 that specify aircraft right of way rules (within 14 CFR Part 91 Subpart B – Flight Rules). As specified in 14 CFR §91.113, right-of-way rules provide basic requirements for pilots to see and avoid other aircraft, including head-on trajectories, overtaking scenarios, and in other situations where specific rules help mitigate the risk of Mid-Air Collisions (MAC). For shielded operations, right of way rules may be significant since current regulations, as specified in Part 107, require that sUAS yield to all manned traffic, regardless of the scenario.

2.2 Right of Way Rules

Aircraft Right-of-Way Rules are clearly defined in 14 CFR §91.113 "Right-of-way rules: Except water operations." 91.113 is concise and divided into seven subsections. A general description is provided for weather conditions [Instrument Flight Rules (IFR) and Visual Flight Rules (VFR)] and "…vigilance shall be maintained by each person operating an aircraft so as to see and avoid other aircraft." This is the only mention of see-and-avoid in the rule. When another aircraft is given right-of-way, "the pilot shall give way to that aircraft and may not pass over, under, or ahead of it unless well clear." An aircraft in distress is given right-of-way over all other aircraft. Convergence of aircraft of the same class is addressed as well as a 'hierarchy' by class of vehicles. Course alteration directions are provided for approaching head-on, overtaking, and landing.

The right-of-way rules in 91.113 do not apply to operations of an aircraft "on" water. Note that this is not above water, but "on" the water. An aircraft on the water would then follow "on" water operations covered under 14 CFR Section 91.115 "Right-of-Way Rules: Water Operations" and possibly other applicable maritime navigation rules like the U.S. Department of Transportation

United States Coast Guard NAVIGATION RULES INTERNATIONAL—INLAND (COMDTINST 16672.2 Series). The sub-sections below highlight research related to UAS sightings in low altitude environments and UAS right-of-way rules.

2.2.1 UAS sightings in low altitude environments

Two articles were reviewed that provided information related to UAS sightings in low-altitude environments. The first, Wallace et al., (2019) provides a detailed assessment of how well pilots may or may not see sUAS operating around airports. From the Aviation Safety Reporting System (ASRS), in 2019 there were over 100 documented UAS reports. This clearly shows a significant number of events. In 2018, "nearly 22.8% of all UAS sighting reports" were during the final approach phase where the potential is the highest for an issue. Final approach was "defined as the last segment of a flight, generally extending 5 NM (or more, platform-dependent) from the airport to touchdown" (Wallace at al., 2019). Of the FAA sightings reported by Wallace et al (2019), they found that "a disturbing and increasing volume of sightings both around and in the vicinity of the final approach corridor. This could be the result of more complete reporting, a true increase in unauthorized sUAS activity around airports, or both." What makes this more significant is that the pilot generally has a smaller defined Field of View due to the requirements of the final approach. Because of the requirements related to landing, and concentration toward the runway, a smaller volume of airspace may be observed. The problem statement from this research is mentioned below,

> The threat of a midair collision between a sUAS and manned aircraft is heightened during the final approach phase of flight, as aircraft transition from higher-altitude airspace into the low altitude arena now populated by sUAS. Absent benchmarks for electronic detection and sense and avoid systems, pilots rely primarily on visual senses and proper visual scanning techniques to ensure a positive separation and collision avoidance from sUAS platforms during this segment of flight. (Wallace et al., 2019).

Several different articles were cited in the supporting literature review (Kephart & Braasch, 2010; Maddocks and Griffitt, 2015; Loffi, Wallace, Jacobs, & Dunlap, 2016; and Wallace et al., 2018), which focused on manned-on-manned encounters, Visual Observer (VO) observation of targets and UAS, UAS spotting from manned aircraft, and strobe light siting studies respectively. All studies focused on the challenges of spotting UAS under various conditions. The strobe light detection during daytime showed that only 7.7% of the time (3 of the 39) the sUAS was successfully detected and were generally seen at much further distances.

> During each approach, a sUAS performed scripted maneuvers on a perpendicular axis at a distance of 1,000 ft from the airfield along the approach corridor. All UAS flights were conducted at 50 ft above ground level (AGL). The approach Minimum Safe Altitude afforded a 200-ft safety margin between the unmanned aircraft and manned aircraft. (Wallace et al., 2019).

It should be noted that this is less than the allowable margins now used for testing. For this research, four different random encounters were used:

- Control Pass – No UAS in flight (implemented to screen false positive sightings).

- Static-Starboard – UAS flew out to 1,000 feet north of the airfield and performed a stationary, hovering maneuver orientated 100 feet east of the approach course.
- Static-Port – UAS flew out to 1,000 feet north of the airfield and performed a stationary, hovering maneuver orientated 100 feet west of the approach course.
- Maneuvering – UAS flew out to 1,000 feet north of the airfield and transitioned laterally, crossing back and forth up to 200 feet left and right of the approach course (Wallace et al., 2019).

The final number of sightings was overall very low. For each type of encounter, the results were as follows:

- Control Pass – 0 out of 10
- Static-Starboard – 1 out of 10
- Static-Port – 2 out of 10
- Maneuvering – 4 out of 10
- Random Pass – 5 out of 10 (Wallace et al., 2019)

This represents 12 out of 40 passes where the sUAS was identified, with 3 out of 20 static, and 9 out of 20 when the sUAS was moving. It is inherent that movement of the sUAS aids in identification. The static sUAS were seen at a much closer range than the moving sUAS. "The mean detection range for moving sUAS (excluding null sightings) was 1,593.3 feet," whereas the maximum was 2,324 ft (Wallace et al., 2019). "The mean detection distance for static sUAS targets was 746.7 feet, nearly half the distance of moving sUAS detections" (Wallace et al., 2019). Interestingly, the moving targets were seen toward the center of the pilot's vision, and the "static sUAS targets were detected more peripherally." The authors note that the experimental conditions "likely improved sightings beyond what would normally be realized in operational settings" (Wallace et al., 2019). They also stated that "an optical illusion is created due to the tendency of observers to compare the objects as relatively comparable in size subconsciously" (Wallace et al., 2019). The researchers offer two recommendations that address the challenges from both sides. The authors mention that for pilots, there is a need for training regarding scanning techniques to prepare the pilots to adequately employ such techniques to maximize visual detection. "This could also include an effort to make manned pilots more aware of the need for vigilant scanning to detect unmanned aircraft when flying at low altitude or in areas of known sUAS operations" (Wallace et al., 2019). Moreover, the authors noted that the sUAS operator should remain aware of the challenges associated with pilots' ability to detect their sUAS. Additionally, "the sUAS Remote Pilot should take steps to maximize the conspicuity of their platforms, such as using high-contrast UAS colors, performing regular maneuvers, or other strategies to make their operation as visible as possible" (Wallace et al., 2019).

Some of the key take-aways from Wallace et al. (2019) that could be useful to this study are summarized below:

- One key assumption noted in this study was that the positional and altitude information made available from the Cessna C-172/S avionics suite and the DJI Phantom IV telemetry was believed to be accurate. However, subsequent research, notably from the A18 DAA study, has shown that this may or may not be the case depending on the system used because of system errors. This consideration is noted to stress the importance of defining the accuracy for testing.

- All the flights in the study were conducted between 7:30 AM and 12:30 PM local time. The use of such a fixed time period may have impacted the results.
- The collection of local weather information helped determine the environmental impact on visibility. For instance, there was decreased visual clarity due to the low-lying fog on July 8th-10th. In contrast, the absence of such a phenomenon on July 11th contributed to better sighting rates.
- As previously noted, the sighting rate was not high:
    - 12 sUAS detections out of 40 possible events (Overall Detection Rate: 30%)
    - 3 out of 22 possible static sUAS were detected
    - 9 out of 18 possible moving sUAS were detected
- Moving sUAS have a better detection rate (50%) than static sUAS (13.6%).
- Static sUAS have a lesser mean detection range (747 ft) than moving sUAS (1593 ft).
- Moving sUAS targets were detected exclusively towards the center of the pilot's vision.
- Static sUAS targets were prone to be detected more peripherally.
- Pilot participants noted that high contrast between the sUAS and the background aided detection.
- UAS are more likely to be visible from the front and left aspects.

Based on the research, the number of reports (more than 100 annually) is likely significantly underrepresenting potential UAS incidences.

The second article was a continuation of the research by Loffi (2021). Stating the significance of the problem, they indicate that "of the 9,596 UAS Sighting Reports recorded by the FAA, at least 826 (8.61%) were conducted outside of daylight hours" (Loffi 2021). Of the 826 sightings, 64 occurred prior to the start of morning civil twilight, 19 occurred during either morning or evening civil twilight, and 762 occurred after evening civil twilight (Loffi et al., 2021). The prior research that provided a framework for pilot detection of UAS at night was performed by Williams and Gildea (2014) who "identified eight factors that complicate visual detection to potential collision threats". These included:

- Small Visual Angle,
- Cockpit Obstructions,
- Visual Acuity,
- Visual Accommodation,
- Poor Contrast,

- Complex Backgrounds,
- Lack of Apparent Motion, and
- Visual Search Requirements.

Many of these align with the findings from the Wallace (2019) study.

Several other lighting studies, nighttime sUAS visibility studies, nighttime UAS visibility flight testing, and daytime UAS detection studies were referenced. These included USAF (1976), Stevenson et al. (2015), Dolgov (2016), Kephart and Braasch (2010), Maddocks and Griffitt (2015), Loffi (2016), and Wallace (2018). The findings from these studies suggested that "under near-optimal viewing conditions, it is easier to detect and track manned and unmanned aircraft at night than during the day" (Dolgov, 2016).

In the 2021 tests by Loffi and colleagues (Loffi et al., 2021), "during each approach, a sUAS performed scripted maneuvers on a perpendicular axis at a distance of 1,000 feet from the runway threshold along the approach corridor. All UAS flights were conducted at 42 m (approx. 137 feet) AGL." All UAS were fitted with a strobe with a reported visibility of at least 3 miles. There were five different encounters flown (including one control) as follows:

- Pass A – Hover port side of aircraft (East side of Runway 17)
- Pass B – Hover starboard side of aircraft (West side of Runway 17)
- Pass C – Traverse at an oblique angle on the port side of the aircraft (East of Runway 17)
- Pass D – Traverse at an oblique angle on the starboard side of the aircraft (West of Runway 17)
- Pass E – Control Pass, no drone flown (Loffi et al., 2021).

Like the previous testing, the "Geospatial data for aircraft and UAS were presumed to be accurate" (Loffi et al., 2021), which may or may not be a good assumption as noted previously. It is worth noting that all 10 pilots who participated in this study were aged 18 to 29. It is not known if this bias toward younger pilots has any impact on the data and is only noted for reference. Light pollution estimation was included in the data for reference with no real conclusions drawn. "Cumulatively, participants spotted the UAS during a total of 12 of the available 40 passes yielding a success rate of 30 percent, there were no reported UAS sightings during the control pass" (Loffi et al., 2021). A breakdown of the sightings is as follows:

A. Hover PS (2 out of 10),

B. Hover SS (4 out of 10),

C. Traverse PS (1 out of 10), and

D. Traverse SS (5 out of 10).

It is of note that "Participants had equal success spotting both the moving and hovering UAS, with an overall success rate of 30 percent (n = 6)" (Loffi et al., 2021). The hovering UAS were spotted at an average range of 1,705.8ft and a median of 1,474ft, whereas moving UAS were spotted at an average range of 2,555.8ft and a median of 2,579.5ft (Loffi et al., 2021). Like the previously noted research, the port side of the aircraft was more difficult for the pilots for sighting the UAS.

> Participants successfully spotted the UAS during only 20% of hovering passes and 10% of traversing passes, when the UAS was oriented on the port side of the aircraft. Conversely, the participants spotted the UAS during 40% of hovering passes and 50% of traversing passes, when the UAS was oriented on the starboard side of the aircraft (Loffi et al., 2021).

Range estimations were also made, and "participants underestimated the true distance to the sUAS by a mean of 883 feet, and a median of 940 feet" (Loffi et al., 2021). In only 4 of the 12 sightings, the aircraft was identified in time to make an avoidance action. Most identifications occurred after the aircraft had passed the UAS position. Post-flight, one pilot questioned the validity of the sightings and that they may have been from other sources. This is consistent with the additional observations that there was confusion with the airport lighting or approach lighting systems and the orientation of the UAS. The percentage of the sighting was 30%, there was no difference between the static and moving UAS detection, and elevated detection rates occurred on the starboard side of the aircraft.

This research concluded that "the participant's knowledge of the experimental conditions likely enhanced their external scanning vigilance, indicating that even this finding may be inflated" (Loffi et al.,). The research also found that during normal flying conditions at night, the pilot flying would be unlikely to spot a sUAS with enough time to conduct successful evasive maneuvers. "Moreover, this experiment utilized a relatively slow general aviation aircraft as a testbed, meaning that a faster-moving aircraft crew would be even less likely to successfully evade a sUAS during a nighttime approach due to the compressed response timeline" (Loffi et al., 2021).

2.2.2 Current research regarding UAS right-of-way rules

It is noted that UAS are not specifically listed in the 14 CFR §91.113 right-of-way rules. In 14 CFR §107.37, "Operation near aircraft; right-of-way rules" clearly puts UAS at the bottom of the 'hierarchy' in stating the following:

> (a) Each sUAS must yield the right of way to all aircraft, airborne vehicles, and launch and reentry vehicles. Yielding the right of way means that the sUAS must give way to the aircraft or vehicle and may not pass over, under, or ahead of it unless well clear.
>
> (b) No person may operate a sUAS so close to another aircraft as to create a collision hazard.

CFR §107.51 defines the operating limitations for sUAS. In addition to 14 CFR §91.111, 14 CFR §91.113, 14 CFR §91.115, and 14 CFR §107, the Pilot in Command (PIC) and team have the responsibility to comply with 14 CFR §91.119 "Minimum Safe Altitudes: General" and 14 CFR §91.155 "Basic VFR Weather Minimums". With these definitive guidelines that UAS are at bottom of the 'hierarchy', no current research was identified that explores any changes to this or any hierarchy among UAS sizes and types.

2.3 See and Avoid Requirements

As previously noted, in 14 CFR §91.113 "Right-of-way rules: Except water operations," the only mention of see-and-avoid in the rule is "… vigilance shall be maintained by each person operating an aircraft to see and avoid other aircraft."

2.4 Integration of UAS into the NAS

The successful integration of UAS into the NAS entails operating UAS and manned aircraft simultaneously in the same airspace employing identical Air Traffic Management (ATM) systems and protocols. This integration exercise represents a major component in the Next Generation Air Transportation System (NextGen), the effort spearheaded by FAA to revamp the US Airspace system, thereby making flying safer and more efficient (Joint Planning and Development Office Washington DC, 2012). The present NAS environment was created primarily for utilization by manned aircraft. Although many of the same protocols and concepts apply to UAS, there are significant differences in technological maturity, capability, acceptance, and operational experience. In a mixed-equipage operational airspace, performance disparities between UAS and manned aircraft may constrain NAS capacity. The essential need for unmanned aircraft to have less restrictive access to the NAS is being driven by the desire to utilize UAS for national security, defense, scientific research, emergency management, and other civil applications.

The commercial UAS fleet will likely be around 835,000 by 2025, a number which represents 1.7 times the existing number of commercial sUAS (Office of Aviation Policy and Plans - Federal Aviation Administration, 2021a). Another key development highlighted in the cited study is the total number of remote pilot certificates awarded for commercial sUAS operations. Around 206,347 remote pilot certifications have been awarded as of December 2020, up ~47,000 from the same time period the previous year. Starting with a base of 206,347 remote pilot certificates issued in 2020, successful issuance of almost 350,000 remote pilot certifications is expected in the next five years, resulting in a 1.7-fold increase in employment connected with commercial sUAS operations.

Some of the key FAA accomplishments in the integration of UAS into NAS are described below.

2.4.1 Key Integration Accomplishments

2.4.1.1 Small UAS Registration

In December 2015, the FAA published the Interim Final Rule on *Registration and Marking Requirements for Small Unmanned Aircrafts* based on the recommendations of The Registration Task Force (Federal Aviation Administration et al., 2015). This rule established the need to incorporate a web-based registration system for sUAS weighing between 0.55 pounds and 55 pounds. The advantages of the registration process were two-fold: (1) it provided a method to link an unmanned aircraft to its owner, and (2) it educated users to safely operate UAS in the NAS (Federal Aviation Administration, 2015). The registration process enabled the FAA to use the UAS registration database to notify registrants of important safety information and temporary flight restrictions during natural calamities and other hazards.

2.4.1.2 Small UAS Rule

In June 2016, the FAA finalized the operational rules for commercial applications of sUAS titled "*Operation and Certification of Small Unmanned Aircraft Systems"* codified in 14 CFR – Part 107 (Federal Aviation Administration et al., 2016). The introduction of the sUAS rule enabled routine commercial operations for sUAS (55 pounds or less) to be conducted under 400 feet in daylight within visual line of sight of the pilot and not over people (Federal Aviation Administration, 2016). Additionally, 14 CFR Part 107 also brought forth a new UAS-specific airman certificate, called the Remote Pilot Certificate, which could be obtained by passing an aeronautical knowledge examination at an FAA-approved knowledge testing center (Wallace, 2016).

2.4.1.3 UAS Test Sites

The FAA formulated the UAS Test Site Program in December of 2013 to designate six test sites to help support its UAS integration efforts. The test sites have been carrying out flight tests to validate the safety standards of commercial and public UAS (Federal Aviation Administration, 2013). The data gathered from the test sites have been helping the FAA to put regulatory standards and operational procedures in place for commercial and civil applications of UAS. The FAA Extension, Safety, and Security Act of 2016 mandated the induction of another test site into this program (Federal Aviation Administration, 2016).

2.4.1.4 Section 333 Exemption

From 2014 to 2016, the Section 333 exemption of the FAA Modernization and Reform Act (FMRA) was employed to grant commercial UAS operations authorizations on a case-by-case basis. This provision was replaced by the finalization of the small UAS rule in August of 2016.

2.4.1.5 Research and Development

The successful introduction of the Consolidated Appropriations Act of 2014 helped the U.S. Congress in tasking the FAA to establish rules and regulations to increase the potential growth of the commercial UAS market. In May of 2015, the FAA chose the Alliance for System Safety of UAS through Research Excellence (ASSURE) as its Center for Excellence (COE) for UAS. The COE was tapped to conduct extensive research in developing technologies and standards that would positively assist the FAA in its efforts to safely integrate the UAS into NAS (Stansbury & Robbins, 2018).

2.4.2 Benefits

The benefits of successfully integrating the UAS into the NAS would be profound for the aviation industry. The civil application of UAS has the potential to revolutionize old markets and create new ones. A distinctive trait that sets apart the use of UAS from manned aircraft is the operational flexibility it provides, and the lower capital and lower operating costs associated with it. Civil UAS can be tapped to successfully carry out missions that are considered too 'dull and dirty' for manned aircraft. 'Dull' refers to the attribute of the UAS to stay airborne for extensively long hours. The ability of the UAS to be rapidly deployed in disaster regions or search and rescue missions is referred to as a 'dirty' mission (Euteneuer & Papageorgiou, 2011). The complete integration of UAS into the NAS brings with it an abundance of economic benefits. Some of the key enablers of the economic viability of the UAS market is that it offers new business-model provisions such as the pay per use scheme (Ramalingam et al., 2011). Also, since UAS can successfully carry out certain missions that are considered potentially dangerous to human pilots, the political and human cost in the event the aircraft is lost is less.

As the military applications of UAS are constantly increasing, it is also opening doors for commercial applications of UAS. It is estimated that because of the ever-increasing onset of awareness and technological maturity, the civilian application of UAS is going to increase multifold. The most popular civilian applications of UAS include short-range surveillance and photo/videography. According to Cohn et al. (2017), drones capable of performing BVLOS long-range surveillance may enter the market later than the short-range ones. One key market area where the introduction of commercial UAS will revolutionize the functioning of the market is the last-mile logistics industry. Jenkins et al. (2017) ascertained that of the almost 100 million products being sold online every day, 86% to 91% weigh less than 5 pounds (2.267 kilograms). In their optimistic forecast, the authors predict that such less-weight deliveries can be accomplished utilizing UAS for half of the existing operational delivery costs. This constitutes a significant share in the last mile delivery market segment, which is valued at $45.09 billion as of 2021.

2.4.3 Complexities

The following section describes some of the key technological and public policy challenges identified that can detriment the progress of UAS integration.

2.4.3.1 Technology Challenges

2.4.3.1.1 Detect and Avoid (DAA)

According to 14 CFR §91.113, a pilot is responsible to see and avoid other aircraft and to remain "well clear." In the case of BVLOS UAS operations, this functionality is replaced by sensors that function to detect other aircraft. A safe and robust DAA system is vital to ensure that a UAS operating in the NAS is well clear of all hazards, including manned aircraft and other UAS (Federal Aviation Administration, 2020f). It also ensures the facilitation of routine BVLOS UAS flights without the aid of visual observers. According to the research from National Academies of Sciences, Engineering, and Sciences (2018), a UAS system must demonstrate an equivalent level of safety to that of a manned aircraft to be certified. Despite the difficulty in fully defining this standard, implementing performance evaluation approaches comparable to those used in manned aircraft systems such as the Traffic Alert and Collision Avoidance System (TCAS) could help develop a better safety argument. Current research efforts in this paradigm are focused on designing DAA systems that are operational and airworthiness-approval ready and are also compliant with 14 CFR Part 91.113 right-of-way rules. Other avenues of current research investigations are focused on the study of the visual compliance problem of UAS DAA systems and the process of sensor fusion when multiple sensors are employed for remaining well clear (Maddalon et al., 2021). Finally, due to the non-homogenous nature of UAS sizes and configurations, there is a need to investigate the scalability constraints of DAA systems used in those UAS to enable safe and robust integration of UAS into the NAS (Hampton, 2014).

2.4.3.1.2 Command and Control (C2)

The command-and-control link, which serves as a vital connection between the UAS and its pilot, is essential for the pilot to be able to properly control the UAS during normal and emergency situations. Outlining the importance of the C2 link in a UAS operation, Ali and Nguyen (2016) report that the C2 link is utilized to transmit important telemetry information such as altitude, airspeed, and position. This vital information assists the pilot in maintaining control of the UAS system in a wide variety of operational schemes including complying with ATC instructions, keeping away from incoming traffic, and steering clear from bad weather conditions. To give a perspective on the current C2 landscape, Ramsey (2021) states that the present C2 infrastructure consists mainly of hobby-grade equipment, unlicensed frequencies, point-to-point systems that are not scalable, and re-purposed cellular networks. Future applications for UAS such as cargo transportation, industrial surveillance, and search and rescue missions are directly dependent on BVLOS which is the key enabler, and a reliable C2 link is a primary facilitator for such BVLOS operations.

Current research efforts are directed to assessing if the Radio Technical Commission for Aeronautic (RTCA) Minimum Operational and Performance Standards (MOPS) based radio spectrum are safe for use on all sUAS (Kerczewski et al., 2017). Other avenues of research focus are the potential impact of an electromagnetic interference environment on sUAS C2 link performance and the impact of a loss of radio links. According to Kerczewski et al. (2017), commercial LTE networks and ISM band line-of-sight links are two of the key communications links under consideration for Unmanned Traffic Management (UTM) C2. Since the traditional commercial network end-users on the ground and the sUAS in the air will share the same LTE communications network, it poses a significant risk prospect. There's also a need to examine network service priority in the case of unexpectedly strong demand, which could lead to service interruptions and dropped links. Also, research is warranted for contingency and emergency scenarios to gauge the response of a UAS system when the command link is lost. This will further drive the endeavor to establish standards for vulnerability analysis of critical UAS communications (Kerczewski, Apaza, Downey, Wang, & Matheou, 2018).

2.4.3.1.3 Spectrum Management

Many regulatory and standards bodies such as International Telecommunication Union (ITU), International Civil Aviation Organization (ICAO), and Federal Communications Commission (FCC) are working with the FAA and RTCA to ensure the safe and efficient use of radio spectrum resources. These major stakeholders are collaborating to build and refine the regulatory framework that supports the wireless communications demands for UAS operations. At the 2012 World Radio Conference, the ITU allocated a new frequency band – the C-Band 5030-5091 MHz for Aeronautical Mobile (Route) Service to support Line-of-Sight UAS Control and Non-Payload Communications (CNPC) Operations. According to Box and Globus (2011), Radio CNPC are vital for the successful integration of UAS into the NAS. To support CNPC's link and bandwidth requirements, it is highly necessary to allocate spectrum resources. According to a report from the International Telecommunication Union (ITU, 2009), the terrestrial spectrum CNPC link requirement would be on the order of 34 MHz and the satellite spectrum CNPC requirement would be around 56MHz.

The Commerce Spectrum Management Advisory Committee (2021) points out that although there is some ongoing work in the development of regulations for UAS CNPC links, there is no consensus among international bodies in the name and definition of these CNPC links. The study further states that the implementation of CNPC links for UAS can be accomplished in two ways: CNPC link systems specifically designed from the start for UAS and existing link systems that can be adapted to suit certain UAS operational requirements. The report states that the FCC is analyzing two aeronautical allocations for domestic UAS CNPC spectrum rules: 960 – 1164 MHz and 5030 – 5091 MHz. Although the FAA wanted to approve CNPC links in the 960 – 1164 MHz range, it has been reluctant to do so owing to concerns about interference to navigation and surveillance systems. The evolution of different types and sizes of UAS has brought with it the need to introduce a reliable spectrum resource for communication. Primary research foci in this area are directed at mitigating interference in the communication spectrum and at maximizing the sharing of the allocated spectrum based on preferential order (Kakar & Marojevic, 2017).

2.4.3.1.4 Standards Development

According to Public Law 104-113, the National Technology Transfer and Advancement Act of 1996 (Public Law 104-113: National Technology Transfer and Advancement Act of 1995, 1996), the Federal Government is required to lean on industry consensus standards where it is practical to do so. This is true for UAS as the use of industry consensus standards can support rulemaking efforts and help to translate sponsored research into rulemaking while promoting safety and reliability (Foltz et al., 2019). As such, industry consensus standards will play an important role in safely extending operations of UAS in the NAS beyond current regulatory limitations.

To trace the current status of standards development for UAS, the Standardization Roadmap for Unmanned Aircraft Systems Version 2.0 was published by The American National Standards Institute (ANSI) (ANSI, 2020). This roadmap outlines standardization efforts across a broad spectrum of international standards bodies, and it identifies key gaps in standardization efforts where additional focus is required. More importantly, the ANSI Standardization Roadmap for Unmanned Aircraft Systems identifies subject areas between recognized standards bodies such as the American Society for Testing and Materials (ASTM) International and the RTCA to prevent duplication of effort. At the time of this literature review, multiple standardization efforts are underway from many standards bodies. Of particular interest are working groups from RTCA and ASTM International that are deriving standards for DAA equipment and system airworthiness, respectively.

The SC-228, Minimum Performance Standards for Unmanned Aircraft Systems, was introduced by RTCA in May of 2013 (RTCA, 2013). This established the effort to develop MOPs for DAA systems and C2 links. Similarly, ASTM International published ASTM F3442/3442M-20 "Standard Specification for Detect and Avoid System Performance Requirements" that outlines functions and performance requirements for UAS DAA systems. However, it is important to note that the ASTM F3442/3442M-20 is limited in scope to UAS with a wingspan of less than or equal to 25 feet with operating speeds below 100 knots (ASTM International, 2020a). It is also worth noting that a complementary standard to ASTM F3442/3442M-20, being produced by ASTM WK62669 New Test Method for Detect and Avoid (ASTM International, 2018), is currently in development that will define test methods for DAA systems that are pertinent to sUAS BVLOS operations and that fall within the scope of ASTM F3442/3442M-20.

In addition to DAA, type certification and airworthiness represent challenges, particularly for sUAS, as there is often a high degree of variability in their design, configuration, construction, and performance. As such, standardizing a mechanism for type certification and airworthiness has presented numerous hurdles, both for the FAA and standards bodies (Clothier, Palmer, Walker, & Fulton, 2011). However, the FAA has adopted a performance-based approach to airworthiness and type certification for sUAS (or low-risk UAS) that emphasizes demonstrations of fundamental levels of durability and reliability at the system level, scaling to the level of risk (Johnson & Foltz, 2019). The process, known as Durability and Reliability (D&R), enables "…applicants [to] demonstrate that their UAS are reliable, controllable, and safe, and provide the FAA basic assurance that the aircraft will operate as intended" (Federal Aviation Administration, 2020b).

To facilitate the use of the FAA's D&R certification path, ASTM International published a standard, ASTM F3478-20 *Standard Practice for Development of a Durability and Reliability Flight Demonstration Program for Low-Risk UAS under FAA Oversight*, that provides guidance to applicants who wish to pursue airworthiness and type certifications for small, low-risk UAS that meet the criteria for the FAA's D&R type certification path. While D&R does represent a path forward for sUAS airworthiness and type certification, it does not yet capture performance and/or test requirements for DAA systems, as listed in the description of as standard currently listed by ASTM International (ASTM International, 2020b). As such, D&R is a potential avenue for demonstrating the reliability of other aspects of the UAS other than DAA.

2.4.3.1.5 Airspace Management

Another key challenge that hinders the successful integration of UAS into NAS is that the current air traffic management infrastructure may not be able to scale up to meet the demands of the envisioned volume of non-homogenous UAS operating in the NAS (Vascik & Hansman, 2018). The underlying goal behind creating a UTM system is to help enable safe and secure low-altitude UAS operations by providing a range of services such as dynamic geo-fencing and separation management (Kopardekar, 2014). UTM will help support routine BVLOS UAS operations, where there are no air traffic services. The UTM concept is envisioned to be interoperable with existing air traffic systems to facilitate safe and robust operations.

Some of the key gaps identified that, when addressed, can help in the success of this proposed technology avenue are listed below:

- Airspace classification: The current airspace classification schema may not be suited to support BVLOS operations.
- Airspace access: The rules and regulations required for providing equal access to airspace still need development.
- Liabilities: Liability and insurance regulations for UTM providers need to be formulated.
- Certification: Certification of the UTM system and the principles of airworthiness for UAS operating in the NAS needs to be revisited.

Other gaps that can detriment the progress of the UTM architecture are data standards, connection interface between UTM and ATM, data recording, and alerting systems.

2.4.3.2 Public Policy Challenges

2.4.3.2.1 Safety and Education

With the growing number of UAS integration efforts, a UAS piloted by someone with little or no aviation knowledge may now fly in the same airspace as a manned aircraft that requires a qualified pilot and an airworthiness certificate to operate. This in turn increases the odds of a potential conflict between manned and unmanned aircraft (Federal Aviation Administration, 2018). The

FAA is receiving an increasing number of reported UAS sightings from pilots, a considerable amount of which are UAS operations at an altitude higher than what is permitted for commercial operations (Wallace et al., 2019). The FAA, in partnership with Aloft, developed the B4UFLY mobile application to educate recreational flyers about where it is safe to fly their drones. While there is a focus on educating the UAS community, the FAA is well within its provisions to strictly enforce the compliance of its regulations. The FAA's Compliance Program Order 8000.373B states that the FAA establishes the highest level of regulatory standards to ensure safe operations in the NAS. The order further states that while some small deviations from its policy directives may arise, any intentional or reckless deviations from the regulatory standard operating procedure that may present an unacceptable risk of safety to any or all users of the NAS requires strong enforcement (Federal Aviation Administration, 2021a). Additionally, the FAA considers UAS as an 'aircraft' defined in the authorizing statutes of the FAA. Hence, according to the regulations coded in the Federal Aviation Administration, Department of Transportation (2011), it is forbidden for any person to operate an aircraft in a careless or reckless manner endangering the life and property of another person. The FAA understands that it is impossible to actively pursue UAS operators who put the safety of others at risk in the NAS. Hence, it is actively engaging with the law enforcement community to help in its efforts. A guidance document released by the FAA in September of 2020 (Federal Aviation Administration, 2020d) helps to educate public safety and law enforcement officials who are responsible for conducting investigations regarding incidents involving drones.

2.4.3.2.2 Cybersecurity

Cybersecurity concerns surrounding the UAS sector are a subset of the overall concerns corresponding to the aviation industry. The FAA is currently working with industry stakeholders and federal entities to identify, evaluate, and address the cybersecurity risks associated with the airspace system and the highly connected avionic systems that are onboard the aircraft. UAS can also provide a method for threat actors to gain access and proximity to networks and equipment in critical infrastructure sectors, thereby creating the risk of possible exploitation of such systems (Department of Homeland Security & Office of Cyber and Infrastructure Analysis, 2018). Pyzynski (2020) states that although UAS have a variety of applications and advantages, cyber-vulnerabilities bring a plethora of limitations. Since UAS do not have on-board pilots, there is no avenue to monitor any atypical scenarios during their operation. This allows malicious actors to gain access to valuable flight information and provide hostile instructions to the UAS systems, which can eventually result in reprogramming of UAS controls potentially creating irreparable damage.

To better enable UAS end-users to protect their networks, information, and personnel, the Federal Government's Cybersecurity and Infrastructure Security Agency (CISA) has released a manual detailing Cybersecurity Best Practices for commercial UAS (Cybersecurity and Infrastructure Security Agency, 2019). The document details some of the identified best practices that can lower the cybersecurity risks associated with owning and operating UAS. Some of the mitigation measures recommended by the CISA in that manual include encryption of data, installing host-based firewalls, changing default passwords, and installing updates and patches in a timely manner. The document also details the importance of providing personnel operating and maintaining UAS with adequate cybersecurity training.

2.4.3.2.3 Privacy

Integrating sUAS into the NAS raises some privacy concerns that need to be addressed. The U.S. Constitution regulates the right of the people to be secure from unreasonable searches and seizures of property by the Government unless a warrant has been issued with probable cause (U.S. Const. amend. IV). There is much confusion as to whether flying a UAS with a camera above a residential area constitutes a violation of people's rights. Also, there is another question regarding whether future UAS will be mandated by the FAA to operate under VFR conditions or if they will be permitted to operate based on electronic and GPS navigation and not a pilot's direct vision.

This raises an important question since, if UAS operators operate solely on the guidance of satellite-based navigation systems, the UAS can be controlled to power down its visual sensors until it reaches its operational target area. Another question that lingers in the mind of privacy advocacy groups is the possible utilization of UAS for routine mass surveillance (U.S. Department of Justice, 2016).

The U.S. Department of Commerce's National Telecommunications Information Administration published a list of voluntary best practices for both commercial and non-commercial UAS operators (National Telecommunications and Information Administration, 2016). Some of the key tenets from those best practices are:

- Inform the usage of UAS to individuals present/may be present in that area
- Exercise caution and care while operating UAS to collect data
- Limit the sharing of covered data
- Make provisions to secure the covered data
- Observe and comply with evolving Federal, State, and Local UAS laws and regulations

2.4.4 Accidents Involving Small UAS

In a search for incidents and accidents involving small UAS, especially multicopter aircraft, the team identified a total of 73 events across three major aviation accident and safety databases. The U.S. maintains a database of accident investigations via the National Transportation Safety Board (NTSB, 2021a). While dedicated primarily to the investigation of manned aircraft accidents, the NTSB's remit for UAS investigation has expanded via its NTSB 830 requirements since the implementation of 14 CFR part 107 which provides a regulatory structure for commercial UAS operations within pilot line of sight (Federal Aviation Administration, Department of Transportation, 1988; Federal Aviation Administration, Department of Transportation, 2016). Only 5 reports exist in the database, however, reflecting the limited nature of its damage-and-injury requirements and the disconnected nature of popular UAS use from the larger aviation world. With a much less rigid set of reporting requirements, the UK's Air Accidents Investigation Branch (AAIB) has 28 events (UK Air Accidents Investigation Branch, 2021a). Finally, NASA's Aviation Safety Reporting System (ASRS) exists to track safety events via pilot self-reporting, using the promise of the removal of certificate actions by the Federal Aviation Administration (FAA) to encourage participation. Forty events reside in this database (NASA 2021).

Examples of accidents reported in these government databases resulted in serious damage or destruction of the UAS. One aircraft was lost at sea and never retrieved while another caught fire and was destroyed after ground impact. This reflects the fragile nature of most UAS structures and their systems, usually relying on high-energy-density lithium batteries and navigation systems vulnerable to failures without manual pilot intervention (commonly called "fly-away" events). Some accidents involved external damage to property such as rooftops and building walls, but never human or animal injury. One accident in 2017 involved a midair collision with a US Army UH-60 helicopter (NTSB 2021b). While the helicopter sustained damage to its rotor blade and a windscreen, it was successfully landed, and no injuries were reported.

Accidents usually occurred for two reasons: some combination of human factors, some systems failure in power-electronic systems, or a combination of the two. It is noted that accident investigations are usually not conducted sufficiently in-depth to expose distinctions between these two causes.

Fly-away events are common, frequently reported by external observers—air carrier crews spotting a UAS aircraft or other eyewitnesses observing UAS in airspace where they normally should not be flying without authorization. These events happen for any number of reasons including systems failures (loss of navigation) or poor human decision-making (flying in inappropriate airspace). Rogue UAS sightings are naturally not investigated past interviews with observers unless the aircraft or UAS operator can be located. Systems failures frequently involve either the UAS battery, often giving a false indication of charge leading to power loss during the flight, or Electronic Speed Controller (ESC) failure in which the electric motor controls either cause a power loss or abnormal operation. Beyond these accident causes, other systems occasionally fail, such as one accident caused by the erroneous operation of an onboard obstacle collision avoidance system issuing an erroneous avoidance command for a nearby obstacle, resulting in the vehicle colliding with a tree (UK Air Accidents Investigation Branch, 2021b).

Overall, these reports do not provide a complete picture of UAS operations and accidents. The investigatory authority of these national databases tends to be interested primarily in substantial risks to the flying and non-flying public. Most UAS operations are private, non-commercial and accidents never reach beyond the operator or the operator's local neighborhood. While commercial operations have some government regulatory oversight, UAS flights here too tend to be much more informal than manned operations and incidents and accidents are frequently un-reported. To fill in the gap, the Consumer Product Safety Commission (CPSC) National Electronic Injury Surveillance System (NEISS) database of consumer-product related injuries has been used. Conducting a search for injuries reported by hospital emergency medicine departments, a much larger count of injuries ascribed to UAS between the years of 2015 and 2020 was identified (Gorucu and Ampatzidis, 2021). Over this five-year timespan, 4,250 drone injuries were reported, with the majority involving cuts and lacerations. Analysis of this investigation and their related database is ongoing.

2.5 Expanded and Non-Segregated Operations

Expanded and non-segregated operations represent the ultimate end state for UAS operations in the NAS. As the name implies, this paradigm involves full UAS integration into the NAS, where UAS and manned aircraft may operate safely with minimal operational and regulatory barriers. However, multiple challenges must be addressed before such operational freedom for UAS can be achieved. According to Hatfield et al., (2020), "one of the largest barriers in growing the UAS-based economy sector today is the need to responsibly and safely integrate UAS into the NAS." Hatfield et al., (2020) expands further by stating,

> While UAS have been in existence for over a century, integration of these aircraft for civilian purposes into the NAS has not yet been established, as the UAS flight is still too unique to completely adopt General Aviation's current system. (Hatfield et al., 2020)

While 14 CFR part 107 – i.e., the "small UAS rule," does address some of the uniqueness and safety considerations inherent to UAS, it falls short of establishing a means for truly expanded and non-segregated operations. What follows is a discussion of the existing UAS regulatory environment, its limitations, and mechanisms for expanding UAS operations per the existing regulatory framework.

2.5.1 Limitations of Part 107

While 14 CFR part 107 was instrumental in enabling routine commercial sUAS flight operations, it still carries limitations that make expanded and non-segregated flight operations challenging. The following is a list of regulatory constraints imposed by 14 CFR part 107:

- Section 107.25 – Operation from a moving vehicle or aircraft:

  Section 107.25 forbids the operations of an unmanned aircraft from a moving aircraft and restricts operations from a moving land- or water-borne vehicle to sparsely populated areas. This section also prevents operations from moving vehicles when carrying property for compensation or hire.

- Section 107.29 – Operation at night:

  This section outlines provisions for sUAS flight operations at night. The prior amendment 107-8, part of 86 FR 4382 published in January of 2021, restricted sUAS flight operations to daylight hours, requiring a waiver for §107.29 to fly at night. With the most recent amendment, operations at night are permitted as long as the remote pilot has completed an initial knowledge test and the aircraft is equipped with anti-collision lighting that is visible for at least 3 statute miles.

- Section 107.31 - Visual line of sight aircraft operation:

  This provision is intended to ensure that the remote pilot can fulfil their duty to see and avoid other air traffic. This provision must be waived for BLVOS flight operations, and technical solutions to fulfill the see and avoid requirements are not widely available or technologically mature. As such, this provision greatly restricts the capacity to operate sUAS in BVLOS regimes.

- Section 107.33 - Visual observer:

  As specified in 14 CFR §107.31(b)(2), a visual observer may aid the remote pilot in maintaining VLOS. 14 CFR §107.33 outlines requirements for a visual observer. As mentioned previously, technological replacements for a visual observer are not widely available, and the technology of DAA systems is not yet mature enough for broad use. As such, 14 CFR §107.33 also restricts the capacity to operate sUAS BVLOS.

- Section 107.35 - Operation of multiple sUAS:

This provision within 14 CFR Part 107 prevents the operation of more than one sUAS by a single remote pilot. This provision is subject to waiver.

- Section 107.39 - Operations over human beings:

  Prior to Amendment 107-8, part of 86 FR 4382 published in January of 2021, 14 CFR §107.39 prevented sUAS flights over human beings. However, the most recent amendment has added 14 CFR Part 107 Subpart D – Operations Over Human Beings. These provisions outline requirements for operations over human beings that are broken into categories, with category 1 being the most permissive and category 4 being the most restrictive.

- Section 107.51 - Operating limitations for sUAS:

  14 CFR §107.51 lists basic operating limitations for sUAS. These limitations restrict sUAS to the following performance and weather limitations:

  1. Ground speed may not exceed 87 knots,
  2. Altitudes less than or equal to 400 feet AGL or within 400 feet of a structure, and
  3. Minimum flight visibility of 3 statute miles; cloud clearances of 500 feet below and 2,000 feet horizontally.

- Section 107.145 - Operations over moving vehicles:

  Finally, 14 CFR §107.145 defines restrictions on when and how a sUAS may be operated over moving vehicles. It is important to note that §107.145 references operational categories listed under 14 CFR Subpart D – Operations Over Human Beings, and the requirements to operate an sUAS over moving vehicles increase in rigor with sUAS operational categories.

It is important to note that the limitations within 14 CFR Part 107 are aimed at maintaining the safety of the NAS and people and property on the ground. However, there are also instances where it is both practical and appropriate to waive specific provisions within Part 107 to enable operations to occur beyond the normal scope of existing sUAS regulations. To that end, Part 107 includes (1) specific provisions outlining policy for waiving certain requirements, and (2) a list of regulations subject to waiver. These elements recognize that there are instances where an applicant may be able to operate outside of Part 107 if an applicant can demonstrate an equivalent level of safety.

2.5.2 Current Waiver Process

Recognizing the dynamic nature of commercial UAS applications, the FAA, on a case-by-case basis, issues waivers enabling remote pilots to fly safely and responsibly outside the normal provisions of Part 107 using a Part 107 Certificate of Waiver (COA). According to 14 CFR §107.200, if the FAA administrator can determine that a proposed sUAS operation, although outside the regulatory purview of Part 107, may be conducted safely, he/she may issue a COA authorizing that deviation from the provisions of §107.205. Waiver applications should be submitted electronically using the FAA DroneZone portal. Some of the key factors considered by the FAA in the adjudication of waiver applications are the type of aircraft flown, the nature of the proposed operation, the uniqueness of the environment in which the operation is scheduled to take place, the hazards unique to the proposed operation, and the corresponding safety mitigation provisions. The waiver application is evaluated primarily based upon the applicant's Concept of

Operations (ConOps) and the operational hazard and risk analysis. The ConOps should primarily consist of the proposed sUAS operational description, location, limitations, and procedures. A risk analysis should include the severity and likelihood of each hazard and the respective risk mitigations. The waiver approvals usually come with conditions and limitations that must be complied with called ‘common provisions’ and ‘special provisions.’

A certificate of waiver issued pursuant to §107.200 may authorize a deviation from the following regulations of this part:

- Section 107.25 - Operation from a moving vehicle or aircraft:

  A successful waiver under this section shall permit sUAS operations from a moving land or water-borne vehicle if the desired operation is conducted in a non-sparsely populated area, not carrying property for compensation or hire.

- Section 107.29 (a)(2) - Operation at night:

  A successful waiver under this section would permit a sUAS to operate at night without an onboard anti-collision lighting system.

- Section 107.29 (b) - Operation at night:

  A successful waiver under this section would allow sUAS to operate during periods of civil twilight without anti-collision lighting.

- Section 107.31 - Visual line of sight aircraft operation:

  A successful waiver under this section would allow the remote pilot to operate a sUAS BVLOS. For a successful issuance of a 107.31 waiver, the evaluator among other things assesses the signal spectrum used by the sUAS and the DAA system onboard the sUAS.

- Section 107.33 - Visual observer:

  A successful waiver under this section would permit an sUAS operation with the help of a visual observer without following all visual observer requirements. Waivers under this section are not issued by the FAA separately, rather these waivers are issued in conjunction with other waivers.

- Section 107.35 - Operation of multiple sUAS:

  A successful waiver under this section applies to any remote pilot or visual observer who is responsible for more than one sUAS in flight at the same time.

- Section 107.39 - Operations over people:

  The FAA published the operations over people rule in the Federal Register on the 15th of January 2021 and it became effective from April 21, 2021. This final rule amended the waiver provisions that were part of the small UAS rule. The final rule brought forth four new categories of sUAS operations over people. They are described below (Federal Aviation Administration, 2020e):

  1. Category 1: This consists of sUAS with an overall weight less than 0.55 pounds and having no exposed rotating parts that could lacerate human skin. sUAS under this category does

not require FAA accepted Means of Compliance (MOC) or Declaration of Compliance (DOC).

2. Category 2: sUAS eligible for Category 2 must not cause human injury that is greater than or equivalent to injury severity caused by a transfer of 11 foot-pounds of kinetic energy upon impact from a rigid object. sUAS under this category should not contain any exposed rotating parts that could potentially lacerate human skin and not contain any safety defects. MOC and DOC are required for Category 2 sUAS operation.
3. Category 3: The human injury severity of a Category 3 eligible sUAS must be greater than or equivalent to the injury severity caused by the transfer of 25 foot-pounds of kinetic energy upon impact from a rigid object. Additionally, Category 3 sUAS must not have any exposed rotating parts and not contain any safety defects. Category 3 sUAS operation requires MOC and DOC.
4. Category 4: Category 4 eligible sUAS must possess an FAA Part 21 airworthiness certificate and must be operated in accordance with the operational limitations specified in the approved Flight Manual or as otherwise specified by the Administrator.

- Section 107.51 - Operating limitations for sUAS:

  (a) A successful waiver under this section would permit sUAS operation at a ground speed exceeding 87 knots.

  (b) A successful waiver under this section would allow the sUAS to operate above 400 feet AGL while not within 400 feet of a structure.

  (c) A successful waiver under this section would allow a sUAS operation with less than 3 statute miles visibility from the control station.

  (d) A successful waiver under this section would allow the sUAS to operate closer than 2000 feet horizontally or 500 feet below a cloud.

- Section 107.145 - Operations over moving vehicles:

  The final rule mentioned in the description of section 107.39, provides certain provisions for operations over moving vehicles. Particularly, the final rule provides permission for operations over moving vehicles, provided that the proposed sUAS operation falls under the purview of Categories 1, 2 or 3 mentioned above and either:

  - The sUAS remains within or over a closed or restricted access site and all people that are inside the moving vehicle within the closed-or restricted-access site are informed that a sUAS may fly over them; or
  - The sUAS avoids maintaining sustain flight over moving vehicles (Federal Aviation Administration, 2021b).

2.5.3 Approved Waiver Descriptions

According to the FAA Aerospace Forecast 2021-2041, night operations account for almost 9 out of every 10 approved waivers, followed by operations over people (around 1 in 20 approved waivers). It is worth noting that night operations and some operations over people are now governed by approved rules, and waivers are no longer required. Requests for BVLOS waivers account for around 13% of total requests, while requests for altitude limits account for 9% of total requests, with approval rates of 2.8% and 2.9%, respectively.

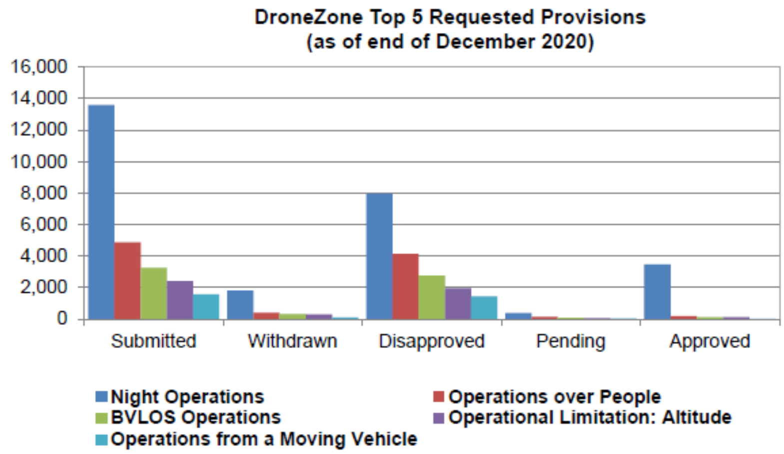

Figure 1. Waiver Requests and Approvals Trend (Office of Aviation Policy and Plans – Federal Aviation Administration, 2021).

Based on an examination of the FAA's Waiver Trend Analysis document, some of the key waiver application elements and their individual characteristics that led to the successful award of the top three types of waivers, which are listed below.

1. Night Operations Waivers (Federal Aviation Administration, 2020g):
   - Maintaining VLOS and sUAS Visual Conspicuity:
     a. The lighting system on the sUAS would be visible for at least 3 statute miles.
     b. There was at least one visual observer for the proposed operation.
     c. The waiver application contained proper documentation showing the communication protocol between the sUAS and the remote pilot.
     d. The waiver application recorded the procedure the remote pilots and visual observers would follow if they lost sight of the sUAS during their operation.
   - See-and-Avoid Methods:
     a. The waiver application reported the method used by the sUAS to detect other aircraft and avoid them.
     b. The waiver application characterized the method used by the sUAS to locate and avoid causing a hazard to non-participants.
     c. The waiver application clarifies the method employed by the sUAS to avoid operations over non-participants and the procedures the remote pilot and the visual observer would follow when a non-participant is in the ground operations area.
   - Continuous Knowledge of sUAS's Location and Movement:

a. The waiver application communicated sufficient information about how the remote pilot would receive and monitor telemetry data sent from the sUAS.

b. The waiver application described how onboard lighting on the sUAS would help in making the determinations required in §107.31.

c. The waiver application informed how the visual observer would communicate the location of the sUAS to the remote pilot.

- Participant's Knowledge Requirement:

a. The waiver application detailed the training that all participants of the sUAS operation would undergo.

b. The waiver application indicated how the participants received this training and provided a means to ensure that the training transferred the minimum required knowledge for the operation to remain safe.

2. Operations Over People (Federal Aviation Administration, 2020h):

- Ground Collision Severity:

a. The waiver applicant provided their own impact/injury severity tests for their sUAS or used a sUAS for which the impact/injury severity test data was readily available and furnished along with the waiver application.

b. The waiver application characterized proper mitigation measures that reduced the impact severity.

- Laceration Injuries:

a. The applicant furnished their own laceration tests for their sUAS or used a sUAS for which laceration test data was readily available and furnished it along with the waiver application.

b. The applicant outlined mitigation measures that reduced laceration injury.

- Operational Description:

a. The waiver application appropriately discussed the various operational limitations such as altitude, airspeed, range, environmental limitations, etc.

b. The waiver application accurately described the operating conditions, such as emergency safety equipment and training provided.

- Unique Remote Pilot Experience:

a. The waiver application chronicled the applicant's list of qualifications and prior experience operating over people.

3. Beyond Visual Line of Sight Operations (Federal Aviation Administration, 2020a):

- Command and Control (C2):

a. The waiver application defined the maximum range envelope the C2 can operate in considering the geographic area and terrain.

b. The waiver application reported the complete working description of each emitter in the sUAS.

- Detect and Avoid Methods:

a. The waiver application provided a description of risk mitigation procedures to avoid collisions with aircraft.

- Weather Tracking and Operational Limitations:

a. The waiver application communicated when weather reports were generated, what the weather reports conveyed, and where the weather reports were generated.

b. The waiver application stated the sUAS weather limitations information that was provided by the sUAS manufacturer.

- Training Requirements for Pilots and Other Participating Persons:

a. The waiver application elucidated the method employed to verify the efficacy of the training accorded to pilots and other employees in that organization.

On the airspace authorizations and waiver front, almost 50% of requests were approved for controlled airspace. In the classification of airspace, Class D airspace accounted for more than half of the approved waivers (54%), followed by Class C (18%), Class B (16%), and Class E (11%) (Office of Aviation Policy and Plans - Federal Aviation Administration, 2021).

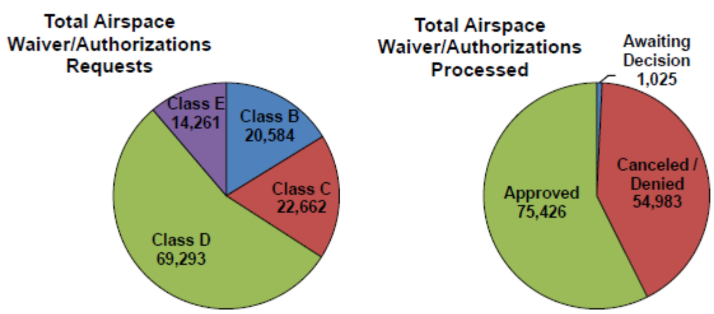

Figure 2. Waiver / Authorization Request by Airspace Class (Office of Aviation Policy and Plans - Federal Aviation Administration, 2021).

The FAA has been working consistently with various industry stakeholders to develop a new capability that allows for rapid adjudication of airspace access requests. It is called the Low Altitude Authorization and Notification Capability (LAANC), and it helps provide UAS pilots with instantaneous access to controlled airspace at or below 400 feet. It also provides air traffic controllers the visibility of where UAS are being operated. The LAANC interface is web- and mobile-based, and it helps users submit speedy authorization requests and helps the FAA in transmitting approval information to the user swiftly (Wallace et al., 2020). Prior to the introduction of LAANC, UAS operators would submit airspace authorization requests on FAADroneZone, which sometimes took several months to receive approval.

Some of the key features of LAANC are:

- It provides access to regulated airspace at or below 400 feet for UAS operators.
- It contributes to the awareness of where pilots can and cannot fly.
- It provides Air Traffic Control professionals information regarding where and when UAS are operating.

Since its inception in May 2017, LAANC provides authorizations at about 726 airports. As of December 2020, LAANC has successfully approved 289,749 requests for airspace access from Part 107 users and 141,123 requests from recreational operators as defined by 49 U.S.C §448029 (Office of Aviation Policy and Plans - Federal Aviation Administration, 2021).

2.6 Aircraft Separation

2.6.1 RTCA SC228 and Other-than-Small UAS

The Science and Research Panel (SARP) developed the initial recommendation for well clear for other-than-small UAS. As described by Cook et al. (2015), this recommendation is a modified tau (τ_{mod}) for horizontal well clear, with 35 seconds from collision or a minimum of 4000 ft separation, and a fixed vertical distance of 700 ft. This was accepted by RTCA SC228 for other-than-small UAS, and then was modified, with FAA concurrence, such that the vertical distance is reduced to 450 ft. The RTCA SC228 has used this well clear definition for other-than-small UAS to further develop concepts relative to well clear, including prediction of loss of well clear and TCAS interoperability.

2.6.2 SARP and Small UAS

The SARP developed the initial recommendation for well clear for other-than-small UAS. After this, the SARP was charged with developing a well-clear definition for sUAS operating at low altitudes.

The development of a well clear definition for sUAS operating at low altitudes generally followed the same process applied in the development of the well clear definition for other-than-small UAS. However, efforts for sUAS operating at low altitudes were significantly limited by lack of data regarding how intruders commonly fly at low altitudes. These intruders are most commonly in areas away from airports, emergency medical aircraft, crop sprayers, and possibly aircraft that have emergencies. Some limited data regarding these types of flights were obtained. A combination of actual flight data and simulated flight profiles (e.g., for UAS flights at low altitudes) were utilized to help develop the needed well clear definition. The final result was risk based, with the risks of a Near Mid-Air Collision (NMAC) given a well-clear violation and of a MAC given NMAC determined through Monte Carlo simulations (with no assumed maneuvering to avoid either NMAC or MAC). Based on these, a risk-based definition for well clear that is solely distance-based was produced. The driver for use of a distance-based definition, as opposed to a time-based definition (τ), is the relatively low speeds of sUAS relative to intruders. This performance differential resulted in time-based definitions providing no significant advantages to distance-based definitions. The final recommendation is separations of 2000 ft horizontally and 250 ft vertically (Weinert et al. 2018).

2.6.3 UAS Safe Standoff Distances Research

UAS must keep a safe distance away from every aerial, dynamic, and static object to prevent a possible collision, conflict, or interference. As mentioned in the research by Ippolito et al., (2019), object classification includes a) Static Ground Objects (SGO) and b) Dynamic Ground Objects (DGOs). Static objects include building structures, towers, billboards, trees, cables, scaffolding, tethered balloons, and powerlines; many static objects are hard to detect, especially power lines, which are characterized by a long and thin geometry. Dynamic objects include pedestrians, automobiles, and other aircraft (manned and unmanned), which are difficult to detect, predict, and avoid. According to the authors of this work, utilizing current commercially available sUAS technology for BVLOS urban environment operations would represent an unacceptably high risk.

In another study performed by Rattanagraikanakorn et al. (2018), the main goal is to identify and classify objects that create UAS collision risk. For ground objects, the authors used different kinds of maps—for example land-use, satellite, or land elevation—during the object identification process. The most representative maps include forests, parks, agricultural areas, meadows, low-rise building areas, high-rise building areas, pedestrian areas, cycling areas, railways, motorways, and roads. Additionally, airborne objects were identified based upon rules that specified what types of aircraft were allowed to operate within the airspace. These include commercial airliner, flight training, leisure flight, commercial flight, and rotary-wing used by the military, law enforcement, emergency services, news, and media, which operate at very low-level altitudes. Lighter-than-air vehicle types like balloons are also identified as susceptible to UAS collision risk. A collision between UAS and birds is also considered a relevant collision threat. Figure 9 shows a flowchart of object classification for ground and airborne objects.

2.7 Low-Altitude Aircraft Operations

2.7.1 Broad Review

Weinert and Barrera (2000) aggregated information from a broad set of sources to conduct an extensive review of low-altitude manned aircraft operations. While additional information regarding low-altitude manned aircraft operations may be gleaned from other sources (e.g., Xue et al., 2018; Weinert et al., 2019; Underhill and Weinert, 2021), Weinert and Barrera (2000) represents the most comprehensive review available and is the focus herein.

A summary of the information provided by Weinert and Barrera (2000) is provided in Table 1. In this table, specific CFR sections area provided for some operations in parentheses. As shown in this table, Weinert and Barrera (2000) analyzed 11 low-altitude manned aircraft operational use cases. They excluded ultralight vehicles but provide information regarding them from Markowski (1982).

Table 1**.** Summary of very low level manned aircraft operations from Weinert and Barrera (2020).

Operation	Flight Altitudes (ft AGL)	Speeds (kts)	14 CFR Part	Comments
Spraying and Dusting	2-20	50-120	137	
Insect Release	300-2500	78-88*	91, 135	Uncertainty regarding 14 CFR part (depending on who executes flights).
Fish Release	150-300	70	91, 135	Uncertainty regarding 14 CFR part (depending on who executes flights).
Helicopter Air Ambulance	0 and up	Not Provided	135 (135.271)	
Helicopter Air Tours	400-3300	Not Provided	91, 119, 121, 135, 136 (91.147	Aircraft models can be used to obtain airspeeds.
Helicopter Offshore Operations	500 and up	Not Provided	135 (135.181)	Aircraft models can be used to obtain airspeeds.
Helicopter News Gathering and Public Safety	500-3280	0-140	119, 135	
Training	500 and up**	Not Provided	121, 129, 135, 137, 141	Aircraft models can be used to obtain airspeeds.
Animal Sciences	30-4590***	19-175****	91, 135	
Earth Sciences	100-2130	27-120	91, 135	
Plant Sciences	<500-32,000	11-200	91	

*Average speeds based on operational guidance.
**Based on regulations.
***Many operations are reported to occur below 500 ft AGL.
****175 kt flights at altitudes 1200-2000 ft AGL. Highest speed for altitudes < 700 ft AGL is 108 kts.

2.7.1.1 Spraying and Dusting

As indicated in Table 1, spraying and dusting are executed at very low altitudes (2-20 ft AGL), indicating that relative to these operations the ground does not provide shielding benefits. Further information regarding these operations is provided in the upcoming section regarding ASSURE efforts to understand low-altitude manned aircraft operations.

2.7.1.2 Insect and Fish Release

Both of these operations occur at relatively low altitudes. The speeds at which these occur are consistent with general aviation single-engine aircraft speeds (e.g., Underhill and Weinert 2021).

2.7.1.3 Helicopter Air Ambulance (HAA)

As with other types of low-altitude manned aircraft operations, data regarding HAA operations is lacking. This includes the number of flight hours per year. Estimates vary from 100,000-300,000 for the years 1991-2003 to 900,000 from 1993-2003 and 1,600,000 in 2004 Weinert and Barrera 2020). Speeds are not provided in Weinert and Barrera (2020). However, Underhill and Weinert (2021) found that rotorcraft tend to be flown at lower speeds relative to fixed-wing aircraft at low altitudes (with similar accelerations, vertical rates, and turn rates). They also found that they tend to fly lower than fixed-wing aircraft, though they likely had a limited sample of crop dusters in their data set.

2.7.1.4 Helicopter Air Tours

In addition to the 14 CFR Part 91.147 regulations, local rulesets can also govern these operations. Nationwide data regarding flight hours are hard to find. However, some local statistics are available (e.g., New York). The altitude range provided in Table 1 is based upon company websites and a few informal phone surveys. It is expected that some air tours may operate below the 400' lower limit listed in Table 1. Flight characteristics are likely to be similar to those identified by Underhill and Weinert (2021), with lower and slower flight relative to fixed-wing aircraft and similar accelerations, vertical rates, and turn rates.

2.7.1.5 Helicopter Offshore Operations

These operations involve transport of passengers or supplies. Data regarding these operations are limited. Such operations are commonly compared to HAA operations, though differences have been noted.

2.7.1.6 Helicopter News Gathering and Public Safety

Information regarding these use cases was difficult for Weinert and Barrera (2020) to identify. Consequently, the information is drawn from publications that describe specific operations and does not represent a large and rigorous data set. Reported speeds for such operations reach a relatively high value (140 kts), though these operations are likely conducted at relatively lower speeds such as those identified by Underhill and Weinert (2021) as lower speeds would commonly enhance mission effectiveness for these use cases. From the limited information available, altitudes are ≥ 500 ft AGL. Very little information regarding flight hours is provided, and what is provided would not easily be extensible to the NAS (though reasonable assumptions could be made to estimate flight hours in major cities).

2.7.1.7 Training

Training operations are conducted at heights ≥ 500 ft AGL, based upon regulations. The aircraft that are used for training are generally single-engine fixed-wing aircraft, for which characteristics are known (Underhill and Weinert 2021). While information regarding flight hours is limited in

Weinert and Barrera (2020), part 141 schools do track flight hours and, thus, such information could be established.

2.7.1.8 Animal, Earth, and Plant Sciences

For these operations, flight altitudes can be < 500 ft AGL. In addition, speeds can reach fairly high values, though most of the reported values are near the peak for general aviation single-engine aircraft speeds (Underhill and Weinert 2021). Moreover, the reported values do not exceed values observed by Underhill and Weinert (2021). For some of these missions, helicopters are used at low altitudes (e.g., animal sciences). In addition, many animal sciences flights (wildlife searches) are typically conducted at low altitudes, while mapping of animal habitats involves flights at a wider range of higher altitudes.

Weinert and Barrera (2020) conclude that Earth science missions commonly are not conducted a low altitudes, although some missions do occur at altitudes down to ~100 ft AGL. These missions are conducted with a variety of aircraft (helicopters and single- and multi-engine fixed-wing aircraft).

Plant sciences operations can extend to low altitudes (< 500 ft AGL) and can utilize multiple aircraft types (fixed- and rotary-wing aircraft). Speeds for such operations cover a broad range. Very little information regarding flight hours is provided.

2.7.1.9 Ultralight Vehicles

Weinert and Barrera (2020) do not include ultralight vehicles in their analysis but do provide characteristics from Markowski (1982). From Markowski (1982), ultralight vehicles are generalized as having cruise speeds of ~43 kts, stall speeds down to 22 kts, and vertical rates of 500 ft min^{-1}. Ultralight operations are governed by 14 CFR Part 103 (Federal Aviation Administration, Department of Transportation, 1982). Ultralights may not be operated in Class A, B, C, D, or within the lateral boundaries of the surface area of Class E airspace designated for an airport unless prior authorization from the ATC facility having jurisdiction over that airspace is obtained. Thus, ultralight flights are generally confined to Class G and E airspace. Because ultralight pilots are not certified, it is difficult to find information regarding the number of active pilots and flight hours. It is noted that these are referred to as vehicles because the FAA considers them as vehicles, which means that they do not have an airworthiness certification.

2.7.2 ASSURE Efforts

As part of the project "A18_ A11L.UAS.22 – Small UAS Detect and Avoid Requirements Necessary for Limited Beyond Visual Line of Sight (BVLOS) Operations: Separation Requirements and Testing" (A18), researchers at Mississippi State University's (MSU's) Raspet Flight Research Laboratory (RFRL) analyzed flight characteristics of crop sprayers. These data were obtained through a partnership with the National Agricultural Aviation Association (NAAA), with the privacy of those who provided data carefully protected. Analysis results are provided herein with permission of RFRL.

Many different characteristics can be evaluated. To date, aircraft trajectory angles relative to the Earth's surface during descent-into and ascent-from spraying runs, turn rates between spray runs, spraying speed and altitude, and cruise speed and altitude, have been analyzed and described in Raspet Flight Research Laboratory (2020).

Results for descent-into and ascent-from spraying runs are shown in Figure 3. The descent-into values have an average of approximately -8.2° and the ascent-from values have an average of approximately 8.43°. Standard deviations are 1.6° and 1.0°, respectively. More extreme values have absolute values in the range of 11-13° for both descent-into and ascent-from.

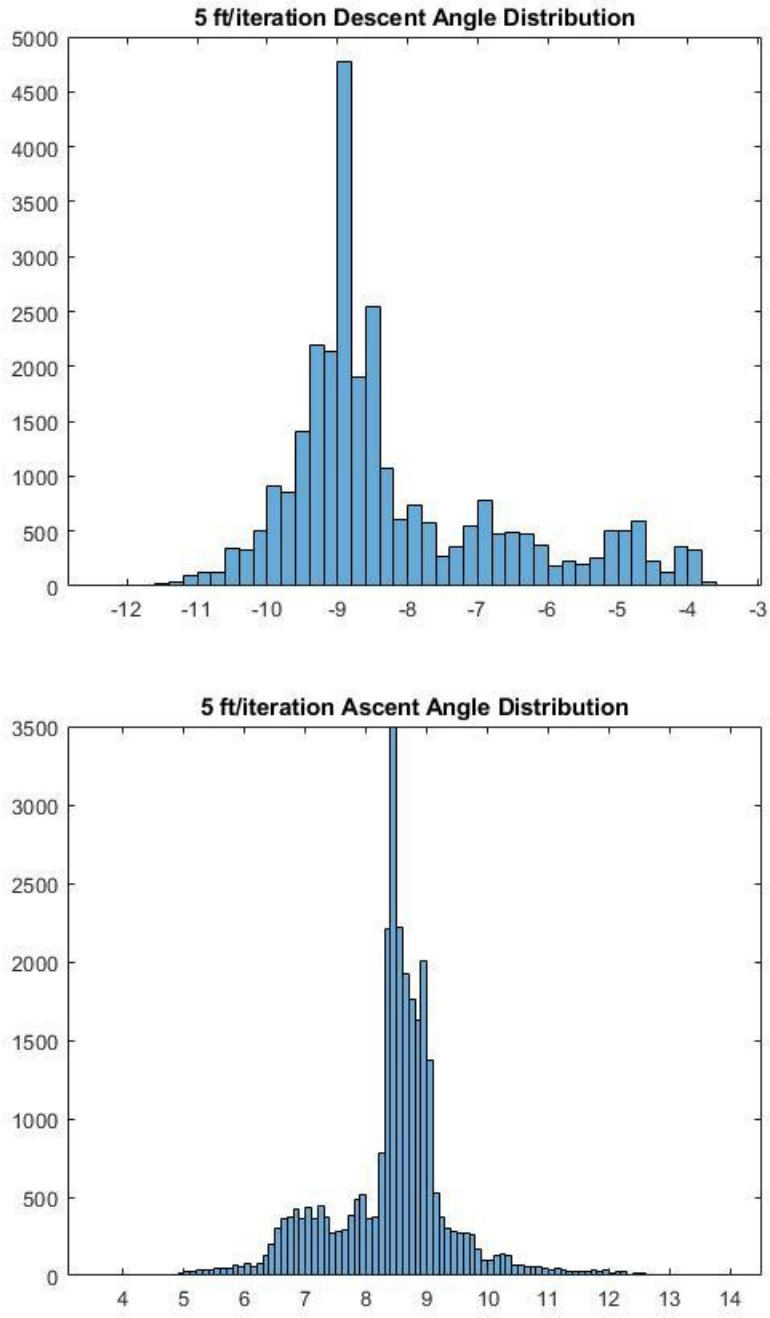

Figure 3. Aircraft trajectory angles relative to the Earth's surface for descent-into (top) and ascent-from (bottom) spraying runs. Number of files are on the vertical axes (Raspet Flight Research Laboratory, 2020).

Characteristics of turn rates between spray runs are illustrated in Figure 4. Not surprisingly, crop sprayers maneuver aggressively, with an average turn rate (6.34° s^{-1}) that is more than twice the standard turn rate (3 ° s^{-1}). More extreme values are in the 12-14 ° s^{-1} range. It is noted that an alternate method of estimation produced an average turn rate of 6.34° s^{-1}.

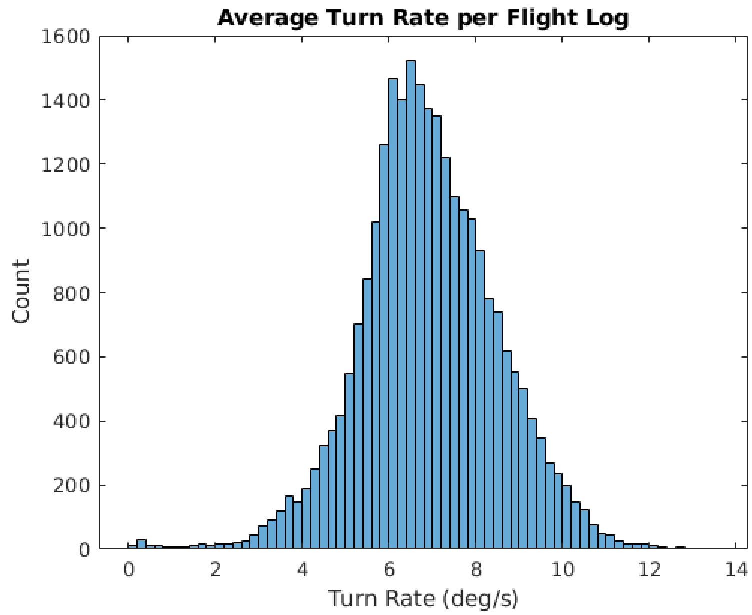

Figure 4. Aircraft turn rates between spraying runs, with number of files on the vertical axis (Raspet Flight Research Laboratory, 2020).

Figure 5 provides an illustration of average spraying speeds during spraying runs. The average value is 121.21 kts, with some values reaching > 160 kts. These values are significantly larger than those identified by Weinert and Barrera (2020).

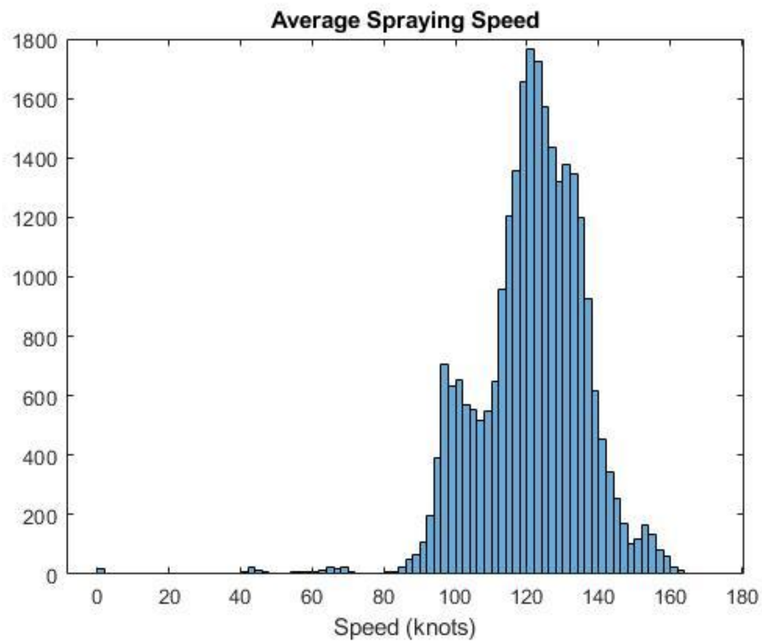

Figure 5. Spraying speeds, with number of files on the vertical axis (Raspet Flight Research Laboratory, 2020)

Spraying altitudes are generally low, with an average of 37.99 ft (Figure 6). This is higher than the range provided by Weinert and Barrera (2020), although many of the values in Figure 6 are within the 2-20 ft AGL range. It is noted that some values are negative, which are non-physical and are assumed to result from a combination of errors in GPS altitudes and errors that arise when converting these altitudes from heights above an ellipse to heights AGL, which require use of a digital elevation model and conversion from ellipsoidal altitude to geoidal altitude. A small number of crop dusters utilized laser altimeters. Results from those data indicate spray altitudes having a minimum near 5 ft AGL, a peak near 13 ft AGL, and a tail extending to higher altitudes (Kyle Ryker 2021, personal communication).

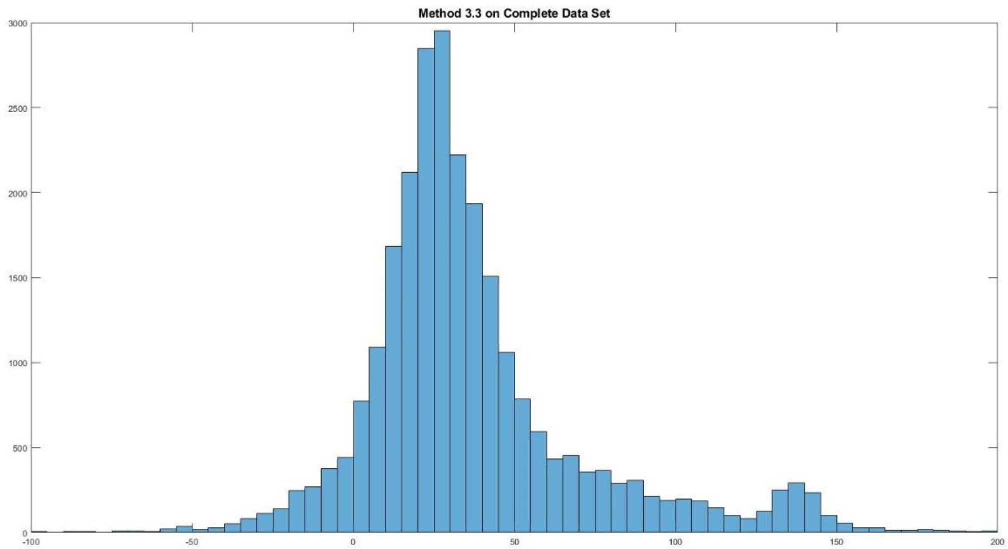

Figure 6. Spraying altitudes (ft AGL), with number of files on the vertical axis (Raspet Flight Research Laboratory, 2020).

Figure 7 illustrates cruise speeds and Figure 8 illustrates cruise altitudes. These may be biased low owing to challenges associated with identifying cruise periods (they may include portions of flight involved in take-off, landing, and application). The cruise speed distribution agrees well with the range identified by Weinert and Barrera (2020), with only a relatively small portion of the values exceeding their upper limit of 120 kts and residing in the 120-140 kts range. On average cruise altitude appears to be below 500 ft, but this is likely affected by inclusion of non-cruise periods.

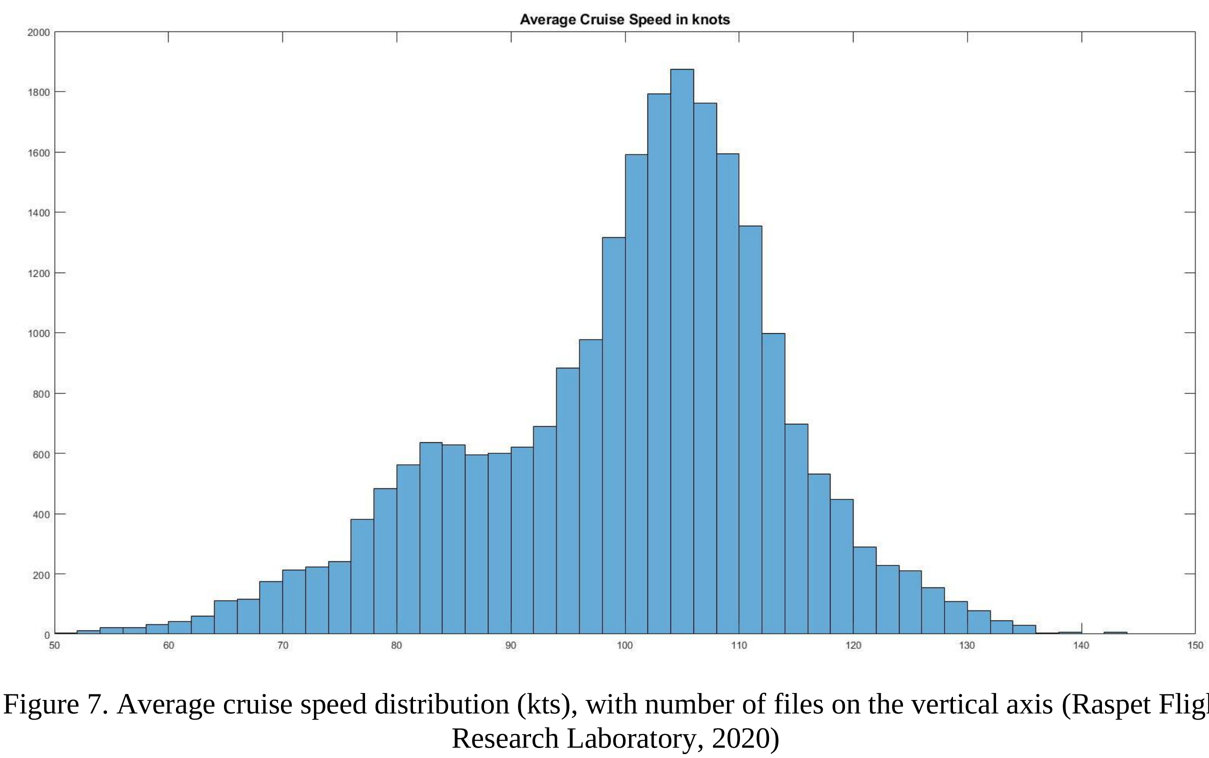

Figure 7. Average cruise speed distribution (kts), with number of files on the vertical axis (Raspet Flight Research Laboratory, 2020)

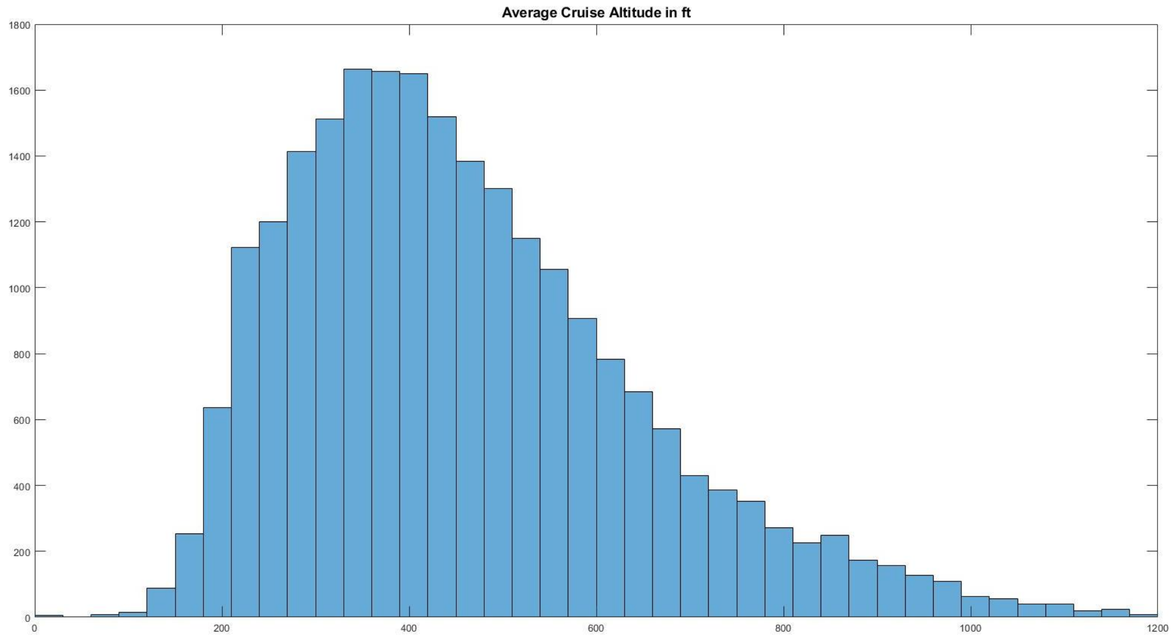

Figure 8. Average cruise altitude distribution (ft AGL), with number of files on the vertical axis (Raspet Flight Research Laboratory, 2020)

2.8 Shielded UAS Operations

The exponential growth of applications using small UAS in low-altitude environments, at or below 400 feet, poses significant risks and challenges to the U.S airspace due to the need to develop technology and regulations for avoiding and protecting the static and dynamic obstacles present in these operations. Urban environments generally pose the greatest challenges as they contain dangerous and unpredictable hazards that translate into high uncertainty and risks characterized by unsteady winds, complex urban topologies, and flying near people, critical infrastructure, and other aircraft. Moreover, such operations, especially in urban environments, are expected to experience degraded navigation systems (e.g., due to the urban canyon shadowing effect). While autonomous systems have been widely studied, there is no general agreement on specific requirements for autonomous systems for shielded operations.

2.8.1 Introduction and Background

Civil unmanned operations with recreational or commercial purposes have increased over the last years, resulting in more crowded skies, especially for Very Low Level (VLL) operations due to new applications and their potential to generate significant economic growth. To take advantage of this potential, the aviation industry desires policies to make shielded operations safer considering the hazards of flying at low altitude and close to critical static and dynamic obstacles. Shielded operations are complex because most of them are performed near critical infrastructure such as buildings, cell towers, and power lines or near congested airspace. These operations require introducing a high degree of automation and autonomy and identifying requirements to make these operations safe.

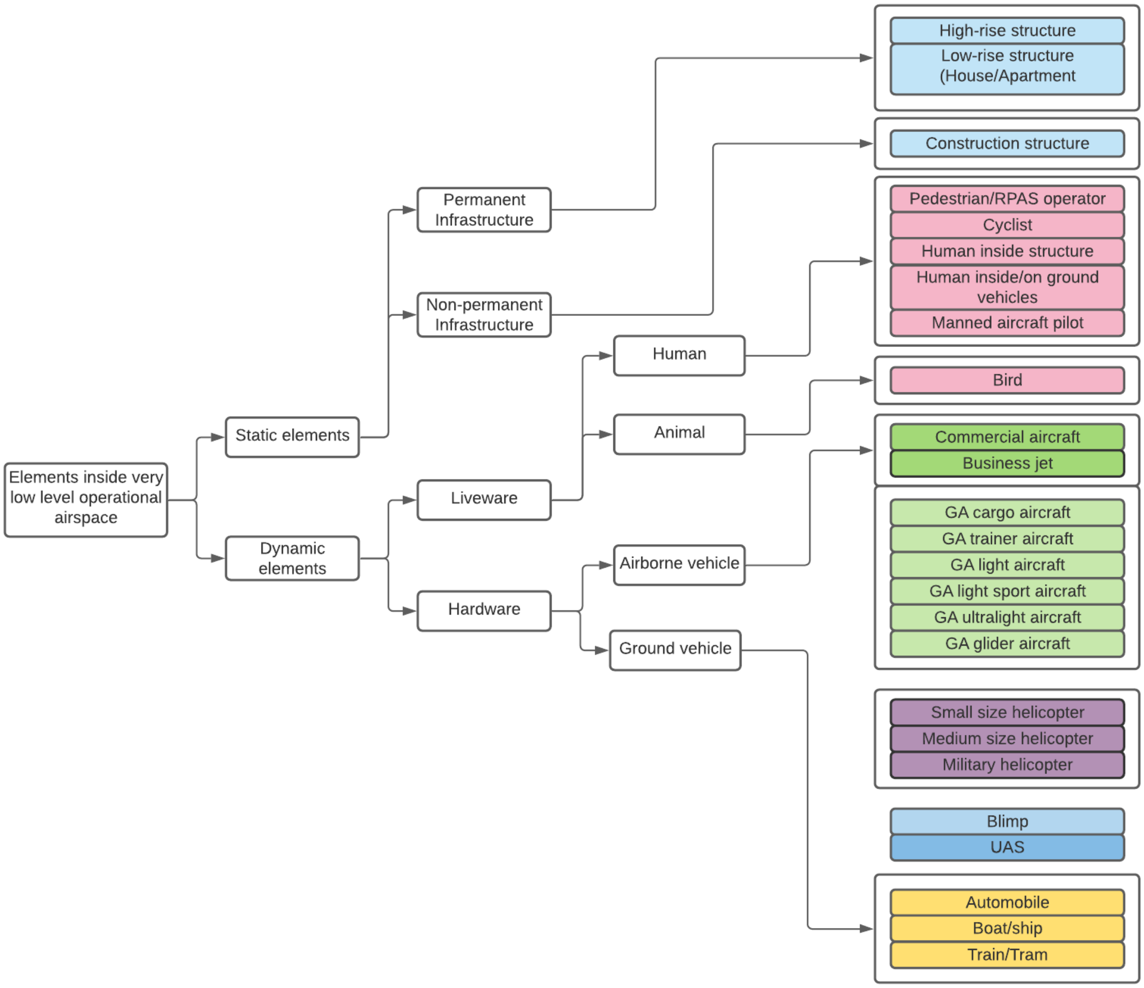

Figure 9. Object classification flowchart, both ground and airborne objects (modified from: Rattanagraikanakorn et al., 2018).

In addition to the motivations for conducting shielded operations, in (Federal Aviation Administration, 2020c), the UAS Facility Maps Tasking Group recommended that the FAA establish a process to facilitate shielded operations. This would convey a positive sentiment to new recreational fliers. Additionally, this will reinforce the critical safety requirements of flying below the top of obstacles and structures when flying under shielded operations.

2.8.2 Use Case and Aircraft Requirements and Limitations

The FAA guidelines governing the UAS operational approval process require details about the system, environment, and hazard and risk analyses. In Guterres et al. (2017), the authors reviewed significant developments in the legislative and regulatory frameworks associated with the use of sUAS for commercial purposes.

Petrovsky et al. (2018) emphasize the importance of collecting and ensuring good quality obstacle data (for both manned and unmanned aviation). The author claims that the challenges posed by drones navigating in complex urban environments could be alleviated by implementing geofencing. A geofence is a virtual three-dimensional boundary that restricts access to drones and is usually defined around obstacles to create No-Fly-Zones (NFZs). However, detailed obstacle information is required to design geofence zones in the airspace effectively. According to the authors, requirements for obstacle data need to be within 1 m accuracy (both vertical and horizontal) with a 1 m resolution provided with a confidence level of 95%. Obstacle accuracy data will enable geofencing techniques to be implemented more effectively in terms of position, height, and type of obstacle.

In the SAFE50 design study (Ippolito et al., 2019), several measures have been proposed to establish, analyze, and validate an end-to-end reference design for fully autonomous UAS operations. In this study, two primary use cases are analyzed; the first one is a point-to-point scenario, and the second one is an emergency response scenario. The point-to-point scenario represents one of the broadest use cases regarding development and elaboration. The emergency response scenario was selected as an extension of the point-to-point use case with the notion of priority access. One of the features that each use case must have is the UAS operator will provide mission objectives to the UAS through an onboard system that includes destination and emergency landing locations. The UAS must autonomously generate possible flight plans, including a primary/nominal plan and potential alternative plans. These plans must avoid areas where winds or traffic may be high.

Additionally, it is proposed that the UAS must calculate "operational volumes" around a planned trajectory and submit the volume information to the UTM system. Another required capability is identification of emergency landing zones. The SAFE50 design study incorporated the idea of applying for an airspace authorization to an FAA Approved UAS Service Supplier (USS). If the USS rejects the plan, the UAS is required to generate a new plan until approved. Finally, the UAS sends a UTM all-clear message and can start the mission. In the case of a contingency event, the UAS must immediately execute the contingency plan and broadcast the event to surrounding vehicles through a vehicle-to-everything (V2X) communication link and notify the USS through an air-ground link and then successfully execute an emergency landing.

Use case data have been collected as part of previous efforts for the FAA. For example, Cathey and Hottman (2017) provide an overview of use cases for BVLOS operations. Eleven general use cases were identified. However, given the variety of applications, type of vehicle and size, not all use cases require the same set of rules. The use cases identified are grouped into two categories: applications defined or desired to fly BVLOS and applications not defined to fly BLVOS. These categories encompass the following use cases:

- Defined or desired to fly BVLOS: Aerial Data Collection, Aerial Surveying/Mapping, Agriculture, Emergency Services, Inspection, Research, Search/Rescue and Surveillance/Monitoring.
- Not defined to fly BVLOS: Aerial Photography/Videography, Flight Training/Education and Marketing.

Additionally, Cathey et al. (2019) identified 47 subcategories. This effort allowed for the collection of a greater amount of information considering new emerging applications and industry needs.

Based upon the use-case taxonomy developed by Cathey and Hottman (2017) and Cathey et al. (2019), the following use case areas are most ideally suited to readily leverage shielding:

- Aerial Data Collection (e.g., construction)
- Aerial Photography/Videography (e.g., construction)
- Aerial Surveying/Mapping (e.g., engineering)
- Flight Training/Education (e.g., sUAS training)
- Inspection (e.g., wind power, oil/pipeline, etc.)
- Marketing (e.g., aerial images)
- Multiple Applications
- Research
- Surveillance, Monitoring, etc.
- Other UAS Applications

Of these, inspection stands out as a use case for which shielding is currently being applied and for which there is significant demand for shielding (Interdrone 2021). From their taxonomy, use case areas that are not listed above are:

- Agriculture
- Emergency Services
- Search/Rescue

Even for these, novel approaches might try to leverage shielding. Thus, shielding could be utilized for a large set of use cases.

2.8.3 SARP Research on Shielding Concepts

The SARP provided three recommendations for maintaining well clear in a terminal environment: the well clear recommendation for sUAS (Weinert et al. 2018), obstacle-shielded operations, and airspace structure (Lester and Weinert 2019). The final recommendations for these means are provided in an unpublished manuscript but are described with little deviation from the final form by Lester and Weinert (2019). For obstacle-shielded operations, Lester and Weinert (2019) defined Unmanned Aircraft (UA) to be well clear of manned aircraft if they:

- Remain within 50 ft vertically and 250 ft horizontally of a natural or man-made obstacle.
- Remain at least 2000 ft horizontally away from the movement and non-movement areas of airports (runways, taxiways, and ramps), helipads, and low-altitude helicopter routes.

The 50 ft vertical recommendation assumes that aircraft will attempt to maintain at least 100 ft vertical separation from obstacles. This is supported in part by the recognition that helicopters operating below 50 ft (presumably within 50 ft of an obstacle) would be in ground effect, which Lester and Weinert (2019) state is avoided operationally except for take-off, landing, or hover taxing. The degree to which ground effect is avoided, however, is not clear, as ground effect does provide performance benefits (e.g., U.S. Department of Transportation 2019, Chapt. 7). The 250 ft horizontal recommendation is based upon analysis of manned Helicopter Air Ambulance (HAA) flight activity in the city of Boston.

Lester and Weinert (2019) highlight the need for a containment system (e.g., geofence) to ensure that UA do not get too close to movement areas, non-movement areas, helipads, and low-altitude helicopter routes. They also highlight the need for a containment system to ensure that the sUAS remains an appropriate distance from an obstacle or terrain, with a possible option being §2.5.3 of the JARUS SORA (Joint Authorities for Rulemaking of Unmanned Systems Specific Operations Risk Assessment; JARUS 2019). Lester and Weinert (2019) also indicate that additional considerations are needed for existing low-altitude operations such as agricultural spraying, parachute operations, and powered/unpowered ultralight operations.

2.8.4 NASA Work on Shielded Operations

One of the research efforts related to shielded concepts is the NASA Safe Autonomous Flight Environment for the Last 50 Feet (SAFE50) presented by Ippolito et al. (2019). This project aims to establish, analyze, and validate a reference design for fully autonomous large-scale UAS operations, seeking to enable low-altitude high-density urban operations through advanced autonomy. Verification and validation of the design are performed through simulation, hardware prototyping, and flight testing. NASA is developing an UTM research platform that instantiates an Application Programming Interface (API) based coordination of UAS operations and services into a research software development. At the time of publication (2019), the UTM system design concept is at the Technical Capability Level 3 (TCL-3), allowing BVLOS operations away from people, property, and other air vehicles. The TCL-4 capability level includes operations over highly populated urban environments, high-density populations, higher levels of vehicle autonomy, and inter-vehicle interaction. The SAFE50 requires all vehicles to be equipped with the requisite cooperative SA/CA system, including the Vehicle-to-Everything (V2X) communication and avoidance control laws. The concept involves interaction between the UTM and UAS and requires submitting a mission objective and contingency plan that contains destination and emergency landing locations. If a contingency event occurs, the UAS will broadcast the emergency to surrounding vehicles through the V2X communication link and send an emergency notification to the USS when the air-ground link allows. The vehicle will execute either an emergency landing at a designated safe landing location, execute an emergency landing at a safe location determined by the dynamic ground object detection system, or perform a flight termination maneuver (Ippolito et al., 2019).

2.8.5 Current Standards Efforts

The ASTM working group "WK74215 - Revision of F3442/F3442M-20 Standard Specification for Detect and Avoid System Performance Requirements" is evaluating shielding as an option for maintaining well-clear of manned aircraft. Aircraft data have been analyzed to estimate stand-off distances relative to man-made obstacles. This work has not been publicly released. However, the results of this work have been shared within the working group and with this ASSURE research team (Andrew Weinert 2021, personal communication).

2.8.6 Factors Affecting Shielded UAS Operations

To safely integrate shielded UAS operations into the NAS, UAS collision risks need to be properly understood and addressed. The identification of obstacle objects sharing the airspace with UAS consists of both airborne and ground objects. Rattanagraikanakorn et al. (2018) clearly identify these objects and systematically analyze collision consequences.

Moreover, a risk and hazard analysis was performed for the SAFE50 design study (Ippolito et al., 2019). In this study, the identified actors involved in the development of shielded UAS operations include the general public, supplemental service data providers, regulatory agencies, insurance companies, other aircraft, DGOs, and SGOs.

Global Navigation Satellite System (GNSS) vulnerability due to shadowing, signal attenuation, multipath, and signal blockage typical from urban environments also affect shielded UAS operations, making UAS flights vulnerable to navigation issues. Additionally, intentional denial, spoofing attacks, or jamming also affects UAS operations relying on GPS sensors. Therefore, according to Strümpfel et al. (2020), to enable UAS operation at any time in any environment a navigation capability is required that is robust enough and not solely dependent on GNSS. Alternatives to GPS have been widely studied in the literature and are mentioned in Section 2.8.4.

Moreover, high quality and accurate obstacle data is an important factor for shielded operations since, most of the time, these operations will happen in complex environments autonomously and in BVLOS conditions. These drones will need to ascend/descend in very close proximity to man-made structures such as buildings, cell-towers, and high-voltage electrical power cables. The study published by Hunter & Wei (2019) summarizes some of the challenges for UAS separation assurance and identified two key factors affecting UAS operations: the lack of airspace structure and unclear responsibility and legal authority. From the same study, Table 2 summarizes some of the significant challenges that sUAS faces with respect to traditional manned aviation. According to the authors, geofencing, No-Fly zones, and dynamic restrictions all add structure to the airspace. But they often are temporary and sometimes dynamic, adding more complexity to the factors affecting shielded UAS operations.

Table 2. sUAS Separation Assurance Challenges - Modified from Hunter & Wei (2019).

Traditional Manned Aviation	**Small UAS Challenges**
Consistent vehicle performance	Diverse vehicle performance
Good maneuvering capability	Limited maneuvering capability
Performance robust in weather	Performance poor in weather
High situational awareness	Limited situational awareness
In situ decision making	High levels of autonomy
Highly reliable communications	Communication link failures common
Emerging, ADS-B, surveillance	ADS-B not scalable to dense ops
Air data and weather radar in situ	Little or no in situ weather data
Ground-based surveillance radars	No independent surveillance
Ground-based navigational aids	No navigational aids
Structured routes and airspace	Little airspace structure
High-altitude flight, good LOS	VLL, often blocked LOS, clutter
NAS-wide ATC services	No ATC services

Homogeneous O-D missions	Diverse mission types
Ops segregated from public	Ops integrated with public
Scheduled predictable ops	Unscheduled, unpredictable ops
SAA is time-tested and mature	DAA can fail in high density ops
Simple separation criteria	Complex separation assurance
Clear lines of legal responsibility	Legal responsibility unclear

2.8.6.1 Wind and Turbulence Effects

The study of wind around buildings in urban environments is fundamental for wind flow problems, including natural ventilation design, pedestrian comfort, pollutant dispersion, and operation of aircraft, among others. Wind tunnel experiments are considered the most suitable approach for evaluation of wind flow, velocity, and turbulence intensity; however, with the growth in computer technology, numerical methods have emerged as an alternative for studying complex wind flow scenarios through Computational Fluid Dynamics (CFD). Most wind flow investigations are focused on flow around a standard shape, cubes, or prisms, and very few studies exist for non-standard building shapes (Hassan & Anina, 2014).

The work presented by Tutar & Oğuz (2004) focuses on the numerical evaluation of wind effects around buildings with different configurations (two or more buildings). The CFD was used in this study, given that most of the experimental data and studies available in the literature are available for single building configurations. The two-building model demonstrated that the passage between buildings forms a channel along which the airflow passes, known as “channeling effect,” which modifies the wind flow, sometimes causing dangerous environmental conditions. The simulation performed indicated that an increase in the passage width causes a decrease in the strength of the wind vorticities and the velocity. Another concluding remark from this study is that in reality, wind flow is not laminar but turbulent, and it can come from any direction with different speeds. For instance, the turbulent flow is almost always a disturbed layer whose thickness can be greater than the height of a building. Liu et al. (2018) concluded that the surrounding buildings had a considerable impact on wind flow due to the sheltering and channeling effect. These results were achieved using a CFD simulation that used detailed building structures representation. The results from this study can serve as a guide for predicting wind flow around buildings.

Another study regarding wind flow near buildings is presented in by Hunt (1975). The authors determined that in the lee of a building the wind speed is reduced, and the gustiness increased, making landing aircraft vehicles near buildings difficult and dangerous. This is one of the reasons why civil aviation authorities are concerned about buildings near airports. Another aspect of consideration from this study is that the velocity of the wind varies with height, and the effect is strongly felt by pedestrians near tall buildings through extreme fluctuations and high winds. According to the authors, since wind speed increases with height, this leads to an upwind and reverse flow near the ground. This effect directly affects shielded UAS operations operating in urban environments, especially in applications such as structural inspections of tall buildings.

In addition, UAS navigation in low-altitude urban environments presents uncertainties and difficulties caused by interactions between the vehicle, wind, and structures. As mentioned in Ippolito et al. (2019), urban environments contain unpredictable atmospheric hazards characterized by unsteady winds. Atmospheric instability occurs when a vertically displaced air particle accelerates in the direction of displacement, which can occur in urban environments and affect vehicle performance. Correction models exist but are not trivially applied to urban environments.

Many of these challenges occur in the Atmospheric Boundary Layer (ABL), which is the wind layer up to altitudes generally ranging between 100 m to 3000 m, varying in time and space as a function of ambient conditions (Luo & Zhou, 2006). Barber et al., (2021) defines the various constituents of the ABL. The Urban Canopy Layer (UCL) is the layer beneath the mean height of buildings and trees that is affected by rapid changes in time and space, where a high variation in wind speed and turbulence is caused due to the high density of structures where the air is recirculated and diverted. The Urban Boundary Layer (UBL) is located above the UCL and includes the vertical structure of the atmosphere in and above cities. The same study further hypothesizes that the UBL is nearly always in a state of turbulent motion. Within the UBL are sub-layers such as the Urban Outer Layer (UOL) and Roughness Sub-layer (RSL). An illustration of the different layers is shown in Figure 10. Other atmospheric hazards that impact small UAS while performing urban operations include regional weather phenomena, thermals, dust devils, and turbulence. The rapidly time-varying atmospheric changes experienced in urban environments are complex, difficult to predict and detect, and represent a high risk to small vehicles.

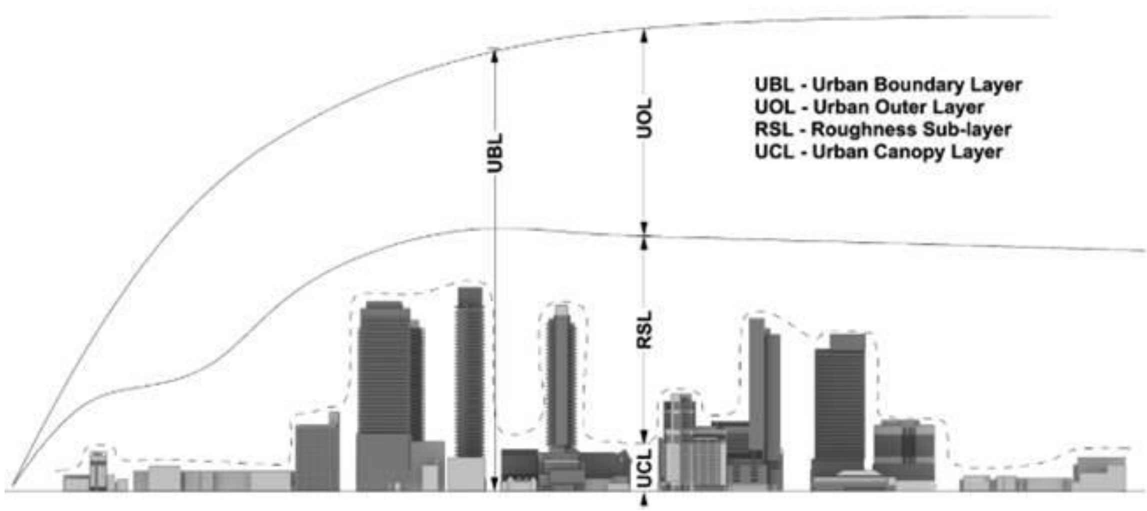

Figure 10. Sublayers of the urban boundary layer (Barber et al., 2021).

2.8.6.2 Bird Densities and Behaviors Near Structures

Effects on birds near structures have been widely studied by Drewitt & Langston (2008). According to the authors, factors that increase collision risk include structure location, structural attributes such as height and use of lighting, weather, and bird morphology and behavior. For example, the use of external and internal lighting in tall buildings is a critical factor related to bird collision since birds are attracted to them or get disoriented. Size and dimensions also influence bird-strike, especially in poor weather conditions and visibility. Another concluding remark from this study is that location increases collision risk if a structure is placed on or near areas regularly used by feeding, breeding, or roosting birds. The most relevant effects of manmade structures include habitat loss, fragmentation, displacement due to disturbance, and death and injury due to collision.

With respect to bird behavior around UAS operations, a relatively sparse amount of work reporting the interaction of birds (avifauna) with UAS operations has been published in the last five years, which suggests that this topic is still being studied and is developing. In the work presented by Mulero-Pázmány et al., (2017), it is indicated that the factors which influence the probability and intensity of animal responses depend on the characteristics of the disturbing agent (e.g., size, noise, speed, distance, angle of approach). Furthermore, the authors were able to analyze data about wildlife reactions towards UAS from 36 published studies. These studies analyzed reactions of flightless birds, large birds, small birds, terrestrial mammals, and underwater species. The study showed that birds are more sensitive to UAS, with flightless birds and large birds being more sensitive. On the other hand, terrestrial mammals are less reactive than birds and aquatic animals are the least affected animal type.

With respect to noise levels, on the same study it was detected that high noise engines produce more animal reactions. The animals are affected by changes on noise intensity, which for UAS is related to speed and trajectory changes. Additionally, the size of the UAS also affects animal reactions, probably because as the size increases the perceived risk and threat also increases. Another concluding remark by Mulero-Pázmány et al., (2017) is that flight patterns trigger bird behavior and have significant effect on animal responses. For example, target flights, mainly for animal photography, nest inspections, or animal control, produce more reactions and higher disturbance. Other flights such as mapping and surveillance, performed at higher altitudes are less likely to disturb animals. As a result, animal responses could be related to anti-predator behavior.

In a recent work presented by Holldorf (2018), an initial identification of factors that affect the behavioral interaction and how birds will respond to UAS operations was performed. The study included a literature review of 38 references, and it was complemented with an original survey provided to the US Department of the Interior Remote Pilots regarding their field observations of avifauna while flying UAS missions. Providing a quantification of taxonomic groups, Holldorf (2018) states that around 87 species of birds including birds of prey, flightless birds, wetland birds, hummingbirds, passerine birds, seabirds, and waterfowl have been exposed to UAS and their response varied largely from being mildly responsive to being severely antagonistic or evasive to the UAS. The study also expands in determining the safety setback distance or buffer for UAS to mitigate potential negative effects on birds. Specifically, the study suggests instituting a 100 m buffer between UAS flights and the nearest bird habitat or individual sightings to avoid wildlife impact, minimize disturbance, or mitigate any behavioral or negative interaction. If there are no predatory birds in the area where missions will be conducted, 75 m is also likely a safe buffer distance to avoid any impacts to avifauna species. If there are birds of prey known to be in the area, or if they are seen overhead foraging, where possible, a 125 m buffer should be in place to avoid any impacts to avifauna species (Holldorf, 2018). These numbers were suggested based on data obtained from initial response distances of avifauna-UAS interaction, as presented in Figure

11. Initial response distances indicate that birds of prey had the highest average distance, and they exhibited a response from the further distance from the UAS operation.

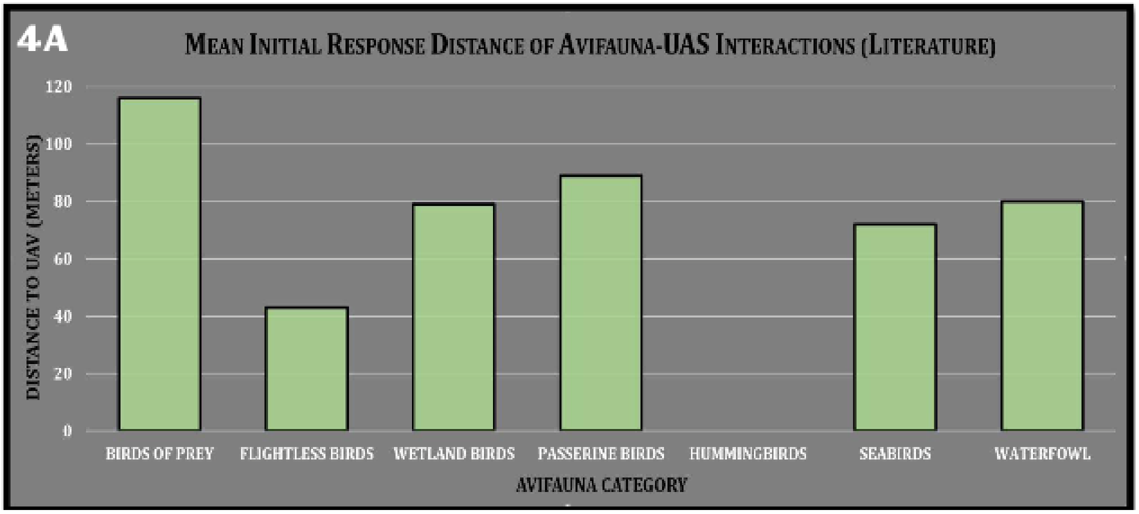

Figure 11. Initial response distance of avifauna-UAS interactions (Holldorf, 2018).

Another concluding remark from this study regarded the type of UAS maneuvers and flight parameters that affect or trigger any specific bird behavior. For example, in the study performed by Vas et al. (2015), the authors found that marked bird reactions were likely when the aircraft was approaching directly overhead of a group of waterfowl – but a decreased vigilance was noticed when the aircraft was approaching the same group from a low angle with respect to the horizon. Another study by McEvoy et al. (2015) stated that a rapid or abrupt approach or overhead changes in direction often caused an increased disturbance resulting in various instinctive reactions from birds. These behaviors are consistent with aerial predator hunting strategies to which birds have developed instinctual responses.

One more aspect to consider when characterizing bird behaviors when interacting with UAS are environmental factors. Wind, vegetation density, noise, and magnetic fields could significantly affect how birds react to UAS. Some studies, such as Hanson et al. (2014) and Hughes et al. (2017) suggest these potential factors without exclusively testing them.

Some measures proposed by Mulero-Pázmány et al. (2017, p.9) to alleviate the high disturbance of bird groups due to UAS interactions include:

- Minimizing noise by choosing electric UAS models over those that are fuel-powered or conducting flights in times of high ambient noise.
- Avoiding the breeding season for sensitive species.
- Conducting flights using slow, sinuous movements like a lawn-mower pattern rather than directly approaching or descending upon the target species.
- Developing situational awareness based on the environmental factors to be included as "avifauna checklist." This should include a local bird identification guide or online range mapper to identify what species might be present in the area and distance thresholds to reduce potential impacts on bird species.

2.8.6.3 Likelihood of GPS Outages

According to Rufa & Atkins (2016), past research has shown that GPS availability rates in urban environments range from 30% to 50%, and that this signal degradation is related to factors such as multipath, significant signal attenuation, masking, or even intentional acts such as jamming, denial, or deception. Some of these types of malicious interventions like jamming and spoofing are described by Nighswanger et al. (2012). In jamming attacks, significant radio frequency (RF) noise is transmitted to prevent the receiver from acquiring a satellite signal. On the other hand, GPS counterfeit signals are generated in spoofing attacks, causing the receiver to have incorrect positions and data. However, in both situations, the attacks are not on the receiver software itself. A deeper analysis of modeling and characterization of GPS spoofing is developed by Larcom & Liu (2013). This work describes attack models in diverse scenarios to analyze possible vulnerable aspects of civilian GPS. In a similar work presented by Kerns et al. (2014), the authors investigated through modeling the sufficient conditions needed to successfully spoof and capture an autonomous drone and demonstrated with field tests the capturing of a simple UAS via civilian-based GPS spoofing. Furthermore, implementing simulation environments, Kerns et al. (2014) showed that by spoofing GPS receivers, if the spoofer's estimation errors of the UAS position and velocity are below 50 m and 10 m s^{-1}, respectively, the spoofer is capable of reliable and covert capture of the target drone's control. The coupled dynamics of the UAS and spoofer showed that a GPS spoofing attack could force a UAS to unknowingly follow a trajectory imposed by the attacker and counterfeit signal. The feasibility of these conditions and spoofing attacks were field demonstrated and confirmed.

As mentioned by Ippolito et al. (2019), flight operations in urban environments are expected to be developed in degraded or denied GNSS/GPS conditions. Moreover, urban canyon environments are not reliable to utilize satellite-based communication for Over-The-Horizon (OTH) communication. Additionally, operations near urban canyons represent a challenging RF environment, resulting in disruptions to wireless communication, degraded air-ground communication and satellite-based communication, line-of-site blockage, and signal reflections.

From the cyber-security perspective, since GPS localization relies on active communication, signals are transmitted and received between different nodes, exposing itself to external intervention. As presented by Yu et al. (2012), weaknesses in the software of GPS manufacturers can be identified. Although security measurements have been taken to overcome this problem—validation algorithms in the communication protocols, filters, and attack detectors, for example—the constant innovation of technology also allows for new jamming and spoofing techniques that exploit hardware and software weak spots.

As mentioned by Haider & Khalid (2017), spoofing counter-measure techniques could include monitoring GPS signal strength, satellite identification codes, timing comparison, and counter checks with IMU or sensor data.

2.8.6.4 Electromagnetic Interference (EMI) and Communication & Control (C2) Degradation

In recent years, the integration of unmanned aircraft and inspection robots in electromagnetically polluted environments has expanded, reducing operating cost and improving operating efficiency. An example of these applications is the inspection of power lines and converter station equipment inspections, which strongly interfere with the C2 systems of the drones and might cause collisions of drones with the inspected structure. C2 degradation can also take place in urban concentrated radio frequency (RF) environments where high level of noise and RF line of sight obstructions represent sources for degraded air-to-ground (AG) communications. Additionally, satellite-based communications, specifically GPS satellites that operate at 1.5GHz are affected when solar storms produce changes in the ionosphere characteristics. These events cause signal fades and add small delays in the GPS signals. This also makes difficult to gain and maintain satellite signal locks.

Li et al. (2021) addresses the importance of analyzing the characteristics of the interference from power converter station equipment with UAS. According to the authors, the sources of Electromagnetic Interference (EMI) experienced by UAS can be divided into 'in the system' and 'outside' the system. Table 3 shows sources of EMI that can affect C2 and other systems.

Table 3. Sources of UAS electromagnetic interference and coupling methods (Li et al. (2021).

Source of Electromagnetic Interference			**Electromagnetic Coupling Approach**
	UAS Power Ignition Devices		Power Port
In the system	Airborne measurement and control launch equipment		Digital signal Port
			Low frequency analog signal port
			Radio frequency port
	Actuating device and equipment with large current changes and intermittent contacts		Power port
	High current inverter power supply and switching power supply		Power port
	High-IF digital circuit and mission load with similar circuit structure and radio transmission		Digital signal port
			Radio frequency port
Out of the system	Natural electromagnetic phenomenon (high altitude)	Atmospheric noise	
		Cosmetic Radiation	
	Man-made electromagnetic phenomena (low altitude)	Various electromagnetic fields intentionally generated by radio transmitters and additional electromagnetic fields generated by these transmitters and other technical equipment	

Additionally, Li et al. (2021) mention that the effect of electromagnetic interference in the control communication system of a UAS can be divided into the UAS data link communication system and the UAS navigation and positioning system. The UAS data link communication system is responsible for transmitting the uplink control signal and the downlinked image transmission signal. The UAS navigation and positioning system is responsible for positioning and navigation. If the data link is affected, it may cause the system to lose connection or crash due to the lack of control, which will reduce the reliability of the control system and affect safety. Therefore, the importance of the study of the impact of electromagnetic interference on the UAS data link.

In the same study, the authors state that image signal transmission from cameras under the effect of electromagnetic interference will be distorted, causing the number of transmitted image pixels to be reduced and increased error. Additionally, the UAS components that are susceptible to being affected by EMI mainly include flight control systems, measurement modules (IMU, GPS, barometer, magnetic compass), and signal receivers. Therefore, the goal of designing new methods and measurements to protect UAS against electromagnetic interference relies on how to protect these sensitive devices. Literature has shown that in traditional electromagnetic shielding, conventional conductive or ferromagnetic materials (copper, iron, aluminum, and other metals) are used to protect objects from electric fields, magnetic fields, and electromagnetic waves. However, since drones are built with lightweight materials, conventional shielding materials are usually not used to make UAS fuselages. UAS fuselages are usually made of plastics or carbon fiber composite materials. Despite this, some researchers have made attempts to apply metal layers and other electromagnetic wave shielding coatings to plastic fuselages to turn them into Faraday covers and achieve an anti-electromagnetic interference effect.

Other measures presented by Li et al. (2021) to insulate materials without adding special parts in the UAS include using filling materials to fill all the gaps in the drone to prevent electromagnetic waves from entering. Filling materials include wire mesh pads, conductive cloth pads, and soft metals, among others. Moreover, optimizing the design of the UAS plays an important role—for example, keeping the important system components such as the flight control system and the measurement system away from interface and gap to weaken the effect of electromagnetic waves.

Zhang et al. (2019) established a physical model of the UAS in a complex electromagnetic field to analyze the influence of the UAV on the electric field distortion. They calculated the maximum magnetic and electric field strength that the UAV can tolerate. Their simulation results show that the electric field distribution on the UAS surface is not linear or uniform. The field strength distribution is concentrated at the rotating motor and the tip of the wing, and the electric field distortion is significant. In this study, the authors also found that the UAS safety inspection gave a wind speed of 3 m/s and an inspection speed of 5 m/s with a magnetic field strength of 180 μT and electric field strength of 50 kV/m.

The complete investigation of the UAV inspection's common voltage level also reveals that the relationship between the UAV minimum safety inspection distance and the current in the conductor is approximately d(m) = I (kA). Therefore, when the UAV inspects the power towers or transmission lines, it should maintain a minimum safety distance from power towers. Figure 1 shows the relationship between the maximum electric field strength and magnetic field of the surface of the UAV and the distance.

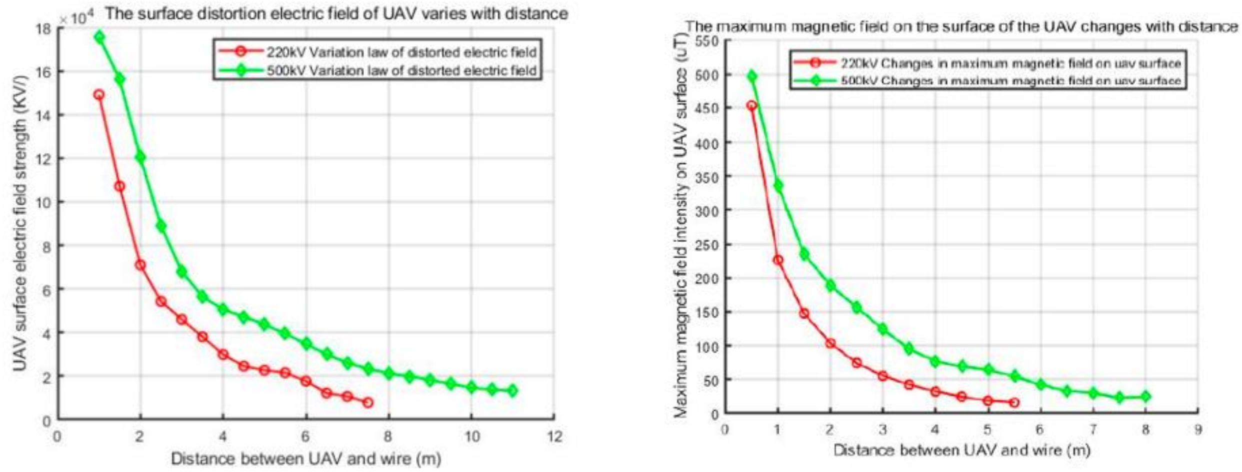

Figure 12. Variation of surface distortion electric field of UAV with distance and Maximum magnetic field on the surface of the UAV changes with distance

Li et al. (2021) developed a mathematical transmission line spatial distribution model to investigate field strength distribution information around overhead transmission lines. In this study, the authors used COMSOL Multiphysics simulation software to analyze electric field intensity distribution law around overhead transmission lines with three voltage levels (110 kV, 220 kV, and 500 kV). Their analysis results show that the electric field distribution around the overhead transmission lines with different voltage levels is approximately the same for the same arrangement (horizontal distribution, regular triangle distribution, or inverted triangle distribution). However, the electric field intensity distribution has a high value near the mid-phase conductor. Moreover, the electric field strength slowly decreases away from the transmission line, with the highest electric field strength at the source, and varies with the voltage level (Figure 2). The higher the voltage level, the faster the electric field strength changes. At the same time, the electric field intensity of different voltage levels at the same location is not the same; therefore, the safety distance of UAV inspection increases as the voltage level increases.

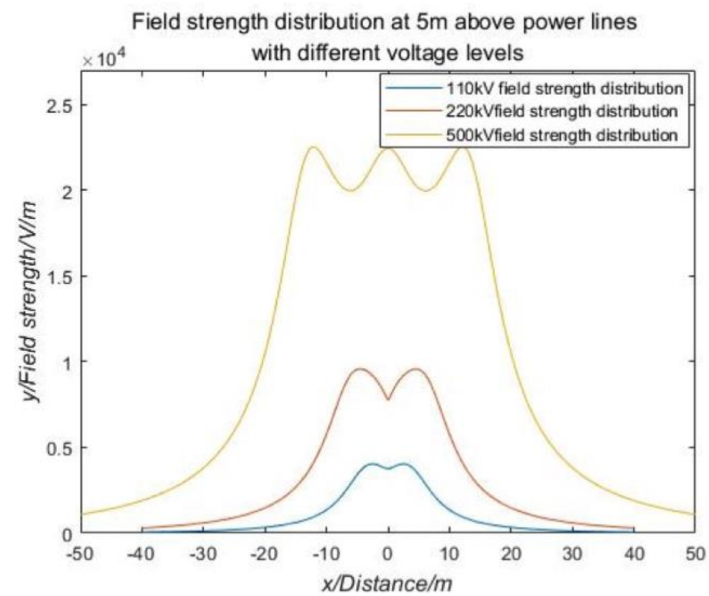

Figure 13. Distribution of field strength at 5m above transmission lines for different voltage levels (Heggo et al. 2019)

In the study performed by Li, Yincheng et al, (2021), the effect of high electrostatic fields on an inspection UAS was investigated regarding AC corona emissions interference and air breakdown voltage. In another article, Heggo et al. (2019) studied the impact of the external magnetic field on the operation of an inspection multicopter's propulsion motors. The simulations and experimental results show the major effects of corona emissions are on the UAV autopilot system and actuation sections. They concluded that failures in the motor and autopilot sections could result in uncontrolled UAV navigation, endangering expensive assets inside the HVDC valve hall.

Esteves et al. (2018) focused on studying the impact of intentional EM interference on UAS by exposing the system to parasitic signals. This resulted in a temperature change of the UAS sensors, leading to erroneous data collection. The sensors reported variations on the vertical speed that influenced the altitude, resulting in a gradual drift of the UAS.

Dixon et al, (2016) monitored the communication systems of the UAV (both data and control links) in the free space environment and in a complex multipath one (multiple EM sources). They provided detailed performance results for the different links in different bands. During the EMI set up, the control link failed as the receiver could not get comprehensible data packets which triggered the UAS to enter the failsafe mode. The authors also concluded that all UAS links are more sensitive to wider bands interference.

Additionally, navigation near structures such as buildings, cell-towers and high-voltage electrical power cables could be alleviated by implementing geofencing systems. These systems have been widely studied by Stevens & Atkins (2018) and are defined as a virtual three-dimensional boundary that restricts access to UA. These are defined around the structure obstacles to create NFZs. Additionally, NFZs can be static or dynamic and their boundaries can be time varying. The federal government is responsible for establishing geofence boundaries around national monuments, national parks, military bases, and other similar areas. In addition, landowners can establish geofences around their property and utility companies can implement geofences around their infrastructure to enable UAS to navigate around lines. Moreover, static geofences may be used to mark constant airspace obstacles, such as buildings.

Qiu et al. (2017) performed an investigation on the propagation channel characteristics of small UAS at heights from 0 to 100m at which the signal propagation is affected by the environment and the heights of the adjoining obstacles. In this work, the authors also developed models to characterize the effects of the reflection, diffraction, and scattering of the environment at low altitude air-to-ground channel. Multiple flight tests were carried out using a 3Kg hexacopter with 2kg payload and 20min flying endurance. A 2.4GHz link was used to control the system which was also monitored from a ground station for height, speed, and position. According to these simulations and experimental measurements from a multi-path rich environment, such as the ones taken in a suburban open area with many buildings, metal containers and trees, it was found that fading behavior of the communication channel to the drone is directly related to the flying height and not the distance or elevation angle at low altitudes. When the altitude of the sUAS is very low, the scatterers near the ground give a large amount of multipath fading to the channel and the propagation is greatly affected, whereas at higher altitudes the influence gets mitigated. For example, in the same study the authors developed a model where it was assumed a reflection from the side of the obstacle with a reversed two-ray model, as shown in Figure 12. As depicted, Hb is the height of the obstacle and hr is the height of the reflection point. While the drone increased altitude, the reflection point starts moving up as well until it disappears when the drone reaches a specific altitude. At this point, the effects of scatterers mitigate and hence the quality of channel communication improves greatly. It was also found that such behavior can result in a decrease of multipath components, which was consistent with observations from measurements performed by the authors.

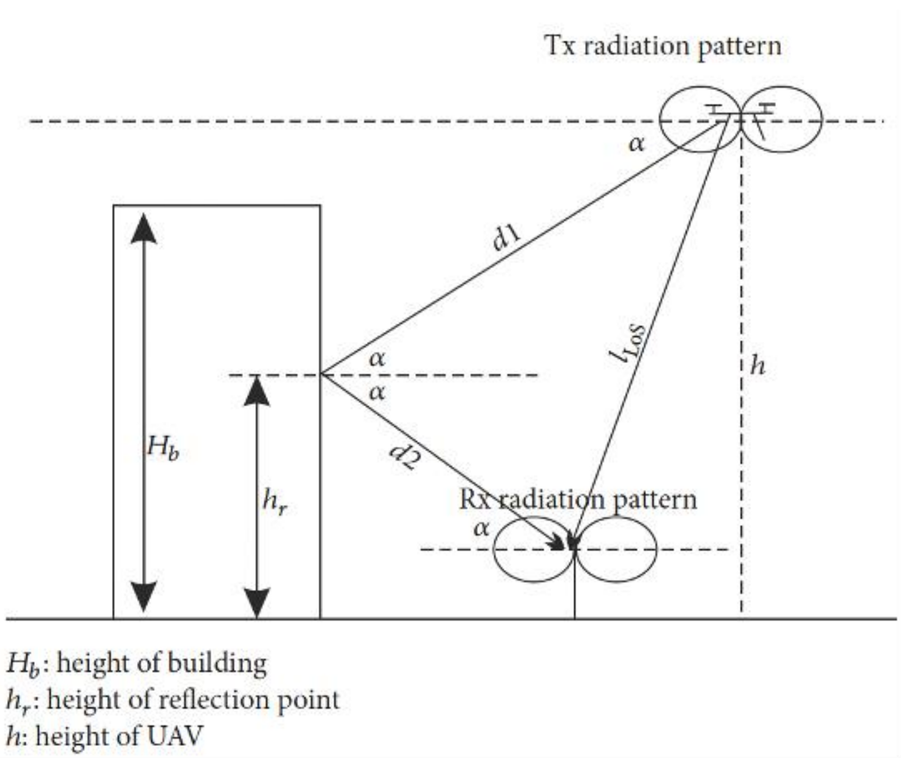

Figure 14. Sketch of the reflection from the sidewall (Qiu, 2017)

In another study performed by Williamson et al. (2016) for FAA, an assessment of Radio Line of Sight (RLOS) coverage and connection for sUAS through flight experiments. The main purpose of the study was to elements in the connection that might affect safety of operations, specifically if flying BVLOS. Various factors that affect RLOS range include type of terrain, weather, frequency in use, antenna gains, transmitter power, received sensitivity. Commercial out of shell radios (3DR v2 telemetry SiK radio with stock antennas) were used for this study. The radios were operating at 915MHz with 100mW transmitters (20dBm). The authors concluded that analytical models available in the literature mostly differ from in field testing performed in the study along with RLOS real world conditions. They pointed out that mathematical model trend to reproduced only ideal conditions and neglect specific influences that actual impact the link distances. Additionally, the authors suggest that supplied radio specifications are provided under ideal conditions and may overestimate RLOS distance in real world conditions and applications.

C2 can also be affected by space weather that refers to environmental characteristics in the space around the Earth and that can be extended up to the Sun. As part of this phenomena, electromagnetic radiation and energetic charged particles interact with Earth's atmosphere and magnetic field. Many systems, such as GPS, that rely on radio-wave signals interacting with the ionosphere to determine range or distance, are particularly affected and vulnerable to space weather. Variations of electron density change the propagation velocity of these radio waves, translating into propagation delay, fluctuation of phase and amplitude of the signals. This effect also known as scintillations, are known to be caused by irregularities of the order of the first Fresnel zone size (Astafyeva et al., 2009). Many other systems and services, such as avionics, high and low frequency communications, satellite communication (200 MHz to several GHz), ground-to-air, ship-to-shore and amateur radio communications, along with VHF propagation (30-300 MHz), can experience degraded operation, short lived communication outages or total loss of function during high solar storms and/or space radiation levels through ionospheric reflectivity (Astafyeva et al., 2014; Rama Rao, et al. 2009).

2.8.6.5 Positional Accuracy of Obstacle Maps

Drone obstacle avoidance capabilities are not always available. In these cases, automated flights are not possible for high-value operations such as infrastructure inspections, package delivery, search and rescue, and disaster relief operations, where drones fly close to the ground, buildings, and trees. This limiting factor always requires a human pilot with VLOS to ensure collision avoidance. Therefore, the acquisition of high positional accuracy obstacle maps is of interest.

Currently, informational maps exist that show the maximum altitudes around airports where the FAA may authorize art 107 UAS operations without additional safety analysis. These maps are UAS Facility Maps and are used for airspace authorizations and waivers in controlled airspace as a quick source of information prior to submitting a waiver request. During the Drone Advisory Committee (2020), the UAS Facility Maps Tasking Group determined that the UAS Facility Maps should be refined since updated data now exists to support more precisely defined margins in controlled airspace. Furthermore, the tasking group recommended grid size on UAS Facility Maps should be reduced from 1° to ½° grid squares given that some zones have unnecessarily low AGL limits and, therefore, no UAS low altitude operations are allowed. Grids previously set to 0 ft AGL could be used for potential UAS shielded operations if they are obstructed by a natural or man-made obstacle. Additionally, during the meeting, the group requested introduction in UAS Facility Maps a "flying below the top of a structure or obstacle" option. It was recommended that the FAA show existing survey or other obstacle data on UAS Facility Maps that could be used for shielded operations approval. The tasking group also mentioned the possible use of dynamic grid maps.

In the study by Denney & Pai (2016), the authors gathered previous UAS missions and identified similarities amongst the specific hazard control mechanisms and the applicable safety systems. Specifically, the prime focus of the paper is to identify safety considerations regarding obstacle avoidance maneuvers. For example, minimum obstacle avoidance maneuver times can be determined from a combination of the times to: detect an intruder, track the intruder and establish that it is a threat (classified as a credible threat, based upon its trajectory), determine the exact avoidance maneuver to be used, command and transmit the maneuver to the UA, process the command and actuate the maneuver, and complete the maneuver given the environmental conditions (e.g., wind speeds). The definition of avoidance maneuvers is based on the determination of key parameters such as vehicle performance, communication, and airworthiness. The process then entails following a logic to select the appropriate avoidance maneuver with an order of preferential execution, i.e., some level of escalation of threat and avoidance that are defined relative to identified contingency locations, including lost-link points, flight termination points, and Divert/Contingency Points (DCPs). Denney & Pai (2016) provides few examples of avoidance maneuvers, notably:

- Abort and return to base, i.e., immediately suspend the current flight plan, and return to the takeoff/launch location at the maximum speed.
- Divert and loiter, i.e., divert to a safe DCP, descending/ascending to a safe altitude, and loiter at that location until otherwise commanded.
- Divert and land, i.e., suspend the current flight plan and descend at the maximum descent rate after navigating to a safe DCP.
- Land immediately, i.e., suspend the current flight plan and descend at the maximum descent rate from the current location.
- Terminate, i.e., immediately shut-off of all propulsion, resulting in a (possibly uncontrolled) descent while taking measures to halt forward motion.

Complementary to this, in the proposed SAFE50 reference design study (Ippolito et al., 2019) it is expected that prior to flying the UAS operator will provide to the UTM a mission objective that meets minimum risk and safety requirements. The mission objective must include destination location and emergency landing locations and ideally, might plan to avoid areas of high winds or traffic. If a failure occurs, the UAS may identify emergency landing zones and identify contingency plans to reach the nearest emergency landing zone.

2.8.6.6 GPS Navigational Performance of UAS

For UAS, GNSS such as the GPS represents one of the most reliable solutions for position and navigation. However, operations in urban environments are often referred to as GNSS-challenged environments due to limited availability and deteriorated navigation performance. This also may include isolated environments with a lack of signal reachability. As described by Pollack & Ranganathan (2018), GPS systems are highly vulnerable to large-scale failures, hacker attacks known as jamming and spoofing, and interference from natural phenomena in specific geological locations and weather conditions.

In a more recent work sponsored by NASA (Ippolito et al., 2019), a set of assumptions, concepts of operations, challenges, and design requirements were investigated to characterize flight operations of emerging sUAS in heavily populated urban centers. One of the goals of the SAFE50 project is to investigate the challenges of integrating and enabling access of sUAS to low-altitude high-density urban environments through advanced onboard autonomy. One of the main concerns discussed in the paper is the flight operations to be developed in degraded or denied GNSS/ GPS conditions. Consequently, operations near urban canyons will result in disruptions to wireless communication, degraded air-ground communication, degraded satellite-based communication, line-of-site blockage, and signal reflections.

Operations within urban environments take place in concentrated RF environments with high levels of noise, degraded signals, and RF issues such as signal reflection, causing impacts on operations relying on GPS signals. Additionally, as mentioned by Strümpfel et al. (2020), potential causes for GNSS unavailability or sparse availability include shadowing effects due to the presence of objects and buildings or deteriorated positioning performance due to multipath and poor available-satellite geometries. Studies have been performed to analyze the relationship between predicted receiver position, satellite constellation positions, and object databases to determine the line-of-sight (LOS) to available satellites.

As previously mentioned, natural phenomena may affect GPS reliability. These include space weather effects such as solar radio bursts, scintillation, geomagnetic storms, and atmospheric refractions and delays. As described by Comberiate et al. (2012), solar flare eruption produces radio waves that reduce the signal to noise ratio of relatively weak GPS signals and interfere with frequency channels used by GPS. In conjunction with solar flares, magnetic storms cause denominated scintillations in GPS signals that arise from spatio-temporal variations in the ionosphere (Alexeev et al., 2001; Alexeev, Belenkaya, Bobrovnikov, & Kalegaev, 2003). Along with this phenomenon, atmospheric effects such as ionic concentrations and temperature, pressure, and humidity variations in the troposphere cause a delay in the communication due to refraction of the signals.

Non-line-of-sight (NLSO) conditions can severely affect the quality of signals and the performance of autonomous UAS. NLSO conditions are common in urban cities where the GNSS signals are partially blocked or reflected by buildings surrounding the UAS. These reflections and disruptions can add significant errors to the expected GNSS measurements and are difficult to account for since these reflections can bounce along various pathways before being received and processed by the UAS. Hsu (2018) investigated NLSO for small UASs in an urban environment. Their GNSS modeling was compared to controlled field tests to assess the modeling accuracy and a mitigation process to reduce noise and error created by the NLSO reflections.

There has been a consensus regarding mitigation strategies in the areas of interest to be investigated: compensation for GPS degradation or absence in the navigation procedure and strategies for detection and countermeasures for cyber-attacks that can disrupt the normal course of action. According to Strümpfel et al. (2020), to enable sUAS operations at any time in any environment, a navigation capability is required that is robust enough and not solely dependent on GNSS. Since GNSS based UAS navigation in urban environments is severely affected by signal degradation and unavailability of GNSS, there is heavy interest in identifying new navigation strategies including trajectory optimization and multi-sensor fusion utilizing a combination of inertial sensors, urban maps, and ground-based navigation.

With the use of these strategies, it is expected that as soon as the GNSS is affected, the technology must assess what alternative positioning strategy is available and switch to a different navigation method. A widely studied alternative is the inertial measurement unit (IMU). The advantage of using IMU resides in the use of only inertial acceleration measurements, which are not affected by disruptions to wireless communication or degraded air-ground communication. However, a significant disadvantage is that such measurements used to approximate position and attitude suffer drift over time.

For GPS-denied environments, modern alternative approaches utilize visual odometry and, more specifically, Simultaneous Localization and Mapping (SLAM) techniques. An extensive survey of these technologies for GPS denied navigation was performed by Balamurugan et al. (2017). SLAM algorithms allow the mobile system to construct a live map of the surroundings from information obtained with the IMU, onboard cameras, and additional sensors. This methodology allows a vehicle to navigate even in environments with no GPS access.

Laser-based solutions have also been investigated along with hybrid approaches that utilize the observation of features in the environment using laser range scanners and imagery. According to Strümpfel et al. (2020), challenging environments are divided into structured and unstructured environments. Structured environment navigation is characterized by well-defined boundaries such as predictable heights, shapes/sizes, room/corridors, and building materials. Unstructured environment navigation, also known as probabilistic environment navigation, is characterized by irregular dimensions and rough surfaces. One of the advantages of using vision-type sensors, as discussed by Rufa & Atkins (2016), is that they do not depend on any man-made electromagnetic transmission to work properly, which makes them a suitable and complementary sensor to GPS.

Additional techniques that rely on visual odometry include optical flow or feature detection/localization. Optical flow, in particular, can be applied to sUAS operating in proximity to urban canyons or buildings. Using a camera with acceptable resolution, this technique calculates the apparent local velocities of adjacent features (e.g., buildings or the street below) to estimate relative positions within a pre-defined reference frame. Numerical simulations and flight tests have shown that vehicles equipped with combined optical flow-stereo sensors can also navigate 90° turns in simulated urban canyons without relying totally on GPS (Chao et al., 2013; Rhudy et al., 2015). Furthermore, feature detection/localization uses vanishing points to measure aircraft pitch and roll angles, which can be used to reset the error in the IMU attitude angle estimate. In addition to supporting navigation, laser and camera data may also be used to support the DAA function to assess the risk of collisions.

Long-term evolution cellular network has also been reported as an alternative concept that could increase navigation accuracy of sUAS in urban centers. Since urban environments usually have numerous towers, the accuracy of localization navigation estimation can be improved as a function of the number of towers available. This concept, however, is still an active area of research (Khalife, 2018).

Network navigation-based techniques that use trajectory optimization of multiple sUASs have been initially studied as a novel solution for GPS-denied navigation. In the work presented by Causa et al. (2018), an optimization algorithm is developed for flying trajectories of multi-UAS missions, associating a vehicle not susceptible to GNSS signal corruption, referred to as “father” vehicle, to support autonomous navigation of a “son” vehicle operating in complex environments. The challenging zones are defined as areas where GNSS satellite signals are not available, and in those areas, the number of father vehicles depends upon the available GNSS information and alternative mitigation sensors.

Light Detection and Ranging (LIDAR) is another potential navigation sensor solution for sUAS navigation in urban canyons. These sensors can operate in GPS- and weather-degraded conditions. According to Rufa & Atkins (2016), this sensor can increase urban canyon navigation accuracy by an order of magnitude compared with traditional GPS/IMU/Odometry. However, the only drawback of using this sensor is the associated high cost for sUAS.

Errors associated with GPS systems in the absence of interference, masking, etc., which are common in urban areas, is important to shielded operations as they help define standoff distances from shielding objects. While enhanced services such as Real Time Kinematics (RTK) are available to be leveraged to provide sub centimeter accuracy for both horizontal and vertical locations, the focus has been on widely available GPS services such as Standard Positioning Service (SPS) and Wide Area Augmentation System (WAAS). SPS is available across the globe, while WAAS covers much of North America, including the continental U.S. and Alaska (FAA Satellite Navigation Branch, 2021a).

As indicated by FAA Satellite Navigation Branch (2021b), the 99.99% errors at FAA WAAS stations for SPS between April and June of 2021 were 6.61 m for horizontal errors and 9.19 m for vertical errors. Since WAAS applied additional corrections, its performance is relatively better. During the same period, the largest WAAS errors for systems having Localizer Performance with Vertical Guidance (LPV) service were 2.41 m for horizontal errors and 5.789 m for vertical errors. It is to be noted that the same study describes that the poorest availability for LPV during the same period was 99.39%.

While GPS performance varies, these values provide guidance regarding standoff distances relative to shielding objects. Means for using such values to mitigate collisions with shielding obstacles, in the context of relevant use cases and the presence of other possible hazards (e.g., turbulent flow), are needed.

Additionally, Rufa & Atkins (2016) performed a comprehensive study regarding sensor accuracy and availability as a function of environmental characteristics. The authors investigated alternative signals to GPS, including cellular network, television, wireless fidelity (Wi-Fi), and signals from other satellites to determine if any of these available technologies would be a viable solution for GPS independent navigation. They concluded that, although LIDAR sensors allow mapping the environment, complementary solutions such as Wi-Fi and cellular network could provide a long-term evolution (LTE) technology to support inertial navigation in GPS denied urban environments. Figure 12 shows a diagram of the possible sensors and existing urban navigation solutions. Furthermore, Table 4 shows the measured states provided by each type of sensor from Figure 12 based on the states for a rigid-body fixed-wing UAS: north position N; east position XE; altitude h; airspeed VT; angle of attack α; angle of sideslip β; the following Euler orientation angles of roll angle φ, pitch angle θ, and yaw angle ψ; and the body-fixed angular velocities of roll rate p, pitch rate q, and yaw rate r.

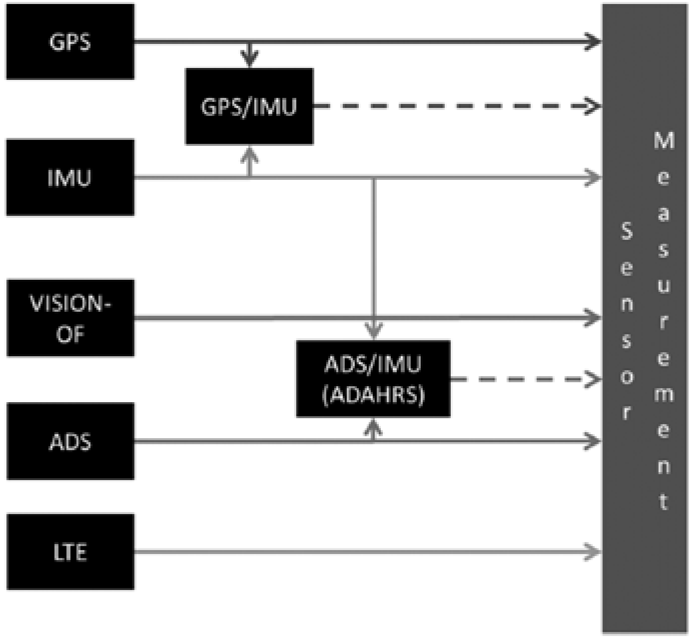

Figure 15. Sensor System Diagram (Rufa & Atkins, 2016).

Table 4. UAS Sensor Information (Rufa & Atkins, 2016).

Sensor	Measured states
GPS	X_N, X_E, h, V_T
AHRS	φ, θ, ψ, p, q, r
Vision	V_T
ADS	h, $V_{T,}$ α, β
LTE	X_N, X_E
GPS/IMU	X_N, X_E, h, V_T, φ, θ, ψ, p, q, r
ADS/IMU	$V_{T,}$ α, β, φ, θ, ψ, p, q, r

Alongside the additional hardware selected for each approach, various guidance algorithms can be integrated as part of a robust navigation solution to address external disturbances and dropouts. These guidance algorithms can enhance the accuracy of the localization, and different hybrid solutions have been studied. As presented in Table 5, possible navigation solutions and a combination of different techniques have been reported in the literature to overcome GPS unavailability (Balamurugan et al., 2017).

One more promising solution for navigation in GPS-denied environments includes nonconventional approaches such as geomagnetic navigation which, combined with machine learning techniques, could represent a potential navigation solution. The United States Air force (USAF) and NASA with the National Oceanic and Atmospheric Administration (NOAA) have been investigating the use of the Earth's geomagnetic field for navigation for over two decades. Some examples are the works of Canciani & Raquet (2017) and Sabaka et al. (2020). This alternative navigation technique, proposed before the GPS era, provides terrain navigation based on map contours. In 1940, Goodyear Aircraft Corporation started developing the Automatic Terrain Recognition and Navigation System (ATRAN), a radar-map matching system capable of correcting flight path deviation by correlating measurements from a radar scanning antenna with a series of maps on board a missile. Later in 1958, this was successfully demonstrated at Holloman AFB by using a three-axis precision magnetometer attached to a plane and finding the best fit between the geomagnetic profile measured during the flight and the corresponding profile in a stored map. With these initiatives, a foundation for modern geomagnetic navigation was established in Goldenberg (2006).

However, this geomagnetic-based methodology is also affected by solar winds and magnetic storms. Currently, machine learning techniques are used to provide support in the forecasting of key magnetic storm indicators for real-time applications, including navigation.

Overall, a combination of multiple approaches is feasible for mitigation of GPS degradation or denial, including permutations of SLAM algorithms, multi-sensor fusion with LIDAR, sonar, IMUs, cameras, and visual navigation, geomagnetic navigation, and machine learning techniques. Regarding spoofing countermeasures, techniques could include monitoring GPS signal strength, satellite identification codes, timing comparison, and counter check with IMU or sensor data as reported by Haider & Khalid (2017).

Table 5. Visual Navigation Solutions in GPS-denied scenarios (Balamurugan et al. (2017).

No	Type of Vehicle	Strategy	Sensors Used	Year
1	AscTec Pelican Quadrotor	Visual Odometry	Stereo camera	2015
2	Quadrotor (GTQ)	Visual SLAM and Laser SLAM with EKF	IMU, Sonar, Scanning laser and Camera	2014
3	Hexacopter	Visual SLAM with EKF	IMU, Monocular camera	2014
4	Mikrokopter	EKF	IMU, Monocular camera, GPS, Barometric altimeter	2014

5	Six Wheeled UGV	Bayesian Information Filter (EKF)	IMU and Stereo Camera	2013
6	AsTec Pelican MAV	VO and SLAM	Stereo camera	2013
7	Simulator with flight data	UKF	IMU, GPS and Camera	2013
8	Quadrotor	Invariant EKF	IMU and RGBD Odometry (Kinect)	2013
9	Astec Pelican Quadrotor	UKF	IMU, Monocular camera	2013
10	Astec Firefly MAV	EKF	IMU, Pressure sensor and Monocular camera	2013
11	Quadrotor	Visual SLAM with KF	IMU with Monocular camera	2013
12	Hexacopter	Visual SLAM with EKF	IMU and WVGA Monocular camera	2012
13	Simulator with data	EKF	IMU, Monocular camera	2012
14	Multi-Stereo Helmet tracking system	EKF	IMU and Monocular camera	2012
15	Test bed which is gas-powered radio-controlled model helicopter	Visual SLAM with EKF	IMU, Monocular camera	2012
16	Quadcopter	Visual SLAM with EKF	IMU, Pressure Sensor, USB Firefly Monocular camera	2011
17	Gas-powered radio-controlled model helicopter	Visual Odometry with EKF	IMU, Monocular camera	2011
18	Scout B1-100 Helicopter	Using Pre-Existing Maps	IMU and Monocular camera	2011
19	Six-Legged Crawler	Visual Odometry	IMU with Stereo camera	2011
20	Simulator with Flight Data	Image Registration using GIS Data	IMU, GPS, Camera and GIS Data	2010
21	Simulator with Flight Data	Visual SLAM	Camera	2010
22	Quadrotor	Visual SLAM with EKF	IMU, Stereo camera, Monocular Color Camera with Laser finder	2010
23	HMAV	EKF	IMU and Wi-Fi camera	2009
24	Quadcopter	KF	IMU and VGA camera	2009
25	Yamaha RMAX Helicopter	KF with Image Registration	IMU, GPS, Camera and Satellite Images	2008

26	Simulator with Vehicle data	Kalman Filter	IMU with Laser scanner	2008
27	Simulator with synthetic MAV flight data	UKF Framework utilizing epipolar constraint	IMU and Stereo Camera	2008
28	Simulator with MAV flight data	Iterative Registration method, UKF	IMU with Monocular camera	2007
29	Simulator with MAV flight data	Visual Odometry with EKF	IMU with Monocular camera	2007
30	Acrobatic 23cc helicopter	Non-Linear observer	IMU and Webcam	2007
31	Simulator with Vehicle data	EKF	IMU with Camera	2007

2.9 Legal Ramifications

2.9.1 Liability

The FAA makes policy-related decisions that impact flight safety, such as reduced or waived DAA risk ratio requirements under regulatory authority granted by 49 USC 106(f) et seq. Other federal agencies are granted similar powers. Historically, such government rulemaking authority has been protected by the doctrine of sovereign immunity, meaning that if a citizen is injured by government or agency action, that injured person was barred from seeking recovery. Congress in 1946 enacted the Federal Tort Claims Act (FTCA), which allows citizens to file suit against the federal government in some cases. However, the federal government is immune from suit if it was performing a "discretionary function." Under the discretionary function exception to the FTCA [28 U.S.C.S. §1346(b); the government retains sovereign immunity from suit for any claim based upon the exercise or performance or the failure to exercise or perform a discretionary function or duty on the part of a federal agency or an employee of the government, whether or not the discretion involved be abused under 28 U.S.C.S. §2680(a). Essentially, this means that if an agency action was optional or not required by law or regulation, it is probably discretionary. If it is discretionary, a fairly robust liability shield is provided by the FTCA.

The United States Supreme Court has formulated a two-step procedure to guide courts in determining whether conduct falls within the discretionary function exception in Berkovitz v. United States, 486 US 531 (1988). First, a court must consider whether the challenged conduct is a matter of judgment or choice, or whether the conduct is specifically prescribed by a federal statute, regulation, or policy. A plaintiff must show that the government violated a specific and mandatory standard for the discretionary function exception to be deemed inapplicable. Second, if the challenged conduct involves a matter of judgment, a court must determine whether that judgment is the kind that the discretionary function was designed to shield. Under the second step of the procedure, the discretionary function exception protects from liability government decisions and actions based on decisions grounded in social, economic, and political policy.

If a mid-air collision occurs during a shielded UAS operation where, for example, the FAA reduced or waived DAA risk ratio requirements proposed in ASTM DAA standards, a court will necessarily follow the two-step procedure provided above. The ASTM DAA standards define specific safety performance thresholds for a DAA system to meet to ensure safe operation of UAS operations BVLOS. This is an optional kind of operation, where the regulatory floor for UAS operations exists in 14 CFR Part 107, and requires (among other things), the flight to be conducted in visual line of sight. Because a BVLOS flight is not specifically prescribed by a statute, regulation, or policy, but rather permitted by FAA's discretion using the DAA standards, the first step for a plaintiff to show that the FAA violated a specific and mandatory standard would be a difficult standard to meet, because a BVLOS waiver is not currently governed by regulation, but rather by a case-by-case discretionary agency decision. Second, the FAA's reduction or waiver of DAA standards is clearly a matter of judgement, and the analysis would proceed to whether that judgement was of the kind the discretionary function exemption was designed to shield. The FAA's decision to reduce or waive DAA standards in a particular case would need to be grounded in social, economic, or political policy for the second step to apply. The application of research-based data or testing for DAA standards would be based on social, economic, and political policy.

If a mid-air collision occurred during a shielded UAS operation where the FAA reduced or waived DAA risk ratio requirements listed in ASTM DAA standards, the discretionary function exemption would most likely enter the analysis. Thus, the FAA would most likely be shielded from liability, as outlined in the above analysis.

Moving the analysis from the FAA to private parties, if a UAS operator causes an accident resulting in damages or injuries, that operator would be liable for its negligent actions under state law. Although the FAA "regulates the licensing, inspection and registration of aircraft and airmen, [i]t makes no provision for its application to tort liability [… or] alter[s] the remedies now existing at common law or by statute" (Rogers v. Gardner Flying, 1970). Any legal impacts or outcomes occurring between two private parties will be determined in accordance with state tort or contract law wherever the accident occurred.

Expanding the liability question, Ippolito et al. (2019) conducted a risk and hazards analysis applied to the SAFE50 reference design project, where four main entities related to UAS vehicle operations were identified. The four main categories are stakeholders, other aircraft, DGOs, and SGOs. Risk for stakeholders includes financial liability in case potential damage was caused by insured and certified vehicles. If the operator is found to not be at fault, other stakeholders may be held liable or be subject to litigation. Additionally, the risk increases as density increases. A categorization of entities involved by UAS operation is shown in Figure 13.

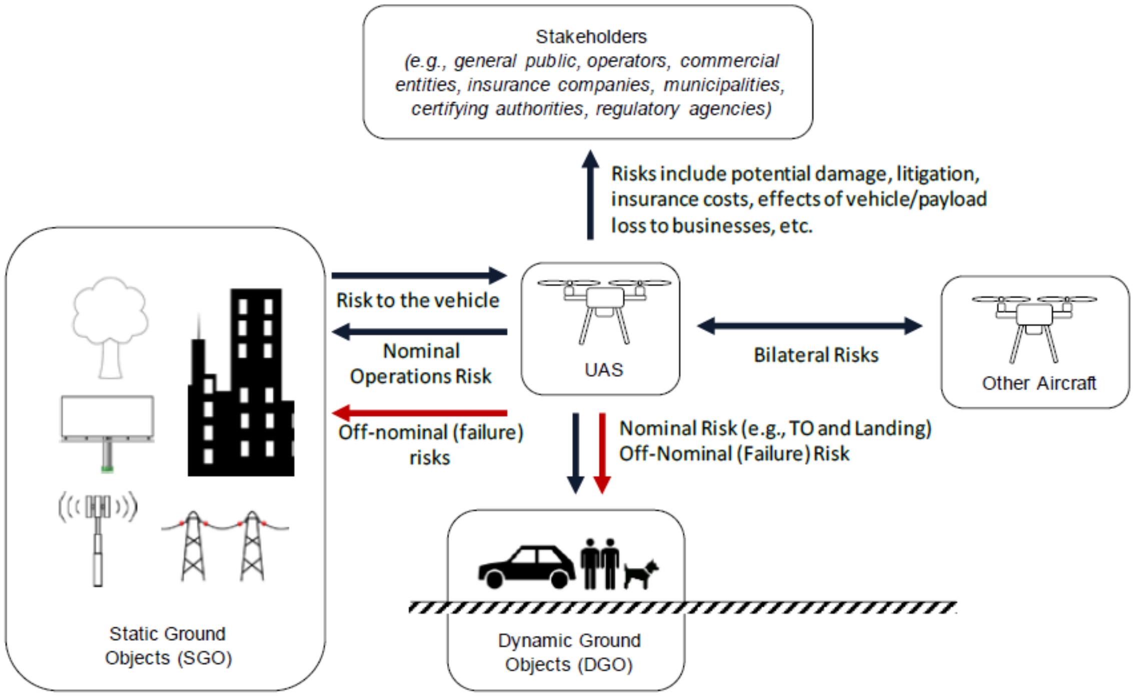

Figure 16. UAS Vehicle-Centric Risks and Hazards (Ippolito et al., 2019) – SAFE50 reference design study for large-scale high-density low-altitude UAS operations in urban areas.

UAS urban operations represent high risk and hazards to dynamic objects in urban environments, given the higher safety concerns of dynamic objects such as pedestrians, manned and unmanned aircraft. Hazards to SGO include critical city infrastructure such as powerlines, bridges, private property, buildings, and towers. According to the authors, implications of collision with critical infrastructure may need to consider reporting and filing cost, structural inspection, and measure of expected versus maximum damage.

2.9.2 Public Perception

Although there have been some midair collisions between UAS and occupied aircraft, thankfully none have resulted in fatalities or catastrophes that would become a touchstone for a strongly negative public perception of UAS activities, especially for activities related to reduced or waived DAA flight activities. While the FAA maintains a database of UAS sightings per quarter, they are difficult to utilize to determine, at a glance, whether a sighting was of an illegal or hazardous flight or one that was performed safely according to regulation yet reported (U.S. Department of Transportation, 2021). On September 18th, 2020, a UAS operating in Los Angeles failed to give right of way to an LAPD helicopter striking the bottom of the helicopter. This resulted in a midair collision damaging the helicopter's nose, antenna, and bottom cowlings, forcing the helicopter to initiate an emergency landing (Rupprecht Law P.A., 2021). This became the first instance of a criminal conviction for unsafe operation of an unmanned aircraft in the U.S. In February 2021, The Federal Bureau of Investigation (FBI) had charged a UAS operator for operating a drone in a FAA issued Temporary Flight Restriction (TFR) area. The TFR was issued as part of the security assignment for Super Bowl LV, in Tampa. The defendant had operated the UAS without maintaining a visual line of sight as required by FAA regulations and flew his UAS over people and moving vehicles (U.S. Department of Justice, 2021). It is however important to note that the number of incidents and accidents in the U.S have been remarkably low considering the total number of registered UAS which is about one million in number. Nonetheless, there is a constant level of news and media reports that indicate that many illegal or unsafe drone flights occur regularly. In the past six years, five drones have crashed into the Golden Gate Bridge in San Francisco, which lies in a no-drone zone (DroneDJ, 2020). Instances like these influence public perceptions.

Recent studies measuring popular acceptance of drones used for public safety surveillance have argued that the results of their research indicate general public acceptance of UAS used for the mission purposes. These include shark monitoring at an Australian beach (Stokes et al., 2020) and using drones as robotic lifeguards (Del-Real & Díaz-Fernández, 2020). However, several studies have shown that public perceptions of UAS depend upon what the UAS are being used for and who is using them (Boucher, 2016; Eyerman et al., 2013).

Considering the combination of the safety-related incidents, the criminal prosecutions, FAA enforcement actions, and the cited survey data, it is likely that reduced or waived DAA activities would probably be supported by most of the public—assuming the operation's mission had some benefit discernable by the public or was well-publicized and explained in advance. It is also safe to assume that approved DAA activities would not be conducted by criminal or amateur-negligent operators, avoiding negative press from that segment. However, any accidents or incidents that did occur would likely bring negative publicity and consequently a negative public perception of other reduced or waived DAA activities by association, proportional to the severity of the incident or accident.

2.9.3 Impact on Critical Infrastructure

Similar to the analysis provided in Section 2.8.1, a collision with critical infrastructure would be legally identical to a mid-air collision, in that the Federal Tort Claim and discretionary function exemption would be at issue. One additional issue arises for ground-based critical infrastructure: a potential plaintiff has a stronger argument that he or she (or his or her property) is non-participating and had no duty to be aware of the potential risks posed by a nearby BVLOS operation, unlike a pilot operating an aircraft would have based on the pilot's duty to become familiar with all available information under FAR 91.103. The United States Court of Appeals, Ninth Circuit in *Sutton v. Earles*, (1994) had ruled that the responsible agency's inaction of not informing of specific or known hazards cannot be construed as a discretionary function shielded by the Federal Tort Claims Act (Sutton v. Earles, 1994). In Sutton, the court held that defendant United States had immunity for failing to monitor the safety of boaters or failed to brief boaters on the rules and regulations for transit within the harbor, because it fell under the FTCA's discretionary function exception. However, the court determined that defendant United States was liable for failing to properly light a mooring buoy or adequately post a speed limit in a Navy harbor. The court also stated that defendant had a duty to protect plaintiffs, and that it was negligent for failing to do so. Applying Sutton to an aviation context, the upshot is that merely warning critical infrastructure owners or operators of BVLOS reduced or waived DAA operations is likely not sufficient by itself. While such warnings are sufficient for other aviation operators (who are required by regulation to know and act on such warnings), a court would likely not find a warning by itself meets the threshold for protection from the discretionary function exemption. The FAA would need to provide something further for ground-based critical infrastructure, at a minimum based on policy or regulation.

3 CONCLUSION

Industry stakeholders are highly interested in utilizing UAS for various commercial applications, most of which are concentrated in low-altitude environments and are considered BVLOS operations. However, the current regulatory and technological outlook for BVLOS operations is far from making them routine.

It is widely agreed upon that although the sUAS rule established in 2016 serves as a great starting point for enabling commercial UAS operations in the NAS, it falls short in what can be called the true expanded and non-segregated operations. While introducing the operational rules for sUAS, the FAA understood that there could be certain operations outside the realm of Part 107 that could be conducted safely. Hence, the FAA administrator issues waivers on a case-by-case basis, approving deviations from the regulatory ambit of Part 107. BVLOS waivers rank as the third most requested and approved waivers under the waiver provisions of Part 107, accounting for 13% of overall approved waivers. There is extreme interest in enabling routine sUAS BVLOS operations. The UAS detect and avoid capability is widely agreed upon as one of the most important pre-requisites for routine BVLOS operations. The current technological readiness level for DAA is still far from maturity, so the UAS industry is believed to be losing out on a lot of new commercial applications, most of which involve BVLOS operations. Shielding operations provide an opportunity to overcome this challenge by enabling sUAS BVLOS operations near buildings or structures which are collision hazards for manned aircraft.

After the SARP developed the initial well clear recommendations for UAS systems, they were tasked to define the well clear requirements for sUAS systems. However, this proved to be difficult due to the limited nature of information available about how intruders operate at low altitudes. The SARP panel utilized flight data and simulation results to run a Monte Carlo simulation to develop a risk-based well-clear definition. One of the SARP's recommendations highlights the importance of utilizing a containment system like geofencing to ensure that UAS does not get close to movement and non-movement areas. Another research effort that aims to enable high-density low-altitude UTM operations is NASA's SAFE50 study.

Shielded operations present the perfect opportunity to operate sUAS in such low-altitude environments, safely navigating and avoiding dynamic and static obstacles present there. There is a high-level of complexity surrounding shielded operations since they are usually performed near critical infrastructure such as building, cellular network towers, and power transmission lines. An ASTM Working Group (WK 74215) from the F38 Committee on Unmanned Aircraft Systems is currently evaluating shielding as an option for maintaining well clear of manned aircraft.

There are a variety of factors that influence the successful implementation of shielded operations. Some of the critical lessons learned from reviewing literature related to the factors affecting shielded operations are described below:

Wind and Turbulence Effects: Wind effects are generally studied using wind tunnel experiments and CFD studies. These help in understanding various phenomena that influence the effects of wind and turbulence. There is a stark difference in wind effects in buildings with single configurations and multiple configurations. This is due to airflow in the passage between the buildings, called the ‘channeling effect,’ which modifies wind flow, causing potentially dangerous environments for sUAS to operate. Additionally, landing aircraft near buildings can be extremely challenging due to the increase in gustiness near buildings. This is a significant factor affecting the proposed shielded operations. Most of the wind-induced challenges occur at altitudes ranging between 100 m to 3000 m, called the Atmospheric Boundary Layer.

Bird Densities and Behaviors Near Structures: Some of the key factors that increase the collision risk between UAS, and birds include structure, location, bird morphology, and UAS intrinsic attributes such as height, use of lighting, and weather. There is also a high collision risk if a structure is located near areas frequented by birds for feeding and breeding. High noise produced by engines contributes to the increased collision risk. Additionally, the size of the UAS can influence bird reactions since it increases the perceived risk. A rapid or abrupt approach or sudden change in the direction of the sUAS can significantly cause increasingly disturbing bird behavior. Wind, vegetation density, and magnetic fields can significantly impact how birds react to UAS. Some mitigation measures to overcome these effects were discussed.

GPS Outages: Studies show that in urban environments, GPS availability ranges from 30 to 50% due to a variety of intentional and unintentional factors. Unintentional GPS degradation measures like spoofing and jamming can cause catastrophic consequences, including forcing the UAS to follow the trajectory imposed by the malicious actor.

Electromagnetic Interference: UAS operating near structures run the risk of a deteriorated data transmission rate because of electromagnetic interference. To protect UAS from electromagnetic interference, new test methods such as Faraday shielding by coating metal layers on UAS fuselage materials are being implemented. Other measures, including overcoming electromagnetic interference by utilizing filling materials such as wire mesh pads, are being tested. Potentially, proper geofencing of buildings and cell-towers can help in overcoming this complication. UAS Facility Maps are predominantly used to assist the FAA in providing airspace authorizations in controlled airspace. However, there is an increased need to refine these maps to cater to improve accuracy levels. RF environments in urban settings where there is high level of noise and RF line of sight obstructions can cause C2 degradation resulting in degraded air-to-ground communications. Natural phenomena such as solar storms can denude satellite-based communications giving rise to signal fades and delays in GPS signals. Effect of electromagnetic interference in the UAS command and control can result in loss of connection and control thereby affecting system reliability and safety. Image signal transmission under the effect of electromagnetic interference can cause pixel strength reduction and increased data errors. In terms of effects due to multipath interference, the fading of signal strength is highly dependent on the sUAS altitude and not a based on the distance or elevation angle at low altitudes. Hence, sUAS at low altitudes are greatly affected by multipath disturbances whereas as the altitude increases, the effect decreases.

GPS Navigational Performance of UAS: UAS operations in urban environments are highly challenging due to the deteriorated navigational availability. Further, GPS reliability is highly contingent upon natural phenomena such as solar flares and geomagnetic storms. Also, since the urban landscape has too many structural disturbances, GNSS measurements for non-line-of-sight operations are seldom accurate. Hence, the industry stakeholders have a clear concord to design and implement UAS navigational capabilities that are not heavily dependent on GPS. Alternate navigational techniques like visual odometry and SLAM can help in overcoming this challenge. The possible utilization of cellular network towers to help in localized navigation is of interest to researchers. LiDAR can also be possibly leveraged for navigation solutions for sUAS, although the cost proposition associated with installing such a system can be a cause of concern. There is also high interest in utilizing cellular networks and Wi-Fi to help in providing inertial navigation services in urban environments.

Government rulemaking bodies such as the FAA are generally protected by the doctrine of sovereign immunity when making important policy decisions that influence flight safety. Although the introduction of the Federal Tort Claims Act allowed citizens to file suit against the federal government, it provided immunity to the government if the activity was considered a “discretionary function.” Hence, if a mid-air collision were to occur during a shielded UAS operation, the FAA would most likely be shielded from liability based on the discretionary function exemption, assuming a warning notice was published for other aviators. However, the UAS operator would still be liable for their negligent actions as applicable under state law. There is a need for the FAA to promulgate policy and rulemaking addressing DAA waived UAS collisions with critical infrastructure. Current law suggests FAA would have a duty to adequately warn the non-participatory public of specific, known hazards, and a general warning would not be sufficient. Public perception of UAS usage is largely dependent on what the UAS are being used for and who uses them. Therefore, there is a high probability that potentially reduced or waived DAA UAS operations may bring about a positive public reaction if the operation and its benefits get well-publicized in advance.

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