A45-Shielded UAS Operations: Detect and Avoid (DAA): Final Report

September 2, 2024

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7. Author(s)
Mark Askelson: https://orcid.org/0000-0002-8521-7158
Tom Haritos: https://orcid.org/0000-0001-6546-383X
Sreejith Nair: https://orcid.org/0000-0002-0529-4269
Naima Kaabouch: https://orcid.org/0000-0002-1333-3352
Hever Moncayo: https://orcid.org/0000-0001-5088-9715
Henry Cathey: https://orcid.org/0000-0003-4496-1076
Evan Arnold: https://orcid.org/0000-0002-7725-9067

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University of North Dakota (4201 James Ray Dr. Stop 8367, Grand Forks, ND 58202
Kansas State University (2310 Centennial Rd, Salina, KS 67401)
Embry Riddle Aeron. Univ. (1 Aerospace Boulevard, Daytona Beach, FL 32114)
New Mexico State University (1780 E Univ. Ave., Las Cruces, NM 88003)
North Carolina State University (20 Watauga Club Dr., Raleigh, NC 27605)

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16. Abstract

The demand for Beyond Visual Line Of Sight (BVLOS) operations using Uncrewed Aircraft Systems (UASs) is high owing to the numerous associated benefits. One approach that can enable small UAS (sUAS) BVLOS operations is shielded operations, wherein a sUAS is operated near objects such as buildings, powerlines, etc. This effort executed numerous tasks to understand challenges and opportunities associated with operations in shielded environments.

Hazards and mitigations were evaluated, as were the risks of collisions with Manned Aircraft (MA), the ground, and infrastructure. A shielded operations classification system was developed, as was a mathematical framework for interpreting the benefit of shielding. Several estimates for shielded operations safety benefit were developed.

Impacts of EMI for operations near powerlines were evaluated and safe distances were provided. For wind impacts (straight-line, turbulence, and MA-induced wake vortices), multicopters were found to be more robust than fixed-wing aircraft.

Operation near obstacles can result in significant deterioration of GPS performance. The effects posing the highest risks, in descending order, were dropouts, jamming, and a reduced number of satellites (down to four).

Plans were developed and executed for three rounds of flight testing. These showed that different types of maneuvers have significant impacts on the time required to reach well-clear status. Use of obstacles to place them between the UA and the intruder, thus producing a safe state, can significantly reduce the time required to reach well-clear status and, thus DAA system requirements. Tests also confirmed that operation near buildings can significantly deteriorate GPS performance.

By completing the tasks associated with this effort, the team has significantly advanced shielded operations knowledge. This will enable more rapid integration of sUAS into the National Airspace System.

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Acronym	Meaning
ADS-B	Automatic Dependent Surveillance-Broadcast
AERPAW	Aerial Experimentation and Research Platform for Advanced Wireless
AGL	Above Ground Level
ARC	Aviation Rulemaking Committee
ASSURE	Alliance for System Safety of UAS Through Research Excellence
ASTM	American Society for Testing and Materials
BLOWC	Behind Local Obstacle Well Clear
BVLOS	Beyond Visual Line Of Sight
C2	Command and Control
CFR	Code of Federal Regulations
CPA	Closest Point of Approach
DAA	Detect And Avoid
DOP	Dilution Of Precision
EMF	Electric and Magnetic Field
EMI	ElectroMagenetic Interference
FAA	Federal Aviation Administration
FEM	Finite Element Method
FPV	First Person View
FTP	Flight Test Plan
GPS	Global Positioning System
HE	Horizontal Encounter
HMI	Human Machine Interface
IMC	Instrument Meteorological Conditions
LOS	Line of Sight
LTE	Long Term Evolution
MA	Manned Aircraft
MAC	Mid-Air Collision
MSL	Mean Sea Level
MSU	Mississippi State University
NAAA	National Agricultural Aviation Association
NCSU	North Carolina State University
NMAC	Near Mid-Air Collision
NMSU	New Mexico State University
NPUASTS	Northern Plains UAS Test Site
NSF	National Science Foundation
RC	Remote Controlled
RQ	Research Question
SF	Shielding Factor
SME	Subject Matter Expert
SO	Shielded Operation/Shielding Object
SRA	Safety Risk Assessment
sUAS	small UAS
UA	Unmanned Aircraft
UAS	Unmanned Aircraft System
UND	University of North Dakota
VMC	Visual Meteorological Conditions
VO	Visual Observer
VTOL	Vertical Takeoff and Landing

EXECUTIVE SUMMARY

The demand for Beyond Visual Line Of Sight (BVLOS) operations using Uncrewed Aircraft Systems (UASs) is high owing to the numerous associated benefits. One approach that can enable small UAS (sUAS) BVLOS operations is shielded operations, wherein a sUAS is operated near objects such as buildings, powerlines, etc. Operation near such objects is assumed to produce a safety benefit relative to encounters with Manned Aircraft (MA), since MA will generally maintain separation from those objects. Such operations can also provide challenges, which include maneuver path limitations/modifications owing to the presence of obstacles, possible obstacle interference with Detect And Avoid (DAA) systems (e.g., blocking of signals used for detection), and obstacles affecting Unmanned Aircraft (UA) (e.g., ElectroMagnetic Interference (EMI) near powerlines).

Impacts of obstacles on MA traffic were estimated from subject matter expert input, a survey, and analysis of flight data. Shielding safety benefits varied with distance from obstacles and type of low-altitude MA operation, with almost no benefit for some operations and obstacles (e.g., agricultural operations near powerlines). Analysis of flight data, which is generally lacking for low-altitude MA operations, is the best approach. Curating such data sets should be prioritized.

EMI impacts for operations near powerlines were evaluated. A safe distance 9 m from any individual powerline is recommended. The minimum safe distance during a short circuit/fault increases significantly, with the largest safe distance identified herein being ~40 m. For transformers, safe distances are significantly smaller (< 5 m), and depend upon transformer configuration. Safe distances depend upon many factors and can be significantly reduced by shielding UAS from EMI.

Multicopters were determined to handle MA-induced wake vortices well, with significant impacts occurring only for large MA. They also handle turbulence well, with fixed-wing UA experiencing more challenges with turbulence. For straight-line winds, multicopters perform well, but do have a maximum wind that they can handle that is dependent upon UA characteristics.

Operation near obstacles can result in significant impacts on Global Positioning System (GPS) performance. The effects posing the highest risks, in descending order, are dropouts, jamming, and a reduced number of satellites (down to four). Thus, GPS integrity should be monitored and addressed for operations where these effects may be realized. This is especially true for operations at low altitudes (≤ 16 m) and close to buildings (e.g., within 6 m), for which GPS degradation results in a high likelihood of collisions with buildings unless some sort of mitigation is utilized.

Plans were developed and executed for three rounds of flight testing. These showed that different types of maneuvers have significant impacts on the time required to reach well-clear status. Placing obstacles between the UA and the intruder, thus producing a safe state, can significantly reduce the time required to reach well-clear status and DAA system requirements. Tests also confirmed that operation near buildings can significantly deteriorate GPS performance.

This effort involved a broad set of tasks designed to deepen understanding of shielded operations. Through execution of these tasks and application of the numerous methods required to do so, shielded operations knowledge has been significantly enhanced, which will enable more rapid integration of sUAS into the National Airspace System.

1 INTRODUCTION

The demand for Beyond Visual Line Of Sight (BVLOS) operations using Unmanned Aircraft Systems (UASs) is high. Such operations produce numerous benefits, including humanitarian and economic (e.g., UAS BVLOS Aviation Rulemaking Committee (ARC) 2022). Humanitarian benefits include improving health outcomes (including saving lives), while economic benefits include reduced costs and increased efficiency associated with numerous use cases (inspection, package delivery, etc.). These benefits have resulted in increased pursuit of BVLOS capabilities, with much of the focus being upon small UAS (sUAS) owing to reduced risks (air and ground collision risks) associated with such aircraft.

One approach that can enable sUAS BVLOS operations is shielded operations, wherein a sUAS is operated near objects such as buildings, powerlines, etc. Operation near such objects is assumed to produce a safety benefit relative to encounters with Manned Aircraft (MA) since MA will generally maintain separation from such objects. Such operations can also provide challenges and opportunities for Detect And Avoid (DAA).[1] Challenges include maneuver path limitations/modifications owing to the presence of obstacles, possible obstacle interference with DAA systems (e.g., blocking of signals used for detection), and obstacles affecting UA (e.g., ElectroMagnetic Interference (EMI) near powerlines). Opportunities include decreased risk owing to decreased MA activity near obstacles and the possible placement of obstacles between the UA and MA to enable well clear, which can reduce DAA detection range requirements.

The Alliance for System Safety of UAS Through Research Excellence (ASSURE) project A45-Shielded UAS Operations: Detect and Avoid (DAA) (A45) involves numerous tasks associated with shielded operations. This is the final report for this effort.

2 RESEARCH QUESTIONS

The knowledge gaps/research questions associated with this effort are:

1. What types of sUAS failures may increase collision risks when operating near obstacles, structures, and critical infrastructure? What are some recommended mitigations to address these risks? For instance, are obstacle avoidance capabilities needed for shielding operations near critical infrastructure?
2. What are safe standoff distances (vertical and horizontal) from obstacles, structures, and critical infrastructure for sUAS BVLOS operations?
3. What types of MA operate in close proximity to flight obstacles and structures? How often do they operate in close proximity? How close do they fly to these structures? What are their operational limitations (day only, special procedures, special pilot requirements, etc.)?
4. What other mitigations should be coupled with shielding concepts in order to manage collision risks with MA and with obstacles?
5. To what degree can DAA requirements to avoid other aircraft (manned and unmanned) be reduced during shielded sUAS operations?

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[1] Herein, DAA is the sUAS performing this function relative to an MA intruder—DAA relative to Unmanned Aircraft (UA) and obstacle avoidance technologies are not considered.

6. What regulatory, policy, and legal issues should the Federal Aviation Administration (FAA) consider for shielded sUAS operations? Example topics include:
    a. What should the FAA consider so as to not be negligent in their risk management responsibilities when issuing waivers involving shielding operations?
    b. What are the potential implications if an accident with an MA occurs and the FAA waived DAA requirements?
    c. What are the potential implications if the FAA does not require active obstacle avoidance capabilities and a collision with critical infrastructure occurs?

This report provides a summary of A45 efforts to answer these questions. Answers were developed through a series of tasks described subsequently.

3 TASKS

Tasks in A45 include:

0. Project Management:
    Management of the overall project, including project kick-off, the project research task plan, technical interchange meetings, program management reviews, leadership briefings, and project close out.
1. Literature Review and Risk Identification:
    A comprehensive literature review of shielding research, including terminology, shielding benefits, and identification of risks associated with shielded operations.
2. Shielding Classes, Risk Assessments, and Listing of Mitigations:
    a. Shielding Classes/Categories
    b. Hazard Analysis
    Identification/creation of shielding classes/categories and completion of a hazard analysis in which risks and risk mitigations are identified.
3. Analysis of DAA Requirements and Obstacle Avoidance Requirements:
    Development of a simulation environment that will allow assessment of risks and potential solutions identified in Tasks 1 and 2. Numerical simulations will be performed to analyze the competing shielding requirements to manage risks with flight near obstacles and to manage risks with MA. Risks evaluated include those associated with the type of operation, UAS characteristics, type of obstacle, and type of intruder.
4. Flight Test Plans:
    Development of Flight Test Plans (FTPs) for the most promising types of shielded operations. Operations are based upon industry needs, the need to evaluate performance based on previous findings, and the viability of performing such tests.
5. Tests and Reports:
    Tests and demonstrations conducted using the developed FTPs from Task 4 and documentation of the approach and outcomes. Reports interpret the significance of tests and outcomes and the degree to which results refine and validate previous shielding recommendations.
6. Standards Development:
    Participation in relevant standards development efforts. Results from A45 will be used to enhance those efforts by providing relevant research results.
7. Final Briefing and Final Report:

Summarization of all of the previous papers and reports (excluding meeting notes) into a final report package for the overall project.

8. Peer Review:
   A peer review of the final report.

This report is part of Task 7. It provides a summarization of all of the previous papers and reports.

4 TASK 1: LITERATURE REVIEW AND RISK IDENTIFICATION

4.1 Objectives

The objectives of this task were:

- Perform a comprehensive literature review of shielding research
- Review terminology related to shielded operations
- Review benefits associated with shielded operations
- Identify risks associated with shielded operations
- Consider legal questions (Research Question (RQ) 6 of Section 2)

4.2 Methods

As this was a literature review, the team acquired any relevant material it could identify. This information was summarized in the form of a report (Sugumar et al. 2021).

4.3 Summary of Results

Sugumar et al. (2021) highlight the scarcity of literature regarding shielded operations. Despite this, they identified the risks associated with shielded operations that are discussed subsequently.

4.3.1 Risks Associated with Shielded Operations

The following were identified during the literature review as posing risk during shielded operations. These provide part of the overall answer to RQ1.

4.3.1.1 Wind and Turbulence Effects

These effects depend upon building configuration, as adjacent buildings can create increased winds/channeling, which can create hazards (e.g., loss of controlled flight) for UAS. In addition, gustiness/turbulence near buildings can result in loss of controlled flight. Most wind-induced challenges occur at low levels (within the Atmospheric Boundary Layer).

4.3.1.2 Bird Densities Near Structures

Key factors that increase collision risk between UAS and birds near shielding structures include type of structure, location, bird morphology, altitude, and weather. In addition, the likelihood of collision increases in areas frequented by birds for feeding and breeding. UAS characteristics, such as size, noise production, flight characteristics, and use of lighting can influence UAS-bird collision likelihoods. Operation near structures can result in increased presence of birds and, thus, increased UAS-bird collision likelihood, which can lead to loss of controlled flight.

4.3.1.3 Global Positioning System (GPS) Outages

GPS availability in urban areas ranges from 30% to 50% due to a variety of intentional and unintentional factors. Activities such as spoofing and jamming can result in catastrophic consequences, which can be driven by the UAS being forced to follow a trajectory imposed by a malicious actor. GPS outages can result in collisions with infrastructure, which can produce damage to the infrastructure and have secondary effects such as injuries to people on the ground.

4.3.1.4 Electromagnetic Interference (EMI)

For UAS, EMI can produce:

- Degraded UAS performance;
- Deteriorated data transmission rates; and
- Command and Control (C2) degradation.

The first hazard could result in loss of controlled flight and, thus, collisions.

Mitigations that can reduce risk owing to EMI include

- Use of Faraday shielding or filling materials such as wire mesh to protest UAS from EMI; and
- Use of geofencing to keep UAS away from hazardous EMI.

It is noted that these provide part of the overall answer to RQ4.

4.3.1.5 GPS Degradation

UAS operations in urban environments are highly challenging due to deteriorated navigational availability. Structures block GPS signals and produce GPS signal reflections (multipath). These reduce GPS performance, resulting in increased inaccuracies in location that can result in collisions. One solution for these challenges is utilization of alternative navigational approaches, like visual odometry and Simultaneous Localization and Mapping (RQ4).

4.3.2 Legal Considerations

Regarding RQ6, the A45 team determined the following. 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 that the 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 are well-publicized in advance.

5 TASK 2: SHIELDING CLASSES, RISK ASSESSMENTS, AND LISTING OF MITIGATIONS

5.1 Objectives

The Task two objectives were:

- Creation of classes/categories of shielded operations;
- Evaluation of risk; and
- Identification of mitigations.

5.2 Methods

This task was completed through a combination of leveraging of previous work and analysis. Specifically, shielding classes were identified through leveraging of previously-published work, analysis of regulations, and Subject Matter Expert (SME) input. Risk evaluation was conducted following a traditional Safety Risk Assessment (SRA) approach, with quantification of safety benefits associated with the shielded-operation strategic mitigation estimated through SME input, a survey, and analysis of data regarding low-altitude Agricultural Operations.

5.3 Summary of Results

Results are summarized by Askelson et al. (2023). A high-level overview is provided herein.

5.3.1 Shielding Classes

The set of shielding classes was developed by considering three primary hazard categories: air risk, ground risk, and infrastructure risk. Potential outcomes in these categories are collision with an MA, collision with a person on the ground, and collision with infrastructure.

To understand MA collision risk, characteristics of low-altitude MA operations are needed. The primary challenge is understanding frequency of operations, as data regarding this are severely lacking. Askelson et al. (2023) provide a table that summarizes low-altitude MA operations, which is based upon Weinert and Barrera (2000) and provided herein (Table 1). As indicated in this table, numerous low-altitude MA operations exist. The characteristics of these operations (e.g., flight altitudes, speeds, etc.) vary significantly. This provides part of the overall answer to RQ3.

To further understand low-altitude MA operations, the team also reviewed relevant regulations. This review enabled identification of regulatory drivers of low-altitude traffic. The team also identified other potential drivers, such as location for Spraying and Dusting operations (e.g., growing season vs. non-growing season). Given the identified factors, SME input was used to evaluate expected qualitative traffic levels.[2] This resulted in three air-risk-driven classes:

A1. Instrument Meteorological Conditions;
A2. Visual Meteorological Conditions (VMC) at night; and
A3. VMC during the daytime.

For ground risk, previous work regarding definitions, collision likelihood, and collision severity (Arterburn et al. 2017; Breunig et al. 2018; Joint Authorities for Rulemaking of Unmanned Systems 2019; Primatesta et al. 2020; U.S. Census Bureau 2022) was leveraged to identify classes. This resulted in the classes:

G1. Controlled area with no third-party persons present;
G2. Rural area (< 500 persons mi^{-2});
G3. Urban area (≥ 500 persons mi^{-2}); and
G4. Gathering of people outside (un-sheltered).

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[2] SME input was obtained from A45 personnel, including personnel from the University of North Dakota (UND) and the Northern Plains UAS Test Site (NPUASTS). The UAS experience of these SMEs ranged from 7 to 17 years, with background in areas such as DAA, remote and commercial pilot certification, and, more broadly, integration of UAS into the NAS.

Table 1. Summary of low-altitude MA operations. AGL stands for Above Ground Level and CFR stands for Code of Federal Regulations. From Askelson et al. (2023); adapted from Weinert and Barrera (2020).

Operation	Flight Altitudes (ft AGL)	Speeds (kts)	14 CFR Part	Comments
Spraying and Dusting	2-20	50-120	137	Firefighting with fixed-wing allowed (U.S. Department of Transportation 2017a).
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, Subpart L)	
Infrastructure Inspection (Rotary Wing)	0 and up	0-100	91	A45 added
Infrastructure Inspection (Fixed Wing)			91	A45 added
Infrastructure Work (Rotary Wing)	Infrastructure height	~0	91	A45 added; Example is work on powerlines.
Helicopter Air Tours	400-3300	Not Provided	91 (91.147), 119, 121, 135, 136	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	500-3280	0-140	119, 135	
Helicopter Public Safety	300-3280	0-140	119, 135	
Helicopter External-Load Operations	0 and up		133	A45 added (firefighting, wire pulling, etc.).
Training	200 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	
Recreational Flying			91	A45 added
Ultralight Vehicles	<=12,500	≤ 55	103	A45 added; Supplemental oxygen required for flight > 30 minutes above 12,500 ft; Been flown above 12,500 ft.

*Average speeds based on operational guidance.

**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.

Of the categories, infrastructure risk had the least amount of preexistent effort related to identifying classes. The team identified the following as a set of potential classes:

I1. Non-infrastructure and non-property (e.g., tree rows);
I2. Property;
I3. Infrastructure; and
I4. Critical infrastructure.

The final category that was identified for delineation of shielding classes is the type of Shielded Operation/Shielding Object (SO). The suggested set of classes is:

SO-LL: Long Linear shielding objects, such as powerlines;
SO-R: Rectangular shielding objects, such as buildings (rectangular in both horizontal and vertical planes); and
SO-NV: Narrow Vertical shielding objects, such as towers, wind turbines, etc.

Specification of shielding class requires aggregation of the specific classes for the categories. It is recommended that this be done using a format like SO-X | AN-GN-IN, where X represents of the SO classes and N indicates a number. A specific example is SO-LL | A3-G2-I3, which indicates a Long Linear shielding object with flights in VMC conditions during the daytime in a rural area near infrastructure.

5.3.2 Evaluation of Risk

Askelson et al. (2023) performed a SRA with the assumptions of a Group 1 or 2 UAS, operations occur below 400 ft, and that base equipage does not include a DAA, collision avoidance, or obstacle avoidance system. Based heavily on SME input and UAS BVLOS ARC (2022) recommendations, four shielding levels were identified:

- SL1: Within 50 ft (horizontally or vertically) of shielding object;
- SL2: Within 100 ft (horizontally or vertically) of shielding object;
- SL3: Within 200 ft (horizontally or vertically) of shielding object; and
- No Shielding (NS): Beyond 200 ft (horizontally or vertically) of shielding object.

It is noted that the lack of data regarding low-altitude MA operations leads to difficulty when attempting rigorous data-driven determination of these levels and that other efforts to estimate these (survey and analysis of agricultural operator data) were conducted and are described later in this report.

The SRA followed U.S. Department of Transportation (2017b, 2019) and FAA Air Traffic Organization (2019) with severity scales defined for air, ground, and infrastructure risk. For air risk, a MAC is considered to be catastrophic (severity of 1). This is consistent with Askelson et al. (2017) and Table 3.3. of FAA Air Traffic Organization (2019), both of which consider a MAC to be catastrophic. However, Table 3.3 of FAA Air Traffic Organization (2019) also indicates that "An effect categorized as catastrophic is one that results in a fatality or fatal injury". Moreover, Table C1 of U.S. Department of Transportation (2019) indicates that a severity of 1 (catastrophic) is defined as "Multiple fatalities (or fatality to all on board) usually with the loss of aircraft/vehicle", and the updated guidance (U.S. Department of Transportation 2023, Table C1) defines a severity of 1 (catastrophic) as involving "3 or more fatalities" or "manned aircraft hull loss with at least 1 fatality". Thus, a common theme is that a fatality must occur for a catastrophic severity. The conservative approach wherein a MAC is considered to be catastrophic is used herein because the likelihood of a fatality, given a UA/MA MAC, is not known.

To facilitate quantification, likelihoods are expressed per UAS flight hour, following FAA Air Traffic Organization (2019). The risk matrix that was applied is that used for General Aviation Operations/Small Aircraft and Rotorcraft.

A framework for evaluating the likelihood of events associated with interactions with MA (well clear violation, Near Mid-Air Collision (NMAC), Mid-Air Collision (MAC)) was developed. This framework illustrates how risk ratios, which are ratios of probabilities of events with and without a system (e.g., a DAA system), combine when sequential events occur (e.g., well clear violation, NMAC, and MAC). This framework was also used to illustrate how shielding reduces air risk, with Shielding Factors (SFs) filling the same mathematical role as risk ratios. A mathematical framework for the combined effects of shielding and utilization of Sense And Avoid systems were presented and utilized. It is important to recognize that a strategic mitigation like shielding is different from a tactical mitigation like DAA. Thus, even though SFs fulfill the same mathematical role as risk ratios, they, by their strategic nature, do not absolve responsibility to maintain well clear as delineated, for instance, in CFR Part 91 (91.111 and 91.113; e-CFR 2024).

Traditional methods for evaluating air risk depend upon MA encounter rates. While Askelson et al. (2023) suggest that an alternative approach may be better, details regarding that approach have not yet been developed. Estimation of encounter rates at low altitudes is very challenging given the lack of data regarding low-altitude MA operations. An approach for such an estimation is presented by Askelson et al. (2023). Future work should focus on estimating uncertainties associated with that approach.

Askelson et al. (2023) estimated SFs using both SME input and a survey. The survey was well received, with input provided by 359 respondents.[3] The respondents were predominantly from the Agricultural Application operator category, with the number of respondents for other types of operations at least an order of magnitude smaller. SFs for both horizontal and vertical distances were derived for five types of operations, for which at least five respondents provided input. SF curves vary, with some operations avoiding certain obstacles at relatively large distances (>200 ft) and others regularly flying close (<25 ft) to obstacles (e.g., Agricultural Application operating near Powerlines). Comparison of SME-based and survey-based SFs indicated that SME-based SFs were commonly lower (more safety benefit) than those derived from surveys, with the caveat that SME-based SFs are for all low-altitude MA operations whereas survey-based SFs were for a subset (5) of these operations.

In addition to SME- and survey-based estimates, an analysis of a data set provided by the National Agricultural Aviation Association (NAAA) to Mississippi State University (MSU) was performed. These data were shared with permission of both organizations and were analyzed to estimate clearance distances for agricultural operations near powerlines. This analysis indicates that agricultural operators regularly pass within 25 ft of powerlines, thus confirming results from the survey. Further information regarding this analysis is provided in Appendix A.

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[3] To protect against duplicate and fraudulent responses, indexing of the survey was blocked so that search engines would not include the survey in their results and a tool that provides metrics regarding duplicate and fraudulent responses was utilized in the survey software. Average values for these metrics were very low, with only 9 responses flagged as being possible duplicates and 10 flagged as possibly fraudulent (bot) entries. It is noted that an individual could respond more than once if that person conducts more than one type of low-altitude operation.

Askelson et al. (2023) describe methods for estimating ground and infrastructure risk. Of the risk categories, approaches for infrastructure risk are the least developed. Moreover, severity and likelihood for infrastructure are both dependent on numerous factors (sUAS characteristics, type of shielding object, environment). Thus, an SRA for infrastructure risk requires knowledge of specifics regarding the sUAS, shielding object, and environment.

The air risk for SL1 is estimated to be 1D (yellow) and for SL2-3 and NS to be 1C (red). Required risk ratios to reduce risk to 1E (yellow) are provided for all shielding levels. This results in a significant requirement for DAA systems (MAC risk ratios of ≤ 0.015). Askelson et al. (2023) provide the following suggestions by which required risk ratios can be increased (and required DAA performance decreased):

- Identifying areas of lower traffic densities
- Determining that shielding provides more benefit (if, in fact, it does)
- Incorporating the likelihood of a fatality given a collision with an MA. If that were on the order of 0.1, for instance, that would increase required MAC risk ratios by an order of magnitude.
- Using the target level of safety of 1×10^6 hrs between NMACs as utilized by FAA Sponsored "Sense and Avoid" Workshop (2013, Appendix G), which increases the net risk ratios by an order of magnitude.

It is noted that the material from this section provide part of the overall answers for RQ2, RQ3, and RQ5. RQ2, which will be further addressed in the conclusions section, is challenging given the variability of behaviors that depend upon the type of operation and obstacle/shielding object.

5.3.3 Identification of Mitigations

For all hazard categories, Askelson et al. (2023) provide a list of generalized hazard causes, hazards/hazard outcomes, and mitigations. Mitigations are ranked in order of expected safety benefit. These are provided in Table 2.

Table 2. Generalized hazard causes, hazards/hazard outcomes, and mitigations. Mitigations are ranked in order of expected safety impact. Outcome applicability is indicated with an 'X'. From Askelson et al. (2023).

Causes	**Mitigations Listed in Order of Greatest Safety Impact**	**Hazards**			
		Coll. with Inf.	**Coll. with Ground**	**Coll. with MA**	**Coll. with UA**
Collision with wildlife (birds) that are often present around infrastructure	• Bird detect and avoid system (radar, etc.) • Seasonal restrictions (outside of migration season, winter in a cold region, outside of harvest season) • Time of day (night) • Collision avoidance system (ranked low due to uncertainty of effectiveness) • Bird deterrent system (acoustic system) (ranked last due to uncertainty of effectiveness)	X	X	X	X

EMI effects from infrastructure causing system failures/ degradations	• Shielding of critical systems on UAS • Fly further away from EMI source • Real-time monitoring of EMI onboard UAS • Forecasting EMI potential along flight path	X	X	X	X
Infrastructure causing change in air flow (e.g., turbulence, wind funneling)	• Real-time weather monitoring (onboard measurements) • Automation of control surfaces to account for rapid change in environmental conditions • Fly further away • Weather forecasting system (planning)	X	X	X	X
Degradations/failures of UAS navigation systems	• Redundant/alternative navigation systems • Automation of navigation systems (automatically adapt to degraded navigational performance) • Real-time monitoring of navigation system (human intervention) • Navigation system performance forecasting (planning)	X	X	X	X
Hardware failures on UAS and supporting systems	• Redundant systems • Contingency planning ○ (Health monitoring solutions are inherent in the above mitigations)	X	X	X	X
Loss of Command and Control (C2) owing to structure (interference, blockage, etc.)	• Redundant systems with different coverages [e.g., Point to Point (P2P), satellite, Long Term Evolution (LTE)] • Mesh networked C2 infrastructure • Flight planning to ensure C2 coverage using obstacle map/database • Lost link profile	X	X	X	X
C2 degraded owing to structure (interference, blockage, etc.)	• Redundant systems with different coverages (e.g., P2P, satellite, LTE) • Mesh networked infrastructure • Real time monitoring of the C2 link • Flight planning to ensure C2 coverage using obstacle map/database • Lost link profile	X	X	X	X
Clutter affecting subsystems (e.g., DAA)	• Layered approach to sensors providing data (e.g., radar + Electro-Optical/IR + acoustic, etc.) • Clutter filters/processing for data from sensors • Tracker software that processes sensor data prior to pilot receiving the data • Human in the loop data validation	X	X	X	X
Human error in flight planning and operations	• Automation in the UAS and supporting systems • Human input validation (automated/simulation or secondary human validation) prior to execution of the human input • Monitoring and alerting • Certification requirements or robust training	X	X	X	X

Software errors (geofence failures, etc.)	• Build software to some certification standard • Fully testing software in a controlled environment prior to conducting real-world flights • Automation in the UAS and supporting systems • Human intervention	X	X	X	X
Failure to comply with 14 CFR 91.111 and 91.113 (inability to avoid other aircraft)	• Standards-compliant DAA system • DAA system that is not standards-compliant • UA technical identification capability (includes manned aircraft capability to receive information) • UA visible identification enhancement • Changing of right-of-way priority			X	X
Failure to comply with 14 CFR 91.13 (e.g., inability to avoid obstacles)	• Obstacle avoidance system • Collision impact mitigation system (frangible, cage, parachute, etc.) • Pre-flight planning	X	X		

6 TASK 3: ANALYSIS OF DAA REQUIREMENTS AND OBSTACLE AVOIDANCE REQUIREMENTS

6.1 Objectives

The objectives for this task were:

- Development of a simulation environment that allows assessment of risks and potential solutions identified in Tasks 1 and 2.
- Execution of numerical simulations to analyze the competing shielding requirements to manage risks with flight near obstacles and to manage risks with MA.
- Evaluation of risks, including those associated with the type of operation, UAS characteristics, type of obstacle, and type of intruder.

6.2 Methods

For this task, multiple simulation environments for evaluating risks were developed. These environments were used to perform many simulations to evaluate hazards associated with shielded operations.

Electric and Magnetic Field (EMF), airflow, and GPS hazards are evaluated using multiple models. The EMF model produces solutions to Maxwell's equations using the Finite Element Method (FEM), while the airflow models utilize AirSim, a model that incorporates, among other physical effects, airflow impacts on aircraft. GPS hazards were modeled using a framework comprised of seven components. In this, Matlab and Simulink were interfaced with Gazebo for visualization.

Details regarding the EMF hazards model are:

- Solutions were computed using the FEM within the QuickField (Tera Analysis Ltd. 2018).
    - For transmission line simulations, QuickField simulations were validated using a tool based on analytic methods.
- Transmission line simulations:
    - Transmission lines were considered to be a linear, homogeneous, isotropic lossy dielectric medium.

  - Transmission lines were assumed to be infinitely long, straight, parallel to each other, and parallel to the ground.
  - Transmission line conductors were assumed to be copper cylinders with an assumed electrical conductivity of 6 S m^{-1}.
  - The scalar electric potential along the semicircular boundary (in the air and 320 m from the center of the transmission lines) and along the ground was assumed to be zero.
  - The soil electrical conductivity was assumed to be 0.02 S m^{-1} and the magnetic permeability was assumed to be 1.
  - Simulations were performed for three-phase 345, 500, and 765 kV lines with ground wires.
  - Dimensions and characteristics of the phase conductors for the 345, 500, and 765 kV lines are provided by Bühringer (2010), Brown (2013), El Dein (2013), and Kaabouch and Moncayo (2024).
  - Each simulation required more than a half-million mesh elements.
- Short circuit simulations:
  - Except where noted, settings were the same as in the transmission line simulations.
  - Short circuits were assumed to be either 0.1 s or 1.0 s in duration, which matches the shorter and longer time durations of these events (Finneran at al. 2015).
  - One million mesh nodes were used in the simulations.
- Transformer simulations:
  - Simulations of 3-phase (Hitachi Energy 2022) and 1-phase (ABB 2022) transformers, which are heavily used, were performed.
  - Simulations were performed using Autodesk Inventor (Autodesk 2021) and the FEM analysis plug in EMWorks (2022).
  - Each transformer was surrounded by a 3D cube that simulated air in the environment.

Wind-effects model details are:

- Model basis is AirSim (Shah et al. 2018):
  - Open-source platform that employs high-quality graphics rendering.
  - Includes environmental variations of gravity, the Earth's magnetic field (approximated as a tilted dipole), and air pressure and density using the US Standard Atmosphere model (National Oceanic and Atmospheric Administration 1976).
  - Computes linear and angular drag, and resulting accelerations, for aircraft using linear drag coefficients and integrations of linear drag across surfaces for angular drag.
  - Performs real-time simulations using either direct pilot control or scripted control
  - Supports interfacing with small fixed- and rotary-wing aircraft through MavLink and ArduCopter.
  - Can be used to simulate terrain and object collisions.
- Straight-line winds:
  - Real-world environment at Tiger Mounter in Washington, which includes many powerlines, trees, and non-uniform terrain.

    - Simulations performed for both a fixed-wing and quadcopter UAS performing a powerline inspection mission.
    - AirSim API was modified to include additional control and data.
    - The initial condition for each simulation had a UAS start from at a constant altitude and distance from powerlines.
    - A constant wind blowing towards the powerlines was applied.
- Wake-vortex impacts:
    - Custom algorithms were developed in AirSim to enable these simulations.
    - Multiple aircraft, including the Boeing 737 and 747, a C172 fixed-wing, an AT-502B fixed-wing that is commonly used for crop dusting, and helicopters were used to generate vortices.
    - Simulated inspections were conducted with a multirotor at a fixed speed (12 m s^{-1}) following a path parallel to a set of simulated powerlines 15 m from the middle wires.
    - Three scenarios were simulated:
        - Head-on encounter with a fixed-wing MA.
        - Head-on encounter with a rotary-wing MA.
        - Fixed-wing MA approaching from 90° from the right.
    - The velocity distribution was modeled following the Lamb-Oseen structure, which was determined by Wang et al. (2019) to provide the best flow structure for wake vortices. With this model, the initial wake vortex circulation strength is driven by aircraft weight, wingspan, speed, and air density.
    - Decay of the vortices was modeled following the method described by Hallock et al. (2015).
- Turbulence
    - Wind gust speeds were modelled to follow the Weibell distribution (e.g., Almalki and Nadarajah 2014).
    - Parameters of wind gust speed distributions were derived from wind gust measurements.
    - The result was a set of simulated wind gusts ranging from 2 m s^{-1} to 35 m s^{-1}, with variability on the order of m s^{-1} over a time span of 1 s.
    - For these simulations, the UAS was flown along a path parallel to the powerlines at a distance of 9.1 m.

GPS model details are:

- Seven primary model components:
    - Graphical interface Gazebo:
        - Provides 3D rendering.
        - Provides capability to identify collisions.
    - Communication model Robot Operating System:
        - Coordinates communication between model components.
    - Aircraft model module:
        - Aircraft that was simulated is the 3DR RTF X8 drone:
            - 2.087 kg mass.
            - ~788,000 mm^2 area.

        - ~842,000 mm^3 volume.
        - Average speed of 6.5 m s^{-1}.
    - Control system module:
        - Linear controller used for trajectory tracking.
        - Two loops utilized—an inner controller that minimizes attitude tracking errors and an outer controller that regulates position and velocity errors.
    - Guidance and navigation module:
        - Desired trajectory provided to the system.
        - The navigation algorithm integrates accelerometer, gyroscope, and GPS data, resulting in a loosely coupled inertial navigation system.
    - GPS model module:
        - Simulates GPS satellite acquisition, signal dropout, and attenuation.
        - Model represents typical systems that are commercially available. Thus, very advanced methods for countering GPS-degraded effects are not included.
        - GPS constellation ephemeris data are used to determine the number of satellites within line of sight of the UAS.
        - Blockage of GPS signals (shadowing) within an urban environment is simulated.
        - Degradation of GPS accuracy owing to multipath effects are simulated.
    - Failures module:
        - Enables incorporation of aircraft failures (loss of control, component failures, etc.).

6.3 Summary of Results

A detailed description of Task 3 efforts is provided by Kaabouch and Moncayo (2024). Herein, a high-level overview is provided.

6.3.1 Electromagnetic Fields

Significant research has been conducted over the last decade to understand the effects of EMFs on UAS during power line inspections. Zhang et al. (2019) established that electric fields above 50 kV m^{-1} led to UAS instability, suggesting a threshold for stable UAS operation. They also stated that magnetic fields over 180 µT made UASs drift towards power lines, affecting the magnetometer function; however, their research did not address the response of different UAS models to these disturbances or their operational implications. Furthermore, the United States Department of Homeland Security cited a similar threshold of 50 kV m^{-1} (National Coordinating Center for Communications 2019) for modeling infrastructure resilience against electromagnetic pulses. These thresholds were used by Kaabouch and Moncayo (2024) to estimate safe operating distances for UAS.

Kaabouch and Moncayo (2024) evaluated EMFs for single and double powerline configurations having voltages of 345 kV, 500 kV, and 765 kV. They determined that the magnetic field threshold of 180 µT was the more conservative threshold (relative to the electric field threshold value of 50 kV m^{-1}). For single and double powerline configurations, a safe distance is 9 m from any individual powerline, and represents the most conservative distance (the other two corresponding safe distances are 4 m and 7 m). The minimum safe distance during a short circuit/fault increases significantly, with the largest safe distance for the 180 µT threshold being ~40 m. For transformers, the safe distances are significantly smaller depending, of course, on transformer configuration. Kaabouch and Moncayo (2024) identified safe distances from transformers for the 180 µT threshold that are all < 5 m. It is reiterated that safe distances depend upon many factors and can be significantly reduced by shielding UAS from EMI. Factors that safe distances depend upon include, but are not limited to:

- Powerline configuration
- Powerline voltage
- Orientation of UAS relative to powerline (EMFs are not isotropic)
- Whether a fault is occurring
- Fault intensity
- Orientation relative to a fault
- Transformer characteristics (number of phases, current, etc.)
- Orientation relative to a transformer
- UAS characteristics
    - Onboard system
    - Degree of EMI shielding

6.3.2 Airflow

6.3.2.1 Wind Effects

A multicopter's ability to maintain course or at least resist further displacement after the initial onset of wind effects is predictable and enables provision of guidelines on minimum distances from hazardous areas where EMI effects may further disrupt safe navigation. In the simulations conducted by Kaabouch and Moncayo (2024), winds produced a constant offset from the original UA path. There is also a maximum wind component that will exceed the aircraft's performance envelope, resulting in a no-fly decision by the air crew as the ambient conditions exceed the UAS's ability to navigate.

A multicopter's type, like other copters, is subject to a reduction in performance envelope given strong headwinds; therefore, a strong quartering headwind or tailwind, or even a strong descending wind, will make it harder for the aircraft to maintain course and separation from unsafe EMI distances. This information should be used as part of the pre-flight decision process before launching an inspection mission.

The specific capacity to navigate a mission route depends upon the aircraft's performance rather than a universal distance. Higher performance will result in the aircraft being able to maintain a closer distance to the unsafe EMI area.

6.3.2.2 Wake Vortex Effects

Kaabouch and Moncayo (2024) simulated the interaction of a multicopter with wake vortices produced by both fixed- and rotary-wing MA. Wake encounters were constructed to ensure that the UA flew through aircraft wakes near the center of the rotation shortly after that aircraft's passage.

Wake effects on altitude and attitude displacement ranged from major for the 747 to nearly negligible for the Cessna 172. The rest of the aircraft wake effects from MA sizes of the type expected to be encountered a) at common UAS altitudes and b) in shielded spaces ranged from easily recoverable to negligible.

The implication for safety-of-flight issues is that there remains a small residual risk of displacement or upset that pushes the aircraft into proximity of transmission lines. Otherwise, the simulations do not currently show elevated risk compared to the risks already inherent in UAS/crewed traffic encounters. The remaining exception would be the effects of helicopter rotor wash pushing down on a UA. This, too, presents a scenario where failures of separation have already occurred.

6.3.2.3 Turbulence

Impacts of wind gusts on both fixed- and rotary-wing UA were simulated by Kaabouch and Moncayo (2024). Outcomes revealed a common pattern for both multirotor and fixed-wing configurations. In each scenario, the UAS could not return to the original path and tried to resist the effects of turbulence to fulfill its mission objectives. Despite wind gust speeds surging beyond 30 m s^{-1}, the UAS demonstrated a noteworthy resilience, evading catastrophic outcomes such as collisions or crashes, which can be attributed to the transient nature of these high-speed wind bursts (brief duration). The multirotor exhibited remarkable performance since it never crossed a defined safety boundary. In contrast, the fixed-wing UA experienced more challenges owing to turbulence. It crossed the defined safety boundary (horizontal deviations up to 16 m) and experienced significant vertical deviations (up to ~30 m) as it struggled with the gusts. This divergence underscores the relative stability of the multirotor, which has a robust performance envelope and superior control over attitude angles. The multirotor's ability to withstand turbulent gusts more effectively is attributed to its inherent design, while the characteristics of the fixed-wing UA results in it struggling to maintain both its course and safe distances from sources of strong electromagnetic fields.

6.3.3 Impacts on GPS Systems

As discussed by Kaabouch and Moncayo (2024), GPS satellite signals are susceptible to reflections and diffraction, much like any other electromagnetic wave. The manifestation of these effects, commonly referred to as scintillation, multipath interference, and shadowing, can frequently undermine the precision of GPS positioning, ultimately resulting in either a partial or complete loss of signal tracking. Such occurrences can lead to a decline in navigation performance and in the integrity of aerospace systems.

Kaabouch and Moncayo (2024) modelled these effects and their implications for position accuracy across various urban environments. The impact of signal degradation effects was analyzed by evaluating GPS constellation quality metrics such as Dilution Of Precision (DOP). A high-fidelity simulation environment was developed for operation of sUAS across a range of typical and relevant scenarios.

Autonomous missions designed with high levels of navigation accuracy require low levels of uncertainty, which translates into low DOP values. This becomes achievable when healthy geometries are obtained for the trilateration process and, consequently, a connection with more than seven satellites is commonly needed to obtain enough redundancy to keep DOP low. It is important to note that the geometry of the available satellites is the key factor that influences the DOP.

Analysis of multipath effects can be very complex since this becomes a geometric problem applied to antennas in motion given the complex dynamic behavior of sUAS within urban environments. In this task, this limitation was addressed by implementing a stochastic approach to model multipath effects. Numerical simulations revealed that among the various GPS signal degradation types, those posing the highest risks, in descending order, were dropouts, jamming, and a reduced number of satellites (down to four). Thus, GPS integrity should be monitored and addressed for operations where these effects may be realized. This is especially true for operations at low altitudes (≤ 16 m) and close to buildings (e.g., within 6 m). It is noted that impacts associated with altitudes and distances from buildings identified herein have some dependency upon the specific scenarios considered and, thus, a broader analysis to generalize impacts would be valuable.

To underscore impacts, simulation results for UAS flights in a gap between two buildings 12 m and 40 m tall are provided in Table 3. In these simulations, the UA begins at the starting points relative to the 40-m-tall building indicated in Table 3. Impacts on GPS are significant, with high rates of collision for smaller initial horizontal distances from the building and lower altitudes. This emphasizes the challenges associated with UA operations in urban areas.

Table 3. Rates of collision with building for different initial horizontal distances from the building and different heights.

		Height from Ground					
Distance from building wall		8 m	12 m	16 m	20 m	24 m	28 m
	2 m	100%	87.5%	87.5%	80%	80%	75%
	4 m	62.5%	30%	20%	15%	10%	10%
	6 m	26.7%	6.7%	5%	0%	0%	0%
	8 m	0%	0%	0%	0%	0%	0%
	10 m	0%	0%	0%	0%	0%	0%

7 TASK 4: FLIGHT TEST PLANS

Three rounds of flight tests were conducted by the University of North Dakota (UND)/Northern Plains UAS Test Site (NPUASTS), New Mexico State University (NMSU), and North Carolina State University (NCSU) teams. These test plans were developed using overarching project goals, known capabilities and resources of the respective teams, and experience developed from previous testing/projects. The following sections provide information regarding the test plans for these test campaigns.

7.1 UND/NPUASTS September 2023

This test campaign is described in detail by NPUASTS and UND (2023) and Askelson et al. (2024). A high-level overview is provided herein.

7.1.1 Objectives

The objectives of the September 2023 flight tests were:

- Primary
  - Evaluation of timing impacts of shielding structure on maintenance of well clear using the "standard" 2000 ft horizontal and 250 ft vertical separation definition of well clear.
  - Evaluation of timing impacts/expected benefits of using an alternative approach to well clear wherein ownship is positioned with the shielding structure between it and the intruder. This approach to well clear is referred to as Behind Local Obstacle Well Clear (BLOWC).
- Secondary
  - Evaluation of Human Machine Interfaces (HMIs)/displays that support maintenance of well clear in a shielded environment.
  - Evaluation of methodologies that ensure safe test execution.

7.1.2 Date/Schedule

Tests were conducted during the week of 17-23 September 2023, with the desired set of encounters being completed in two days (18 and 19 September 2023). The planned schedule for that week ran from 7:00 a.m. to 6:30 p.m. local time each day.

7.1.3 Location

The test campaign was conducted approximately 6 nm northwest of Mayville, ND, over a rural farm field with a straight tree-line windbreak that acted as a stand-in powerline. The operational location was chosen due to its low population density and the minimal road and air traffic in the general area. Figure 1 illustrates the geographical location of the test elements. The test area is Class G airspace (up to Class A airspace).

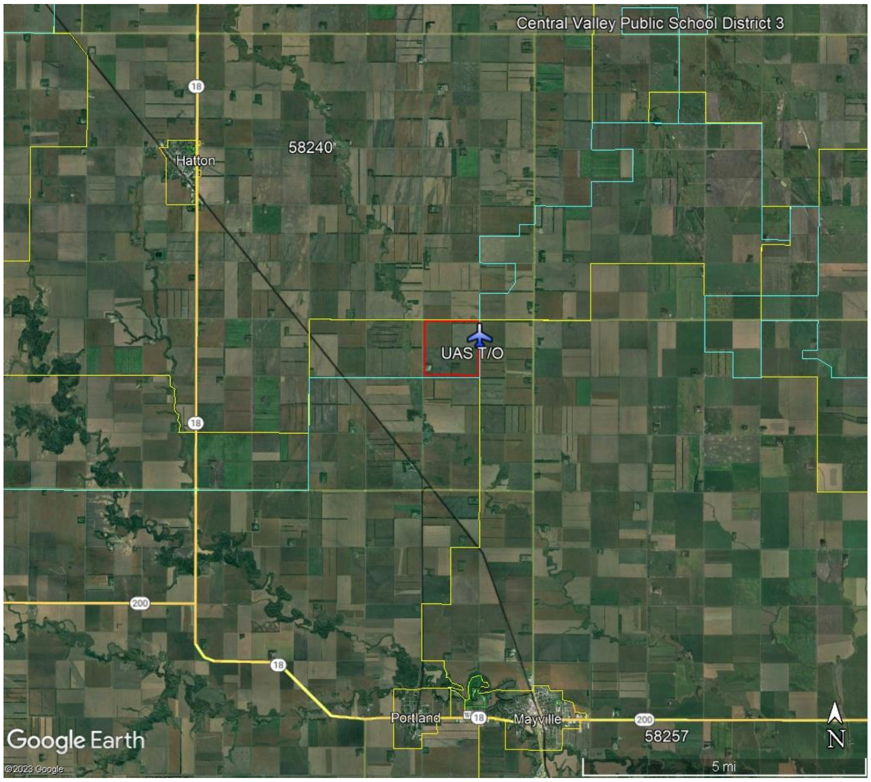


Figure 1. Location of test elements during the September 2023 flight tests. The approximate location of UA operations/test elements and of the well clear "box" are shown by the aircraft icon and red box, respectively.

7.1.4 System Tested

Testing was conducted using Automatic Dependent Surveillance-Broadcast (ADS-B) as the source of aircraft location data (e.g., the sensor) and a Simulyze display system. The focus of this test campaign was on the maneuver step of DAA (as opposed to the detect step). Thus, ADS-B served well as the detection system for this test campaign.

7.1.5 Test Plan Overview

In this test campaign, the focus was on impacts of obstacles on maneuvers and DAA system requirements and not on impacts of encounter type (horizontal vs. climb/descend-into), encounter geometry, and intruder speeds. Thus, only horizontal encounters with an intruder flying at 100 kts (no speed variations) were executed. Because ownship was a multi-rotor aircraft for which an undesirable reverse-course maneuver is likely preferred for numerous encounter geometries, only 0° (head-on) and 225° (overtaking from behind and left) horizontal encounter geometries were utilized. A reverse-course maneuver was not desired because such maneuvers, given the test configuration, did not enable evaluation of obstacle impacts on maneuvers.

Three types of maneuvers were executed:

- Turn: UA turns roughly perpendicular to the MA flight path and flies to a well clear distance.

- Climb and Turn: UA climbs to get above the stand-in powerline and then flies roughly perpendicular to the MA flight path to get to a well clear distance.
- BLOWC: UA climbs, crosses the stand-in powerline, and then descends to put the stand-in powerline between it and the MA, thus reaching a safe (well clear) state.

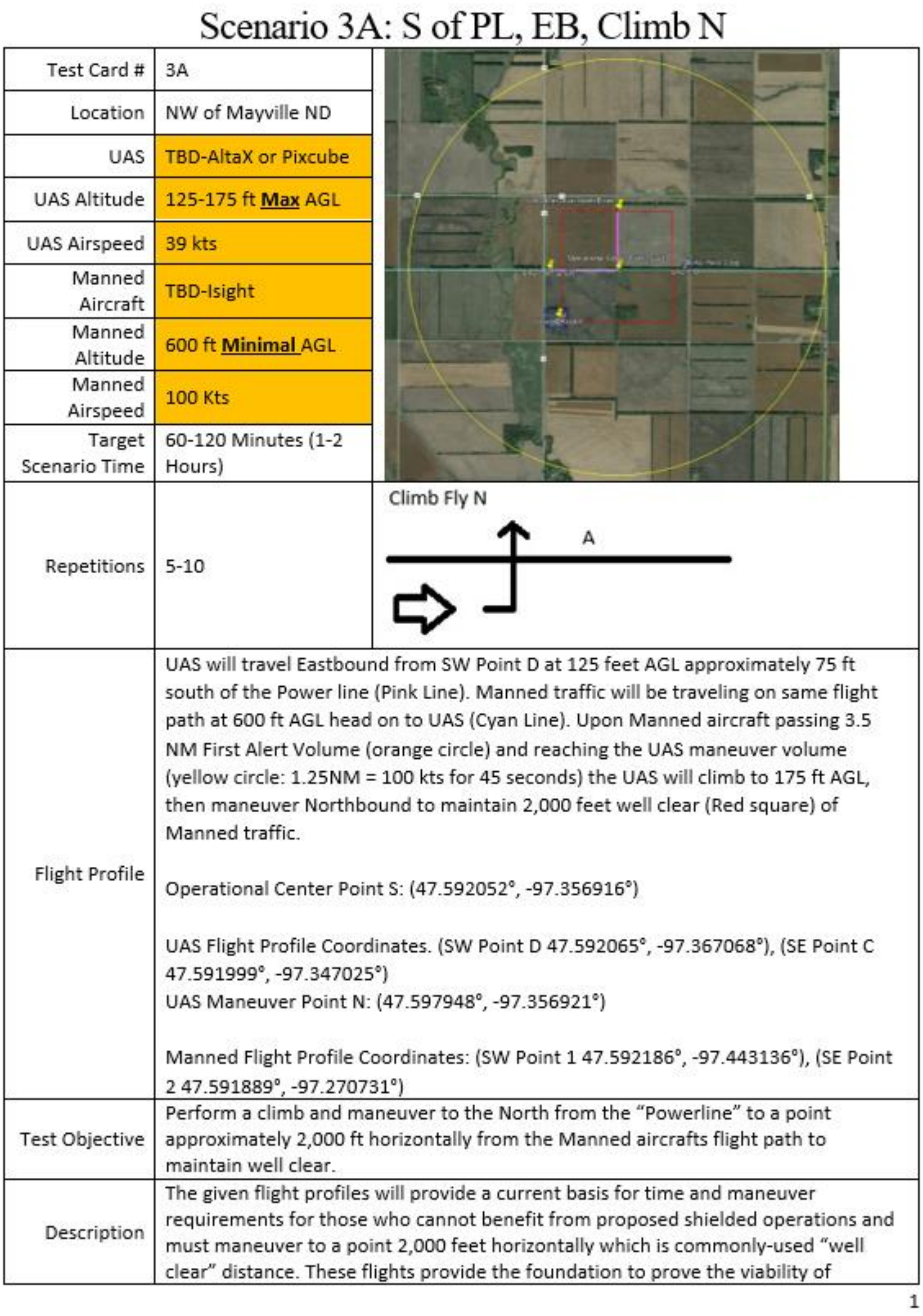
The UA that was flown is the NPUASTS' Freefly Alta X UAS and the intruder was a Cessna 182 that is owned and operated by ISight Drone Services. Information regarding these aircraft is provided by Askelson et al. (2024).

7.1.6 Sample Test Cards

A total of 16 cards were developed from the following variations:

- 1 0° Horizontal Encounter (HE) scenario × 1 intruder speed × 2 UA inbound directions (east/westbound) × 3 maneuver types (turn, climb turn, BLOWC) × 2 UA maneuver directions (north or south): 12 cards
- 1 225° HE scenario × 1 intruder speed × 2 UA inbound directions (east/westbound) × 2 UA maneuver directions (north or south): 4 cards

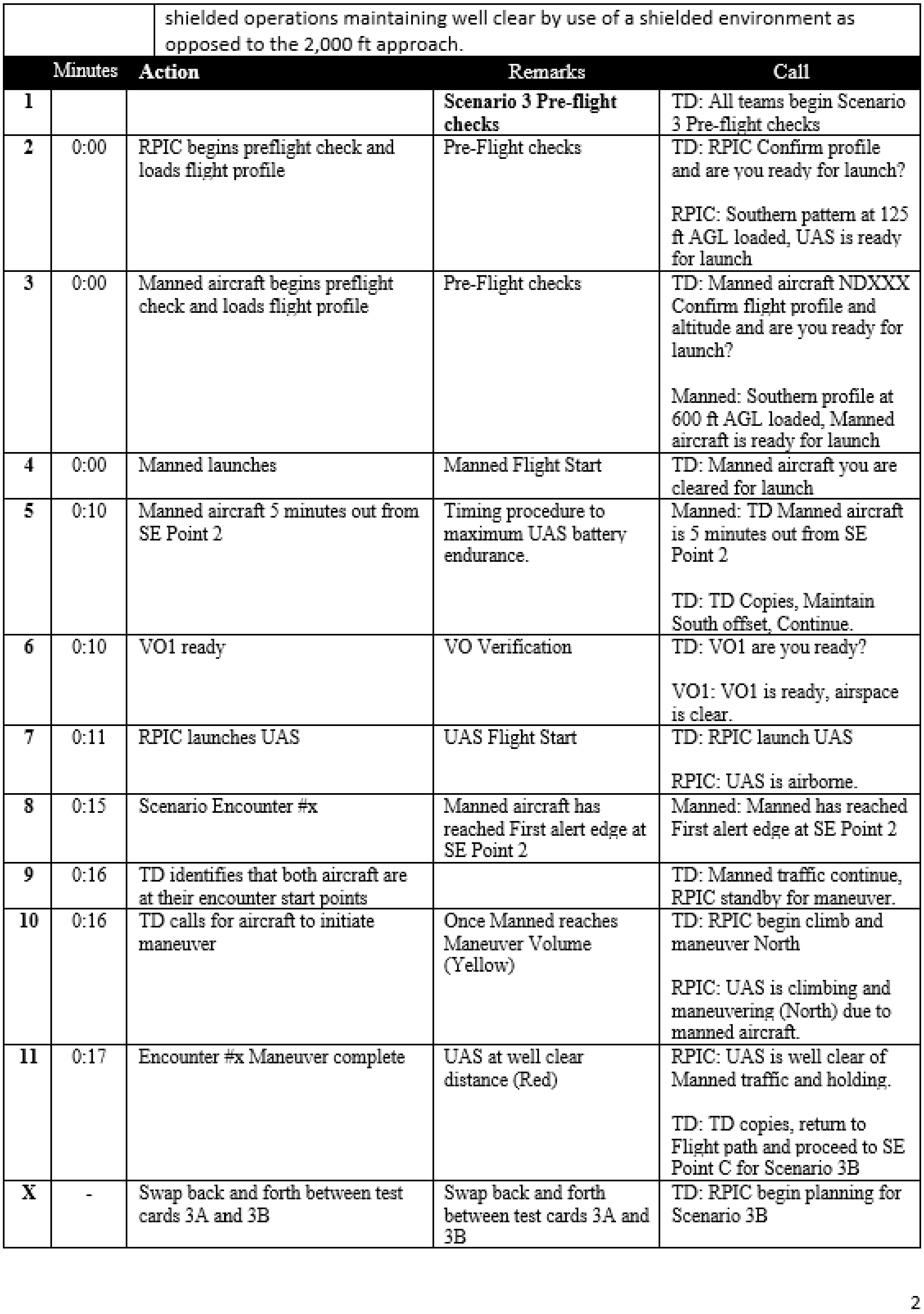
Not all possible variations (inbound direction × maneuver type × maneuver direction) relative to the stand-in powerline were delineated in test cards. An example test card for 0° HE for the UA flying towards the east when inbound to the Encounter Focal Point (EFP) and executing a climb and turn maneuver (to the north) is provided in Figure 2.



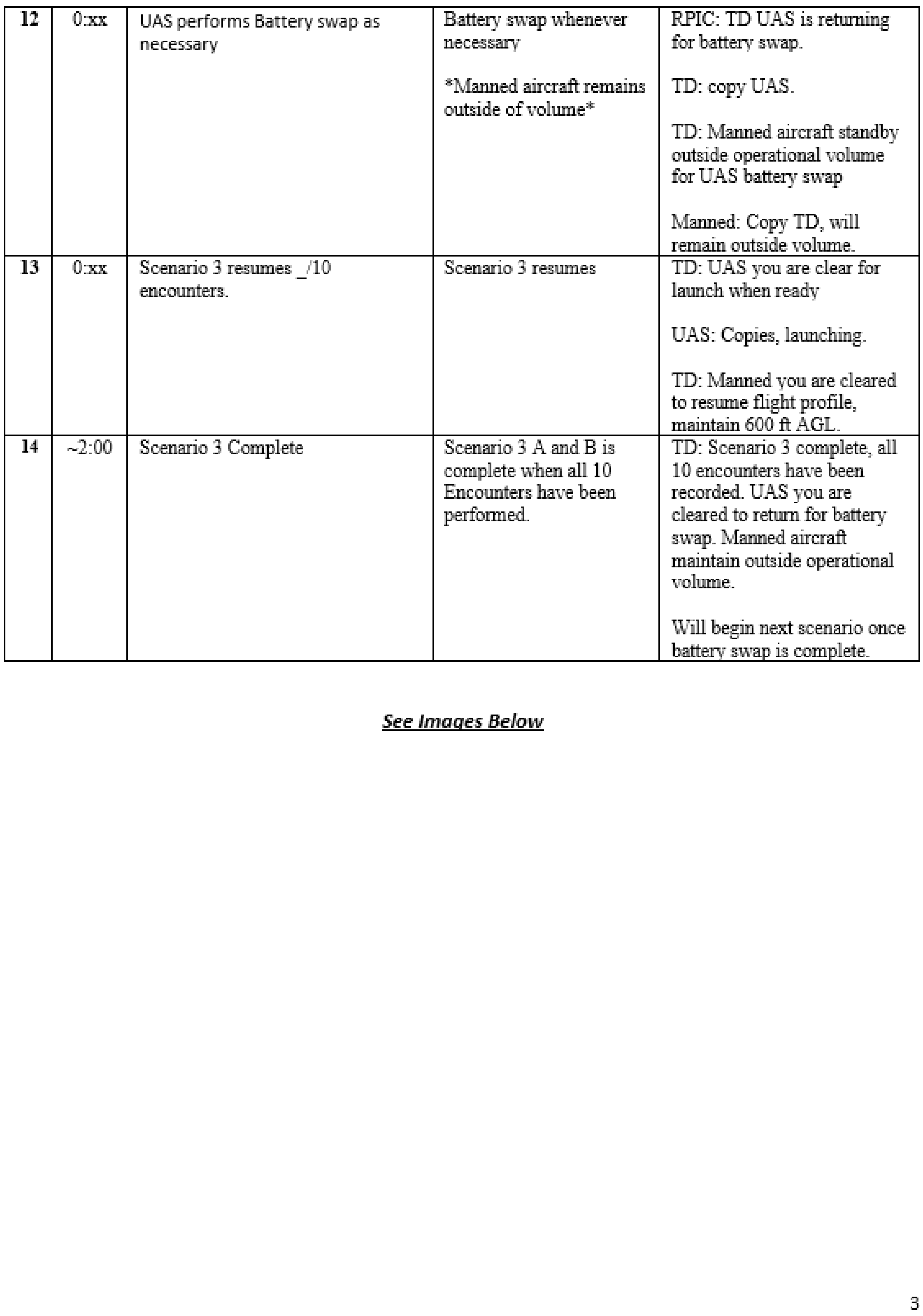
Scenario 3A: S of PL, EB, Climb N

Test Card #	3A
Location	NW of Mayville ND
UAS	TBD-AltaX or Pixcube
UAS Altitude	125-175 ft **Max** AGL
UAS Airspeed	39 kts
Manned Aircraft	TBD-Isight
Manned Altitude	600 ft **Minimal** AGL
Manned Airspeed	100 Kts
Target Scenario Time	60-120 Minutes (1-2 Hours)
Repetitions	5-10
Flight Profile	UAS will travel Eastbound from SW Point D at 125 feet AGL approximately 75 ft south of the Power line (Pink Line). Manned traffic will be traveling on same flight path at 600 ft AGL head on to UAS (Cyan Line). Upon Manned aircraft passing 3.5 NM First Alert Volume (orange circle) and reaching the UAS maneuver volume (yellow circle: 1.25NM = 100 kts for 45 seconds) the UAS will climb to 175 ft AGL, then maneuver Northbound to maintain 2,000 feet well clear (Red square) of Manned traffic. Operational Center Point S: (47.592052°, -97.356916°) UAS Flight Profile Coordinates. (SW Point D 47.592065°, -97.367068°), (SE Point C 47.591999°, -97.347025°) UAS Maneuver Point N: (47.597948°, -97.356921°) Manned Flight Profile Coordinates: (SW Point 1 47.592186°, -97.443136°), (SE Point 2 47.591889°, -97.270731°)
Test Objective	Perform a climb and maneuver to the North from the “Powerline” to a point approximately 2,000 ft horizontally from the Manned aircrafts flight path to maintain well clear.
Description	The given flight profiles will provide a current basis for time and maneuver requirements for those who cannot benefit from proposed shielded operations and must maneuver to a point 2,000 feet horizontally which is commonly-used “well clear” distance. These flights provide the foundation to prove the viability of

1



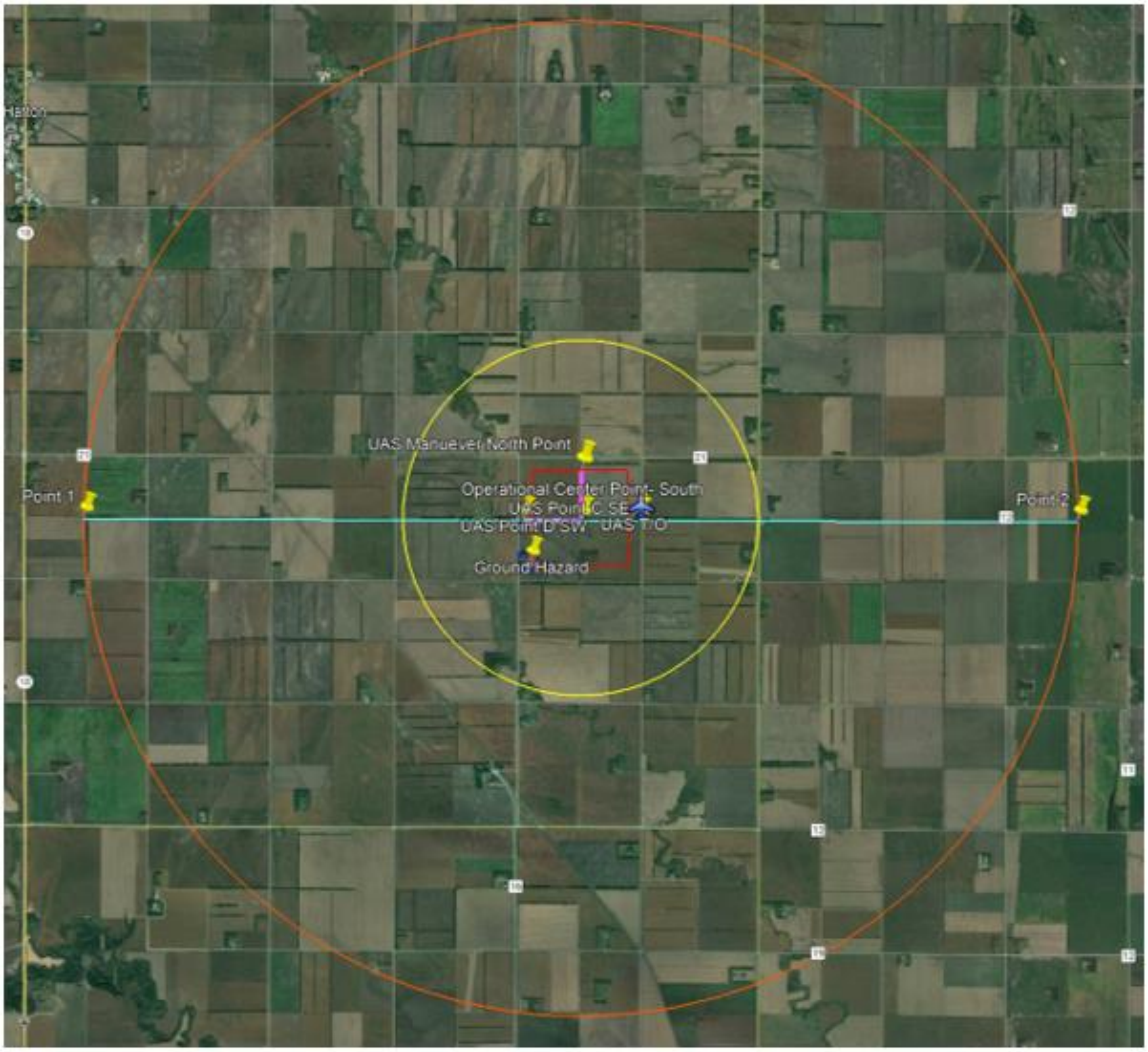
		shielded operations maintaining well clear by use of a shielded environment as opposed to the 2,000 ft approach.		
	Minutes	**Action**	**Remarks**	**Call**
1			**Scenario 3 Pre-flight checks**	TD: All teams begin Scenario 3 Pre-flight checks
2	0:00	RPIC begins preflight check and loads flight profile	Pre-Flight checks	TD: RPIC Confirm profile and are you ready for launch? RPIC: Southern pattern at 125 ft AGL loaded, UAS is ready for launch
3	0:00	Manned aircraft begins preflight check and loads flight profile	Pre-Flight checks	TD: Manned aircraft NDXXX Confirm flight profile and altitude and are you ready for launch? Manned: Southern profile at 600 ft AGL loaded, Manned aircraft is ready for launch
4	0:00	Manned launches	Manned Flight Start	TD: Manned aircraft you are cleared for launch
5	0:10	Manned aircraft 5 minutes out from SE Point 2	Timing procedure to maximum UAS battery endurance.	Manned: TD Manned aircraft is 5 minutes out from SE Point 2 TD: TD Copies, Maintain South offset, Continue.
6	0:10	VO1 ready	VO Verification	TD: VO1 are you ready? VO1: VO1 is ready, airspace is clear.
7	0:11	RPIC launches UAS	UAS Flight Start	TD: RPIC launch UAS RPIC: UAS is airborne.
8	0:15	Scenario Encounter #x	Manned aircraft has reached First alert edge at SE Point 2	Manned: Manned has reached First alert edge at SE Point 2
9	0:16	TD identifies that both aircraft are at their encounter start points		TD: Manned traffic continue, RPIC standby for maneuver.
10	0:16	TD calls for aircraft to initiate maneuver	Once Manned reaches Maneuver Volume (Yellow)	TD: RPIC begin climb and maneuver North RPIC: UAS is climbing and maneuvering (North) due to manned aircraft.
11	0:17	Encounter #x Maneuver complete	UAS at well clear distance (Red)	RPIC: UAS is well clear of Manned traffic and holding. TD: TD copies, return to Flight path and proceed to SE Point C for Scenario 3B
X	-	Swap back and forth between test cards 3A and 3B	Swap back and forth between test cards 3A and 3B	TD: RPIC begin planning for Scenario 3B



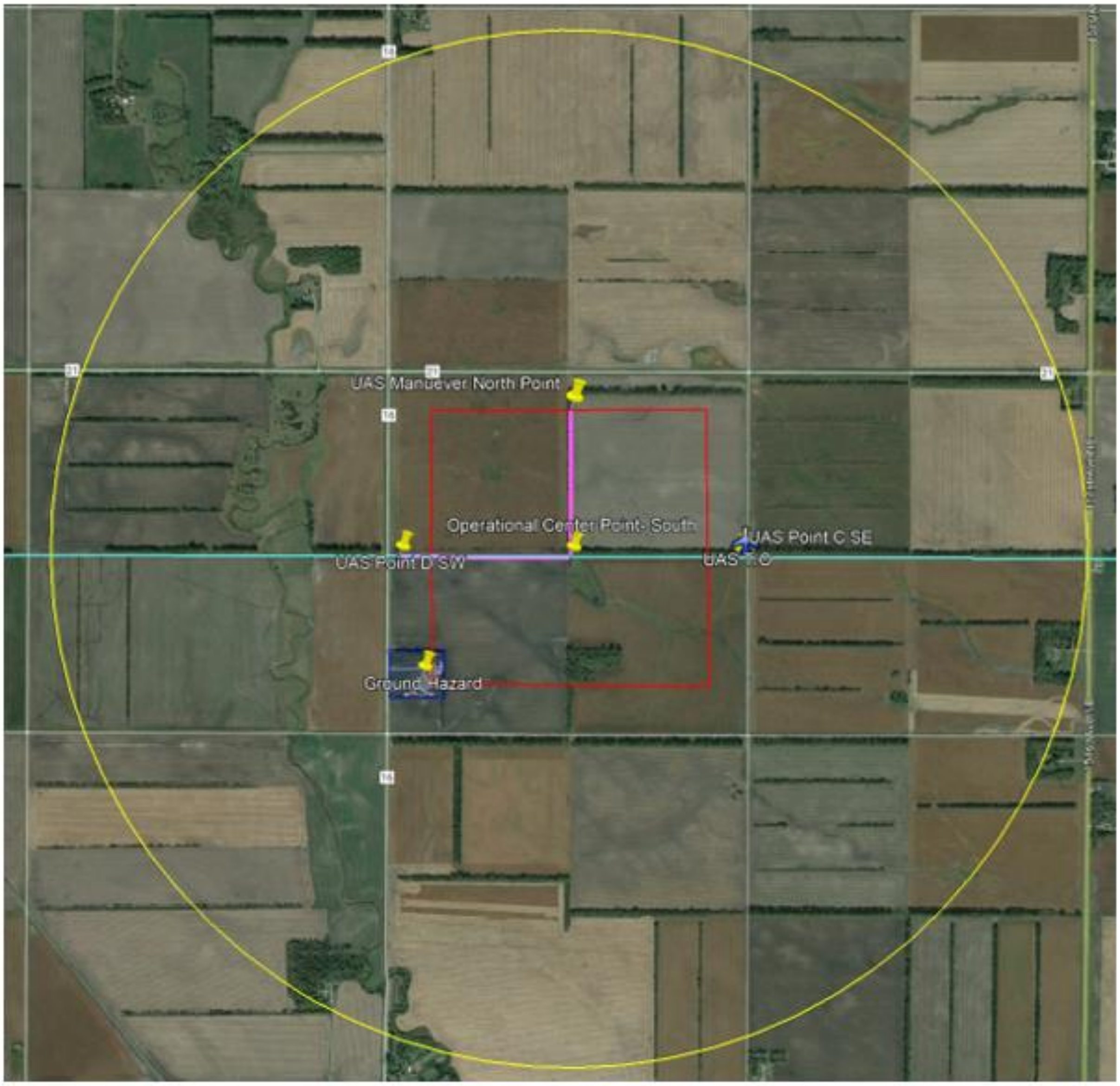
12	0:xx	UAS performs Battery swap as necessary	Battery swap whenever necessary *Manned aircraft remains outside of volume*	RPIC: TD UAS is returning for battery swap. TD: copy UAS. TD: Manned aircraft standby outside operational volume for UAS battery swap Manned: Copy TD, will remain outside volume.
13	0:xx	Scenario 3 resumes _/10 encounters.	Scenario 3 resumes	TD: UAS you are clear for launch when ready UAS: Copies, launching. TD: Manned you are cleared to resume flight profile, maintain 600 ft AGL.
14	~2:00	Scenario 3 Complete	Scenario 3 A and B is complete when all 10 Encounters have been performed.	TD: Scenario 3 complete, all 10 encounters have been recorded. UAS you are cleared to return for battery swap. Manned aircraft maintain outside operational volume. Will begin next scenario once battery swap is complete.

See Images Below

3


Hatton
UAS Manuever North Point
Point 1
Operational Center Point- South
UAS Point C SE
UAS Point D SW
UAS T/O
Ground Hazard
Point 2

4


16
21
UAS Manuever North Point
Operational Center Point- South
UAS Point C SE
UAS T/O
UAS Point D SW
Ground Hazard

6

Figure 2. September 2023 test card for 0° HE for the UA flying towards the east when inbound to the EFP and executing a climb and turn maneuver to the north.

7.2 NMSU February 2024

This test campaign is described in detail by NMSU (2023) and Cathey et al. (2024). A high-level overview is provided herein.

7.2.1 Objectives

The primary test objectives were:

1. Evaluation of timing impacts of shielding structure on maintenance of well clear using the "standard" 2000 ft horizontal and 250 ft vertical separation definition of well clear.
2. Evaluation of timing impacts/expected benefits of using an alternative approach to well clear wherein ownship is positioned with the shielding structure between it and the intruder. This approach to well-clear is referred to as BLOWC.

Secondary test objectives were:

1. Evaluation of HMIs/displays that support the maintenance of well-clear in a shielded environment.
2. Evaluation of methodologies that ensure safe test execution.

7.2.2 Date/Schedule

Tests were conducted during the week of 4-10 February 2024, with flight days on 5, 6, and 8 February 2024. Flight operations were planned to start at 7:00 a.m. and end at 5:30 local time.

7.2.3 Location

Flight operations were conducted at the Jornada Experimental Range approximately 18 nm NE of Las Cruces, NM, over a rural area owned and operated by the United States Department of Agriculture. This area is in the desert landscape which has an elevation change of ~10 feet per mile. The operational location was chosen due to its low population density and the minimal road and air traffic in the general area. UAS operations occurred using a public right-of-way location under Part 107 regulations. Figure 3 illustrates the operational area.

Figure 3. Location of the February 2024 flight tests.

7.2.4 System Tested

As with the September 2023 campaign, testing was conducted using ADS-B as the source of aircraft location data (e.g., the sensor). Since the focus of this test campaign was on the maneuver step of DAA, ADS-B served well as the detection system for this test campaign.

7.2.5 Test Plan Overview

A UA and an MA intruder aircraft were flown on straight-line, constant altitude, collision-type trajectories in which nominally the aircraft, if the UA does not maneuver, arrive at the same horizontal location at the same time. This, like the September 2023 campaign, leverages the approach developed in ASSURE project A18 (e.g., Askelson 2022). The encounters are designed such that at least 400 ft of vertical separation is maintained at all times to ensure safety.

Encounters scenarios include:

1. HE at 0° and turn perpendicular to the powerline and fly to a well clear distance of 2000 ft.
2. HE at 0° and climb over the stand-in powerline and fly to a well clear distance of 2000 ft.
3. HE at 0° and BLOWC.
4. HE at 45° and turn perpendicular to the powerline and fly to a well clear distance of 2000 ft.
5. HE at 45° and climb over the stand-in powerline and fly to a well clear distance of 2000 ft.
6. HE at 45° and BLOWC.

It is noted that for some encounters waypoints were used to maneuver the UA whereas for others a manual override was utilized. Both were used to evaluate timing impacts of these two options.

Two different fixed-wing UAS were used as ownship and are described in Tables 4 and 5. The MA intruder was a Flight Design CTLS (Table 6).

Table 4. Characteristics of the Volantex RC FPV2000. RC stands for Remote Controlled and FPV stands for First Person View.

		The airframe is designed and manufactured by Volantex RC. The FPV2000 was originally designed as a consumer recreational remote control plane for first person view flight. NMSU has installed a Pixhawk 2.4.8 (V1) to add autonomous flight capabilities.	
Wing Span	80 inches	**Cruise Speed**	15-20 kts
Maximum Takeoff Weight	3 lbs with minimal payload (external GPS positioning device for testing)	**UAS Operator**	NMSU
Endurance	50 min	**GCS Type**	Mission Planner
Line of Sight (LOS) Range	LOS Operation	**Autopilot**	Pixhawk 2.4.8

Table 5. Characteristics of the NMSU FIXAR 007.

		This UAS is a commercial-off-the-shelf UAS designed to be a Vertical Takeoff and Landing (VTOL) fixed-wing with limited manual flight control to allow for a more autonomous flight operations. The UAS has a lack of flight control surfaces and instead uses motor speed to control the UAS in fixed-wing and VTOL modes.	
Wing Span	65 inches	**Cruise Speed**	33-65 knots
Maximum Takeoff Weight	15 lbs with minimal payload (external GPS positioning device for testing)	**UAS Operator**	NMSU
Endurance	50 min	**GCS Type**	Proprietary
Line of Sight Range	LOS Operation	**Autopilot**	Proprietary

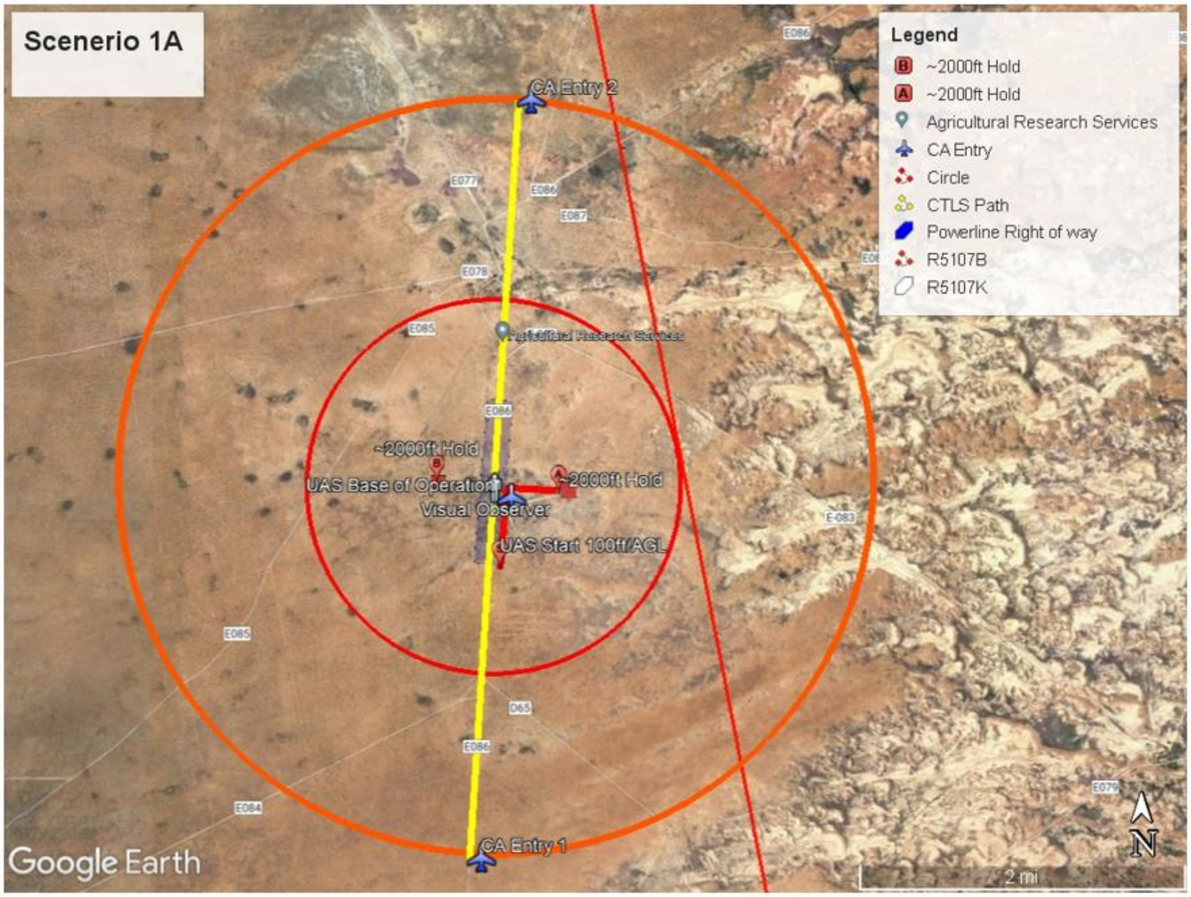
Table 6. Characteristics of the Flight Design CTLS.

	The Flight Design CTLS is a two seat light sport aircraft. It is designed for flight training and personal use. It is noted that the image shown is not the actual aircraft.		
Wing Span	28 ft 2 inches	**Cruise Speed**	100 knots
Maximum Takeoff Weight	1320 lbs	**Operator**	NMSU
Fuel Capacity	34 US gal	**GPS**	G296

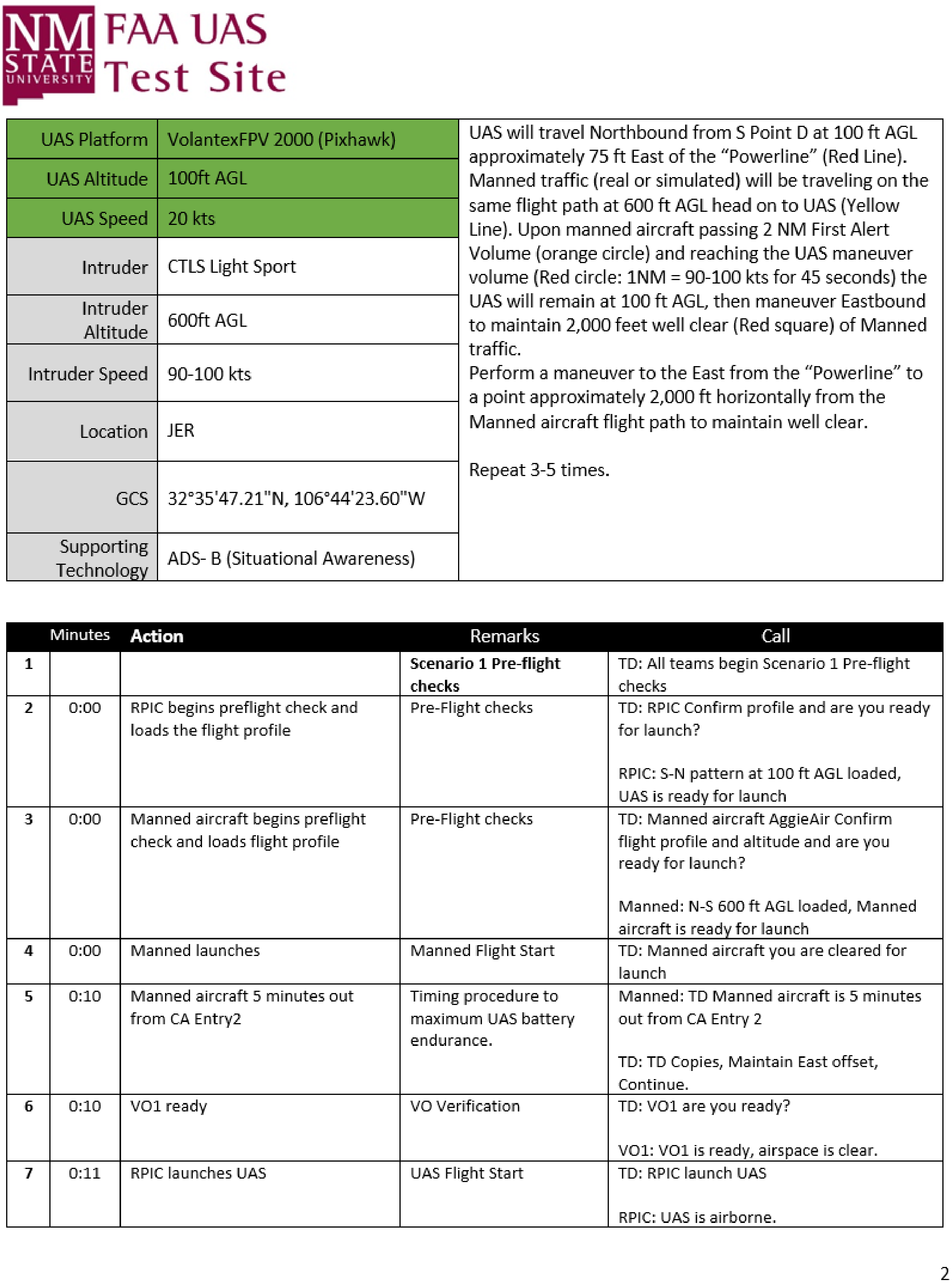
7.2.6 Sample Test Cards

Six primary test cards corresponding to the encounter scenarios provided in the previous section were created. An example test card is provided in Figure 4.

A45 Shielded Operations Test card
Scenario 1A (Simulated Powerlines)



Flight Card #	1A	The given flight profiles will provide a current basis for time and maneuver requirements for those who cannot benefit from proposed shielded operations and must maneuver to a point 2,000 feet horizontally which is a commonly used "well clear" distance. These flights provide the foundation to prove the viability of shielded operations maintaining well clear by the use of a shielded environment as opposed to the 2,000 ft approach.
Date/Time	___________	
Objective	Perform a maneuver to the East from the "Powerline" to a point approximately 2,000 ft horizontally from the Manned aircraft flight path to maintain well clear.	

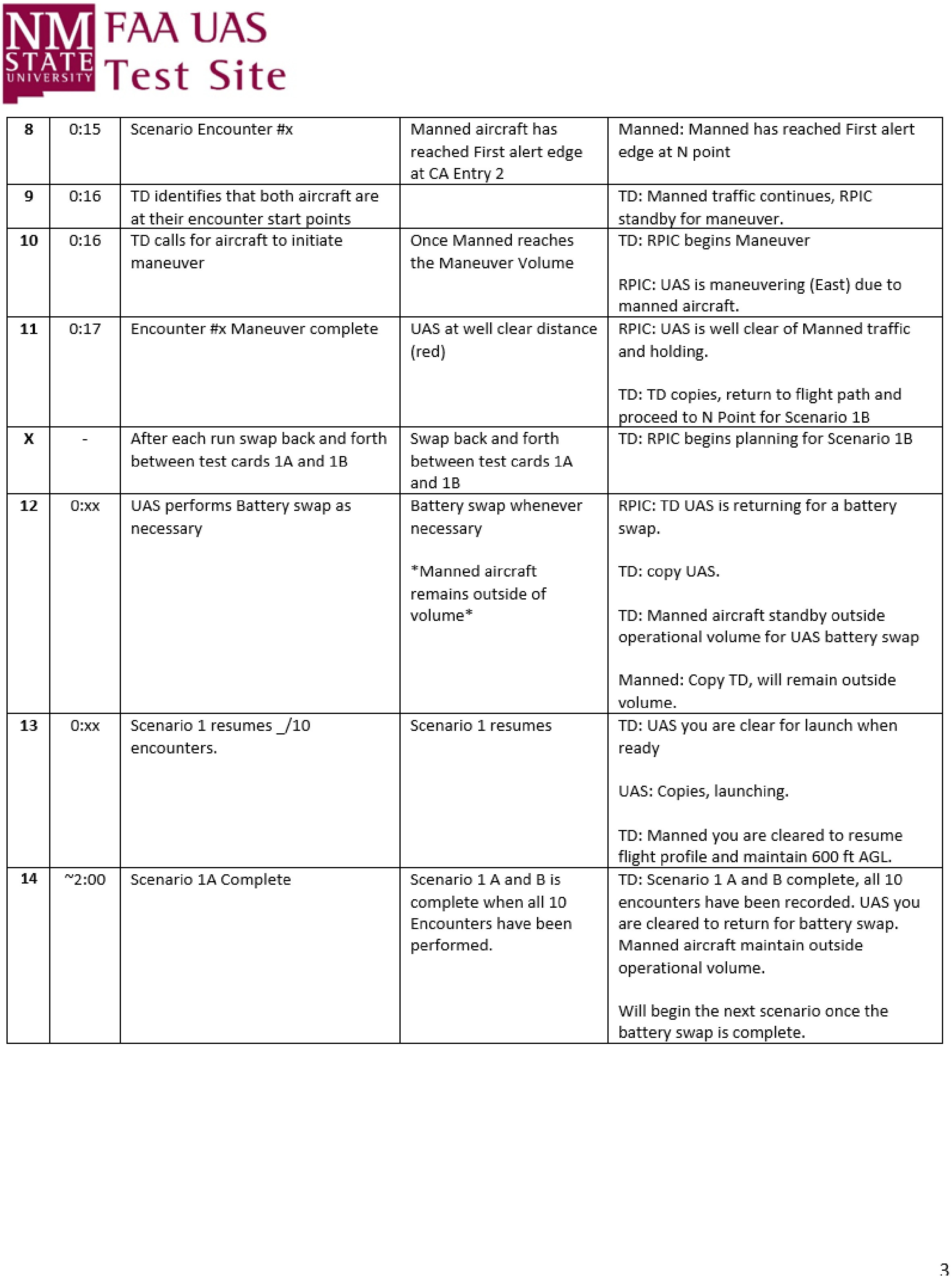


NM STATE UNIVERSITY FAA UAS Test Site

UAS Platform	VolantexFPV 2000 (Pixhawk)	UAS will travel Northbound from S Point D at 100 ft AGL approximately 75 ft East of the "Powerline" (Red Line). Manned traffic (real or simulated) will be traveling on the same flight path at 600 ft AGL head on to UAS (Yellow Line). Upon manned aircraft passing 2 NM First Alert Volume (orange circle) and reaching the UAS maneuver volume (Red circle: 1NM = 90-100 kts for 45 seconds) the UAS will remain at 100 ft AGL, then maneuver Eastbound to maintain 2,000 feet well clear (Red square) of Manned traffic. Perform a maneuver to the East from the "Powerline" to a point approximately 2,000 ft horizontally from the Manned aircraft flight path to maintain well clear. Repeat 3-5 times.
UAS Altitude	100ft AGL	
UAS Speed	20 kts	
Intruder	CTLS Light Sport	
Intruder Altitude	600ft AGL	
Intruder Speed	90-100 kts	
Location	JER	
GCS	32°35'47.21"N, 106°44'23.60"W	
Supporting Technology	ADS- B (Situational Awareness)	

	Minutes	Action	Remarks	Call
1			**Scenario 1 Pre-flight checks**	TD: All teams begin Scenario 1 Pre-flight checks
2	0:00	RPIC begins preflight check and loads the flight profile	Pre-Flight checks	TD: RPIC Confirm profile and are you ready for launch? RPIC: S-N pattern at 100 ft AGL loaded, UAS is ready for launch
3	0:00	Manned aircraft begins preflight check and loads flight profile	Pre-Flight checks	TD: Manned aircraft AggieAir Confirm flight profile and altitude and are you ready for launch? Manned: N-S 600 ft AGL loaded, Manned aircraft is ready for launch
4	0:00	Manned launches	Manned Flight Start	TD: Manned aircraft you are cleared for launch
5	0:10	Manned aircraft 5 minutes out from CA Entry2	Timing procedure to maximum UAS battery endurance.	Manned: TD Manned aircraft is 5 minutes out from CA Entry 2 TD: TD Copies, Maintain East offset, Continue.
6	0:10	VO1 ready	VO Verification	TD: VO1 are you ready? VO1: VO1 is ready, airspace is clear.
7	0:11	RPIC launches UAS	UAS Flight Start	TD: RPIC launch UAS RPIC: UAS is airborne.

2



NM STATE UNIVERSITY FAA UAS Test Site

8	0:15	Scenario Encounter #x	Manned aircraft has reached First alert edge at CA Entry 2	Manned: Manned has reached First alert edge at N point
9	0:16	TD identifies that both aircraft are at their encounter start points		TD: Manned traffic continues, RPIC standby for maneuver.
10	0:16	TD calls for aircraft to initiate maneuver	Once Manned reaches the Maneuver Volume	TD: RPIC begins Maneuver RPIC: UAS is maneuvering (East) due to manned aircraft.
11	0:17	Encounter #x Maneuver complete	UAS at well clear distance (red)	RPIC: UAS is well clear of Manned traffic and holding. TD: TD copies, return to flight path and proceed to N Point for Scenario 1B
X	-	After each run swap back and forth between test cards 1A and 1B	Swap back and forth between test cards 1A and 1B	TD: RPIC begins planning for Scenario 1B
12	0:xx	UAS performs Battery swap as necessary	Battery swap whenever necessary *Manned aircraft remains outside of volume*	RPIC: TD UAS is returning for a battery swap. TD: copy UAS. TD: Manned aircraft standby outside operational volume for UAS battery swap Manned: Copy TD, will remain outside volume.
13	0:xx	Scenario 1 resumes _/10 encounters.	Scenario 1 resumes	TD: UAS you are clear for launch when ready UAS: Copies, launching. TD: Manned you are cleared to resume flight profile and maintain 600 ft AGL.
14	~2:00	Scenario 1A Complete	Scenario 1 A and B is complete when all 10 Encounters have been performed.	TD: Scenario 1 A and B complete, all 10 encounters have been recorded. UAS you are cleared to return for battery swap. Manned aircraft maintain outside operational volume. Will begin the next scenario once the battery swap is complete.

3

Figure 4. February 2024 test card for 0° HE for the UA turning and flying to a well-clear distance.

7.3 NCSU May 2024

This test campaign is described in detail by NCSU (2024) and Arnold (2024). A high-level overview is provided herein.

7.3.1 Objectives

The primary test objectives were:

1. Evaluation of shielding impacts on GPS systems that may impact their fidelity for maintaining position in close proximity to the shielding object.

Secondary test objectives were:

1. Comparison of results with obstacle avoidance and GPS accuracy simulation work performed in Task 3.
2. Evaluation of methodologies that ensure safe test execution.

7.3.2 Date/Schedule

Tests were conducted on 13 May 2024. Flight operations were planned to start at 7:30 a.m. and end at 5:30 local time.

7.3.3 Location

Flight operations occurred on NCSU’s Centennial campus, located in the heart of Raleigh, NC. The nearest airport was Raleigh-Durham International, roughly 9 miles to the Northeast, although a local news station maintains a heliport within 1 mile to the North (2NC3). Multiple locations were identified as suitable shielding areas with different building densities and heights. The area of operation was primarily publicly-accessible walking paths, so pedestrian access was restricted during flight. All flights were conducted under Part 107 and in accordance with university policy. Figure 5 illustrates the airspace of the surrounding environment.

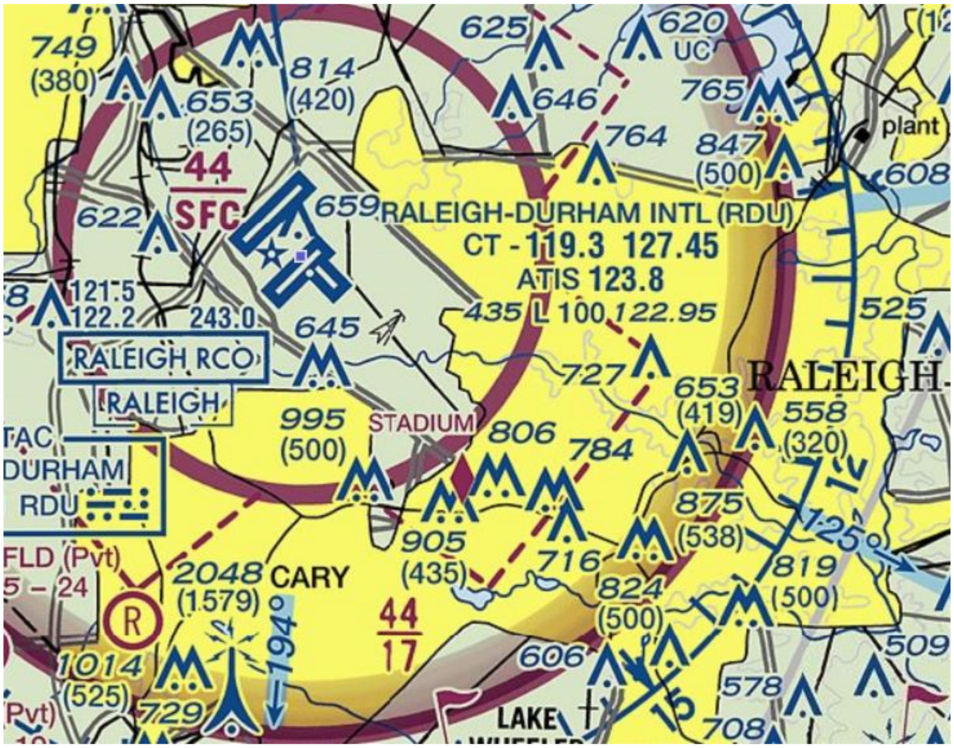


Figure 5. Sectional chart for the May 2024 flight tests.

7.3.4 System Tested

Testing focused on GPS positional accuracy in shielded environments utilizing the onboard telemetry systems of the aircraft. Video was recorded to provide a secondary evaluation of aircraft position during flight.

7.3.5 Test Plan Overview

The flight profile was designed to represent the shielding case of transiting between two large structures. The approximate dimensions of this corridor were 17 m between the two buildings and maximum heights of 19 and 22 m. The UA was flown on a programmed waypoint mission within the shielding corridor at nine altitudes from 2 m to 30 m Above Ground Level (AGL). Each altitude was flown in a single direction before ascending to the next altitude, continuing back and forth until each altitude was flown. This style of experiment was intended for consistent aircraft maneuvering between operations while the mission was flown once an hour throughout the test period.

The aircraft used was designed at NCSU as part of a National Science Foundation (NSF) funded initiative called Aerial Experimentation and Research Platform for Advanced Wireless (AERPAW). Aircraft characteristics are provided in Table 7.

Table 7. Characteristics of the AERPAW aircraft.

		Designed and manufactured by NCSU as part of the NSF funded AERPAW program, the Large AERPAW Multirotor is designed as a payload carrying aircraft capable of achieving greater than 30 minutes of flight with the 3 kg networking payload, and almost 50 minutes with no payload.	
Maximum Takeoff Weight	30 kg (25 kg – Part 107)	**UAS Operator**	NCSU
Endurance	47 min	**GCS Type**	Herelink
Line of Sight Range	LOS Operation	**Autopilot**	Cube
Remote Identification	DroneTag	**GPS**	u-blox ZED-F9P

7.3.6 Sample Test Cards

Test cards were created for each altitude even though the full set would be flown together as one waypoint mission. An example test card is provided in Figure 6.

Test Card #	01-2M	
Location	Centennial Campus, Raleigh, NC	
UAS	AERPAW LAM	
UAS altitude	2m test altitude; 60m Max AGL	
UAS airspeed	2m/s test velocity; 5 m/s Max	
Target Scenarion Time	Individual mission - 5 minutes; Full duration 9 hours	
Reptitions	10	
Flight Profile	UAS will navigate programmed linear flight through building corridor in 2 meter altitude increments until 10m, then 5m until the max shielding object height. Apprioximate corridor dimensions: 17 meters spacing between buildings, northwest building ~ 22 meters, southeast building ~ 19 meters.	
Test Objective	GPS positional accuracy data collection in shielded environments	
Description	The set of missions will provide data for measuring the shielding impacts on GPS systems which may impact their fidelity for maintaining position in close proximity to the shielding object(s). Automated flights will be used for consistency and a safety pilot will always be on hand to take over manual control if necessary.	

	Minutes	Action	Remarks	
1	0:00	Preflight briefing and checks	Preflight inspection, mission check and upload to the aircraft, Pilot in Command briefs all roles	
2	0:00	Takeoff	Automated flight is initiated by PIC	
3	0:01	Mission Underway	PIC confirms aircraft has begun the mission via audio and visual queues from controller, monitors flight to first waypoint and thereafter along straight, horizontal flight profile	
4	0:15	Mission End	PIC confirms the UAS has completed the flight line and is ready to begin the next altitude pass, or return to base upon completion	
5	0:XX	Battery Swap	As required, batteries will be replaced between mission iterations to ensure the UAS is capable of completing the next flight with sufficient reserve power	
6	0:XX	Manual Override	Safety pilot will takeover manual control if aircraft presents a collision hazard to the buildings, or in the event of an incursion or emergency	

Figure 6. May 2024 test card for 2 m altitude transect.

8 TASK 5: TESTS AND REPORTS

8.1 UND/NPUASTS September 2023

8.1.1 Summary of Results

As discussed by Askelson et al. (2024), the use of different types of maneuvers had a significant impact on the amount of time required to reach well clear status—the amount of time after UA maneuver initiation it takes to get to a well clear distance or a safe state for encounters that utilize the BLOWC maneuver. The turn maneuver serves as a benchmark as it is a likely maneuver when no obstacle is present (the climb phase associated with the climb turn maneuver is not needed). If maneuvers such as climb turn are needed in shielded environments having vertical dimensions similar to those assumed herein, the presence of an obstacle increases, on average, the required DAA detection range by ~1013 ft. On the other hand, the obstacle can provide an opportunity to reduce required DAA detection range. For the conditions of this test campaign, the BLOWC maneuver reduced time to well clear, on average, by 13.42 s relative to the turn maneuver. This corresponds to reduction in DAA detection range of ~2718 ft. Thus, the potential to reduce DAA detection range requirements is significant when employing the BLOWC maneuver.

This, then, provides part of the overall answer to RQ5. It is noted that such reductions in DAA detection range may only apply to rotorcraft, as fixed-wing UA may not experience the same type of benefit.

8.1.2 Lessons Learned

Lessons learned from this round of flight tests include:

- Use of redundant GPS pucks/trackers is wise. During this campaign, one set of GPS pucks provided better data than another set.
- A display that provides data that are delayed creates challenges with test execution. While this is not surprising, this test campaign did help verify this expectation.
- As experienced with previous tests, having a UA that is wind tolerant is a major enabler for completing tests.

8.2 NMSU February 2024

8.2.1 Summary of Results

As discussed in detail by Cathey et al. (2024), key findings from the February 2024 test campaign are:

- For fixed wing assets, winds have a significant impact on the resulting maneuvers and response times. Winds impact ground speed, which results in changes in key metrics such as Closest Point of Approach (CPA).
- The autonomous override maneuver (as compared to manual override) was more consistent on how long it took to complete. They were generally not faster for the cases of moving the UAS downrange.
- Maneuvering to the other side of the stand-in powerline and flying to a well clear distance took longer than simply turning and flying to a well-clear distance, as expected.
- There were significant differences in CPA for the head on and the 45° encounters.
- Results for autonomous vs. manual maneuvers are mixed.
- For the BLOWC tests, the manual maneuver approach results in well clear status much faster than the autonomous approach.
- The BLOWC maneuver is effective for a fixed-wing UAS for both manual and autonomous maneuver modes.

8.2.2 Lesson Learned

Lessons learned from the February 2024 test campaign are:

- The remote identification system only collected latitude, longitude, and time. It did not record altitude or other information. This issue was traced to the manufacturer. These data should have been recorded, but were not.
- Consistency in file naming convention is important.
- Data pucks were set to measure once every second, but one of the pucks reverted to once every 5 seconds. The data are accurate, but the associated file contains 80% less data. The use of redundant data pucks ensured no loss of the finer granulated data.
- Longitude in the intruder puck data was listed sometimes as negative and sometimes as positive. Data correction had to be applied to process the data.

- The end of the run/event was recorded, but the actual completion of the maneuvers was not exactly recorded. The UAS repositioned to a new location after each maneuver. Since this was a fixed wing aircraft, this new location was not a singular point—it was a relative distance or around a new location area. The marking of when the UAS reached this proposed "safe location" was not always the same as the "end of the test run". The time to get to this proposed "safe location" was extracted from the flight logs post flight.
- A better method for collecting event elements such as starts, stops, comments/observations, etc., is needed. An automated tool would assist with this.
- For testing, better real-time actual wind data and weather effects could be incorporated into the data analysis. This can help normalize the data sets for comparison.
- Test to test comparisons – there are potential testing approach changes that could allow for better comparison of the data under the "same operational conditions". Two of these are:
    - Fly two aircraft at the same time and test the automated override and manual override "real time" against each other.
    - Fly the test cards in an interspersed mode so that tests that are to be compared are completed in the same flight window with hopefully the same weather conditions.

8.3 NCSU May 2024

8.3.1 Summary of Results

As discussed by Arnold (2024), the main outcome of this testing was a collision with one of the adjacent buildings. The first mission was flown without incident, completing each traverse of the shielding corridor as expected. On the second mission, approximately an hour later, the UA's flight exhibited noticeable position drift during the 4 m altitude pass. After several seconds of observation and communication between the pilot and the Visual Observer (VO), the decision was made to abort the mission, setting the aircraft into an altitude hold mode. As the pilot worked to regain manual control of the flight the drift continued, leading to contact with the building. Analysis of the data indicated that recorded and actual positions differed significantly despite the number of satellites being sufficient for accurate positioning. It is likely that erroneous data were present within the system from one or more sources. This could have been resulted from several factors, including multipath, blocking, and utilization of data from multiple satellite constellations. This incident highlights the increased risk of operating in proximity to obstacles for the purposes of shielding as well as the benefits of mitigations such as obstacle avoidance technologies. It is also validates the identification of this risk in the literature review (Section 4.3.1.5) and the finding of Task 3 that operations near buildings results in significant collision risk (e.g., Section 6.3.3; Table 3). Thus, this provides part of the overall answer to RQ1 and RQ4.

8.3.2 Lessons Learned

Lessons learned from the NCSU flight tests include:

- The use of GPS alone for low-altitude operations in urban environments pose an increased risk of obstacle collision due to a variety of potential navigational error factors that are introduced including multipathing. This supports data gathered from Task 3.
- From a flight-testing perspective, strategic mitigation of risk through the use of VOs and the restriction of pedestrian traffic contributed to mission safety during the incident. The delay in decision making to abort the flight and retake manual control played a role in the ultimate outcome of the mission.

- Several factors limit the conclusions that can be drawn from standard GPS data recording (i.e., the measurement of accuracy information may be skewed by inherent errors from multipath effects and from receiving data from multiple positioning constellations). Furthermore, the accuracy values cannot be broken down into directional vectors, which could potentially show greater degradation in certain aspects based on the geometry of the shielding environment.

9 TASK 6: STANDARDS DEVELOPMENT

The A45 team has supported standard development, with most of the support being within the American Society for Testing and Materials (ASTM). Support has been provided to multiple working groups—especially the ASTM WK62668 Detect and Avoid Performance Requirements Task Group and the ASTM WK62669 DAA Test Methods Task Group. For WK62669, investigator Askelson serves as co-lead.

ASTM WK62668 (performance group) has gone through a revision of its published standard and has started to consider shielded operations. Insights from A45 have been shared to help with further development of this standard. ASTM WK62669 (methods) has reached the point of main committee ballot for its initial version of its test guide. While this group has not integrated shielded operations yet, it is expected to do so in the near future.

The A45 team has supported standards development in numerous ways. These include participation in working group meetings, attendance of in person ASTM meetings, drafting of standards material, and leadership of working groups.

10 CONCLUSIONS

10.1 Research Questions and Answers

The research questions provided in Section 2 are provided here with embedded answers.

Question 1: What types of sUAS failures may increase collision risks when operating near obstacles, structures, and critical infrastructure? What are some recommended mitigations to address these risks? For instance, are obstacle avoidance capabilities needed for shielding operations near critical infrastructure?

Answer: Hazards that can produce this outcome are discussed at various locations within this report and are succinctly delineated in Table 2. They include:

- Collision with wildlife (e.g., birds)
- EMI effects
- Infrastructure causing changes in airflow (turbulence, tunneling, etc.)
- Degradation of UAS navigation systems (e.g., GPS)
- UAS hardware and software errors/failures
- Loss or degradation of C2
- Clutter affecting subsystems (e.g., DAA)
- Human error in flight planning and operations

Mitigations are also provided in Table 2. Beyond UAS system issues that can be handled using proper design processes or utilization of redundancy and human errors that can be addressed through proper training and redundancy, the hazards that increase collision risks are generally environmental. Clutter is being considered in ASSURE project A57 (ASSURE 2024). The other environmental hazards can be addressed through multiple types of mitigations, including use of EMI shielding, use of detection systems to identify hazards (e.g., bird-detection systems, wind-monitoring systems, navigation performance monitoring systems, C2 monitoring systems, etc.), and employment of more robust support systems (e.g., C2 systems, navigation aids, etc.). For environmental hazards, a potentially effective approach is to forecast locations where risk is high (e.g., areas of expected turbulence and GPS degradation) and avoid those. This approach may not be entirely viable, however, if operations are deemed to be required in areas where such hazards exist. Thus, for many scenarios, especially urban operations, use of a collision avoidance system is recommended.

Question 2: What are safe standoff distances (vertical and horizontal) from obstacles, structures, and critical infrastructure for sUAS BVLOS operations?

Answer: The answer to this question is complicated given challenges associated with defining the required level of safety. Avoidance of EMI effects can generally be handled with a standoff distance of 9 m (~30 ft). If short-circuits are possible, this distance increases significantly to 40 m (~130 ft). These distances can be reduced significantly with use of EMI shielding.

The impacts of GPS degradation depends upon the configuration of structures around the sUAS and the positioning of GPS satellites. At this point, no generalized rule of thumb is available in terms of distance, though work herein indicates that, if no mitigations such as an obstacle avoidance system is employed, one would want to maintain at least 8 m (~26 ft) of horizontal distance (Table 3). Because the results herein are not readily generalizable (i.e., the “safe” horizontal distance depends upon the nearby building/structure configuration and height of the sUAS), significant caution should be exercised when operating near buildings, as underscored with the challenge encountered during the NCSU flight tests.

For encounters with MA, estimating risk using traditional methods can be very challenging owing to uncertainties in MA airspace densities and the disparity between DAA impacts on rates of events (e.g., loss of well clear) and the breadth of categories used for likelihood classification (see next subsection). Thus, herein consideration of safe for MA encounters follows an event-based approach such as that used by ASTM (2023) (i.e., risk, ratio). ASTM (2023) defined DAA risk ratio performance requirements for sUAS operating in both low- and medium-risk airspace.[4] For non-cooperative aircraft, ASTM (2023) requires a DAA system to provide a loss-of-well-clear risk ratio of 0.5 for non-cooperative MA intruders. Based upon the 5 low-altitude MA operations for which at least 5 survey responses were provided, shielding results in an estimated fraction of MA traffic of ~0.5 (SF) at a distance of ~100 ft for both the horizontal and vertical

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[4] ASTM (2023) defines low-risk airspace as airspace in which crewed aircraft predominantly do not fly or the MA encounter rate is remote or improbable in accordance with guidelines from the proper authority. Medium-risk airspace is similar, though the MA encounter rate can be occasional.

directions (Askelson et al. 2023). Given that SFs play the same mathematical role as risk ratios, this indicates that the UAS BVLOS ARC (2022) recommendation of defining shielded operations to be within 100 ft is consistent with the ASTM (2023) recommendation for DAA performance in low- and medium-risk airspace. This result is subject to the following caveats:

- Input for all types of low-altitude MA operations was not obtained.
- The survey results have relatively large uncertainty windows (e.g., Askelson et al. 2023, Figure 9).
- This is an average result, with results for specific low-altitude MA operations varying significantly from this value. Survey data for Agricultural Application operators, for instance, have an average SF of ~0.76 (0.87) for a horizontal and vertical distance of 25 ft (100 ft) when operating near powerlines, while Air Ambulance or Medical Services have an average SF of ~0.09 at 100 ft distance (Askelson et al. 2023, Figure 9).
- SME-estimated SFs were less conservative, with an SF of ~0.5 at 200 ft distance.
- While SME- and survey-derived results are useful, the most accurate results would be provided through analysis of data regarding low-altitude MA operations.

Question 3: What types of MA operate in close proximity to flight obstacles and structures? How often do they operate in close proximity? How close do they fly to these structures? What are their operational limitations (day only, special procedures, special pilot requirements, etc.)?

Answer: Leveraging previous work by Weinert and Barrera (2020), the A45 team identified 17 types of low-altitude MA operations (Table 1).[5] The 14 CFR parts under which these operations are conducted are also provided in Table 1.

Limited data regarding low-altitude MA operations are available (e.g., Askelson et al. 2023). Despite this, the A45 team was able to analyze data regarding Agricultural Application operators. These data were provided to Mississippi State University (MSU) by the National Agricultural Aviation Association (NAAA) and were shared with the A45 team with permission from both the NAAA and MSU. This analysis (Appendix A) confirmed that Agricultural Application operators routinely fly close to powerlines (within 25 ft).

Given the lack of data regarding low-altitude MA operations, the benefits of shielding were estimated using both SME input and a survey. Results for operations for which at least 5 survey responses were received are provided in Appendix B of Askelson et al. (2023). As indicated by these results, low-altitude operator characteristics around shielding objects depend upon the operator and the type of shielding object (10 different objects were included in the survey). Moreover, significant uncertainty is present in these results. Despite this variability, average behaviors provide valuable insight, as indicated in the answer to the previous question. Of the 5 types of low-altitude MA operations for

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[5] In Table 1, one type of low-altitude operation is listed twice (once for fixed-wing and once for rotary-wing).

which sufficient responses were received, Agricultural Application, Training, and Recreational operators were identified as having high (H) type SF curves, meaning SF > 0.6 for all distances relative to shielding objects. For these, Powerlines, Powerline Poles/Towers, and Trees/Shelter Belts were objects for which SFs curves were of type H. It is noted that survey results were not obtained for operations that are expected to occur close to at least certain types of shielding objects such as Infrastructure Inspection and Infrastructure Work.

Additional mitigations that are expected to reduce encounters with MA and, thus, enable shielded operations, include (Askelson et al. 2023):

1. Operating in Instrument Meteorological Conditions (IMC), in which MA operations are prescribed to be ≥ 1000 ft above the highest nearby obstacle. Thus, IMC is very enabling of low-altitude UA operations.
2. Operating at times when low-altitude operations are not as common, such as:
    a. At nighttime, when fewer operations are expected at low altitudes given restrictions for ultralights (not allowed at night) and Part 135 operations (higher altitude requirements at night) (Askelson et al. 2023, Table 5).
    b. During the non-growing season, when Agricultural Applicators are unlikely to be operating
3. Operating in locations where low-altitude MA operations are not as common (e.g., Agricultural Application operations are not expected where agriculture, horticulture, or forest preservation activities would not be conducted).

Question 4: What other mitigations should be coupled with shielding concepts in order to manage collision risks with MA and with obstacles?

Answer: As discussed in Section 5.3.2, even though the strategic mitigation of shielding can fulfill the same mathematical role as a risk ratio, it does not absolve responsibility to maintain well clear as delineated, for instance, in CFR Part 91 (91.111 and 91.113; e-CFR 2024). Thus, utilization of DAA during shielded operations is not unreasonable.

Additional mitigations are presented in Table 3 and discussed in the answer to Question 1. Prominent mitigations for handling environmental challenges include planning, forecasting, real-time monitoring, and utilization of an obstacle avoidance system.

Question 5: To what degree can DAA requirements to avoid other aircraft (manned and unmanned) be reduced during shielded sUAS operations?

Answer: If risk ratio is used as a basis of performance as in ASTM (2023) and the ASTM (2023) performance level for non-cooperative aircraft is used, then from an equivalent risk standpoint and, on average (average set of intruders), one could argue that a DAA system is not needed when operating within 100 ft of a shielding object. However, this is modulated by the requirement of maintaining well clear as delineated, for instance, in CFR Part 91 (91.111 and 91.113; e-CFR 2024). If a DAA system is deemed necessary, this effort indicates that a DAA system with a higher risk ratio (lower performance), when combined with the benefits of shielding, would effectively produce the same overall risk.

Both Askelson et al. (2024) and Cathey et al. (2024) explored utilization of shielding objects wherein they are positioned with the shielding structure between it and the intruder

(BLOWC). For rotary-wing ownship, Askelson et al. (2024) showed that the required DAA detection range could be reduced by ~2700 ft. For reference, Askelson et al. (2022, Section 2.4.3) presented results for a relatively-high-performing DAA system (from a timing perspective) that requires 9000-10000 ft detection range to maintain well clear for all intruders within its field of view. Thus, a 2700 ft reduction in detection range, resulting in a required detection range of 6300-7300 ft, is significant. It is noted that this example does not apply to all DAA systems. The exact detection range required depends upon the characteristics of a particular DAA system.

Cathey et al. (2024) tested the BLOWC maneuver with fixed-wing ownship. They concluded that the BLOWC maneuver produced the safest outcomes.

Question 6: What regulatory, policy, and legal issues should the Federal Aviation Administration (FAA) consider for shielded sUAS operations? Example topics include:

- What should the FAA consider so as to not be negligent in their risk management responsibilities when issuing waivers involving shielding operations?
- What are the potential implications if an accident with an MA occurs and the FAA waived DAA requirements?
- What are the potential implications if the FAA does not require active obstacle avoidance capabilities and a collision with critical infrastructure occurs?

Answer: 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 that the FAA would have a duty to adequately warn the non-participatory public of specific, known hazards, and a general warning would not be sufficient.

10.2 Future Work Recommendations

Throughout this effort, areas of future work have been identified. These include:

1. Data regarding low-altitude MA operations: Any means for identifying, collecting, and analyzing characteristics of low-altitude MA operations—specifically flight near shielding objects—would be the most effective means for evaluating associated risk and advancing shielded operations.
2. Risk evaluation methodology: Use of traditional approaches for evaluating risk (e.g., U.S. Department of Transportation 2023) and the benefits of DAA as a mitigation is challenging for several reasons:

  a. Use of DAA systems can seemingly provide no discernable benefit when using traditional approaches for evaluating risk. This occurs because while the rates of occurrence of relevant events (well clear violation, NMAC, and MAC) drop when a DAA system is used, the net result with traditional approaches is commonly a risk that is in the same "box" in the risk matrix (e.g., same severity and likelihood categories). Ways of dealing with this challenge include use of a finer discretization of risk likelihoods or direct utilization of numerical likelihood values.
  b. For traditional approaches to evaluating risk, rates of occurrence of events (well clear violation, NMAC, and MAC) are needed. While Askelson et al. (2023) provide a framework for estimating these rates, estimation of encounter rates, which is needed in this approach, is very challenging and encumbers significant uncertainty. This suggests that an alternative approach for evaluating risk and DAA benefits, such as defining risk matrices based upon likelihoods of outcomes given an encounter, would be more useful. Such alternative approaches should be explored.
  c. Severity for UA-MA collisions is not completely understood and is currently an active research area. Determination of some sort of net or average likelihood of outcomes that are used for risk evaluation as in U.S. Department of Transportation (2023) (e.g., MA hull loss with at least 1 fatality) would significantly reduce uncertainty.

3. Incorporation of uncertainties: Regardless of how risk is evaluated, uncertainty is present. The impacts of uncertainty on estimated values (e.g., likelihoods) should be incorporated such that the range of expected outcomes/performance can be properly understood.
4. Ground and infrastructure risk: While both ground and infrastructure risk were explored in this effort, a great deal of work is still required in these areas. This includes both collision severity and likelihood.
5. Generalization of GPS degradation: Development of "rules of thumb" in this area would be tremendously helpful. One idea for doing so is generalizing GPS degradation based upon the percentage of sky blockage. While this would not provide perfect results since GPS satellites are not evenly distributed in the sky and move, it could be very helpful to quickly ascertain GPS degradation potential. Generalization like this would likely require a large suite of simulations to characterize average impacts and possible variations around average.

10.3 Summary

This effort addressed the following questions:

1. What types of sUAS failures may increase collision risks when operating near obstacles, structures, and critical infrastructure? What are some recommended mitigations to address these risks? For instance, are obstacle avoidance capabilities needed for shielding operations near critical infrastructure?
2. What are safe standoff distances (vertical and horizontal) from obstacles, structures, and critical infrastructure for sUAS BVLOS operations?
3. What types of MA operate in close proximity to flight obstacles and structures? How often do they operate in close proximity? How close do they fly to these structures? What are their operational limitations (day only, special procedures, special pilot requirements, etc.)?

4. What other mitigations should be coupled with shielding concepts in order to manage collision risks with MA and with obstacles?
5. To what degree can DAA requirements to avoid other aircraft (manned and unmanned) be reduced during shielded sUAS operations?
6. What regulatory, policy, and legal issues should the FAA consider for shielded sUAS operations? Example topics include:
    a. What should the FAA consider so as to not be negligent in their risk management responsibilities when issuing waivers involving shielding operations?
    b. What are the potential implications if an accident with an MA occurs and the FAA waived DAA requirements?
    c. What are the potential implications if the FAA does not require active obstacle avoidance capabilities and a collision with critical infrastructure occurs?

These questions were addressed through the following tasks:

0. Project Management
1. Literature Review and Risk Identification
2. Shielding Classes, Risk Assessments, and Listing of Mitigations
3. Analysis of DAA Requirements and Obstacle Avoidance Requirements
4. Flight Test Plans
5. Tests and Reports
6. Standards Development
7. Final Briefing and Final Report
8. Peer Review

Given the broad set of tasks, multiple methods were applied to execute them. These include review of previous efforts (Tasks 1-5), analysis and synthesis (Tasks 1-5), simulation (Task 3), and testing and validation (Task 5).

Results for Tasks 1-3 and 5 are provided in separate reports. The interested reader is directed to those for a detailed description of results. A high-level summary of results is provided herein.

The literature review illustrated a relative scarcity of literature regarding shielded operations. It identified wind and turbulence effects, bird activity, impacts on GPS, and EMI as key hazards. It also provided important legal context, in which FAA is generally protected by the doctrine of sovereign immunity when making important policy decisions that influence flight safety.

Task 2 efforts (shielding classes, risk assessments, and listing of mitigations) resulted in a system for classifying shielded operations. It also provided a framework for interpreting the safety benefits owing to shielding, which casts this benefit, mathematically, in the form of a risk ratio. Risks associated with air collisions, ground collisions, and infrastructure collisions were explored, including a means for estimating air collision rates. Uncertainties with this approach, however, are high, with potential benefits associated with developing different approaches to evaluating air risk. The A45 team also provided a ranked list of mitigations that enhance shielded operation safety.

To understand the safety benefit of shielded operations, impacts of obstacles on MA traffic levels were estimated. Estimates were derived from SME input, a survey, and an analysis of flight data from agricultural operators. The latter is the most promising means for determining shielding safety benefits. Such data, however, are generally lacking for low-altitude MA operations. Efforts should be directed at curating such data sets.

Analysis of DAA requirements and obstacle avoidance requirements (Task 3) resulted in identification of safe distances for powerline inspections. For single and double powerline configurations, a safe distance is 9 m from any individual powerline, and represents the most conservative distance. The minimum safe distance during a short circuit/fault increases significantly, with the largest safe distance for the 180 µT threshold being ~40 m. For transformers, safe distances are significantly smaller (< 5 m) depending, of course, on transformer configuration. Safe distances depend upon many factors and can be significantly reduced by shielding UAS from EMI.

Evaluation of straight-line wind effects using a simulated multicopter indicated that its ability to maintain course or at least resist further displacement after the initial onset of wind is predictable and enables provision of guidelines on minimum distances from hazardous areas. In the simulations, winds produced a constant offset from the original UA path. There is a maximum wind component that will exceed the aircraft's performance envelope, resulting in a no-fly decision by the air crew as the ambient conditions exceed the UAS's ability to navigate. The specific capacity to navigate a mission route depends upon an aircraft's performance rather than a universal offset distance from a shielding obstacle. For turbulence, the simulated multirotor UA exhibited remarkable performance. In contrast, the simulated fixed-wing UA experienced more challenges owing to turbulence. It crossed a defined safety boundary and experienced significant vertical deviations as it struggled with gusts. For wake-induced turbulence created by MA, the simulated multirotor experienced altitude and attitude displacement that ranged from major for a 747 to nearly negligible for the Cessna 172. Aircraft wake effects from MA sizes of the type expected to be encountered a) at common UAS altitudes and b) in shielded spaces ranged from easily recoverable to negligible.

Autonomous missions designed with high levels of navigation accuracy require low levels of uncertainty, which translates into low GPS DOP values. This becomes achievable when healthy geometries are obtained for the trilateration process and, consequently, a connection with more than seven satellites is commonly needed to obtain enough redundancy to keep DOP low. Analysis of multipath GPS effects can be very complex since this becomes a geometric problem applied to antennas in motion given the complex dynamic behavior of sUAS within urban environments. Numerical simulations revealed that among the various GPS signal degradation types, those posing the highest risks, in descending order, were dropouts, jamming, and a reduced number of satellites (down to four). Thus, GPS integrity should be monitored and addressed for operations where these effects may be realized. This is especially true for operations at low altitudes (≤ 16 m) and close to buildings (e.g., within 6 m).

Task 4 (flight test plans) resulted in test plans and test cards being generated for each of the test campaigns, one of which was conducted at UND, NMSU, and NCSU. These plans provide test objectives, test locations/performers, dates of testing, systems used in tests, methods for maintenance of safety during testing, and data collection approaches.

Three rounds of flight testing were conducted (Task 5). Important outcomes of these tests include:

- The use of different types of maneuvers had a significant impact on the amount of time required to reach well clear status—the amount of time after UA maneuver initiation it takes to get to a well clear distance or a safe state for encounters that utilize the BLOWC maneuver.
- If maneuvers such as climb turn are needed in conjunction with powerlines having dimensions similar to those used in UND testing, the presence of an obstacle increases, on average, the required DAA detection range by ~1013 ft. On the other hand, an obstacle can provide an opportunity to reduce required DAA detection range. For the conditions of the UND test campaign, the BLOWC maneuver reduced time to well clear, on average, by 13.42 s relative to the turn maneuver. This corresponds to reduction in DAA detection range of ~2718 ft.[6]
- Winds have a significant impact on maneuvers and maneuver completion times.
- Significant differences in CPA can occur for different horizontal encounter geometries.
- The BLOWC maneuver is effective for a fixed-wing UAS.
- The increased risk of colliding with obstacles when operating in proximity to buildings is very real, as significant path deviation was experienced during flight testing.

The A45 team has supported standards development in numerous ways. These include participation in working group meetings, attendance of in-person meetings, drafting of standards material, and leadership of working groups.

This effort involved a broad set of tasks designed to deepen understanding of shielded operations. Through execution of these tasks and application of the numerous methods required to do so, the A45 team has significantly advanced shielded operations knowledge, which will enable more rapid integration of sUAS into the National Airspace System.

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[6] As indicated earlier, using the example from Askelson et al. (2022) for a relatively-high-performing DAA system (from a timing perspective) that requires 9000-10000 ft detection range to maintain well clear for all intruders within its field of view, this reduction results in required detection ranges in the 6300-7300 ft range. Exact required detection ranges depend upon the characteristics of a specific DAA system.

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Appendix A: Analysis of Agricultural Operator Data

A.1 **Data Set**

Agricultural aircraft, or crop dusters, typically operate at low altitudes a few feet above crops for effective spraying. Due to this low altitude, they must navigate around powerlines, often flying just above them to avoid collisions. Pilots ensure safe operations while maintaining the necessary proximity to powerlines for optimal coverage. This analysis, based on data provided to Mississippi State University (MSU) by the National Agricultural Aviation Association (NAAA) and shared with the A45 team with permission from both the NAAA and MSU, primarily focuses on agricultural aircraft operations in the Illinois region. Flight trajectories are captured using GPS pucks or similar devices, which record data in a format including instance number, altitude Above Ground Level (AGL), latitude, longitude, and speed. While the number field represents the timestamp instance, the track files do not provide explicit timestamp information, necessitating careful interpretation of the data to understand the temporal dynamics of agricultural aircraft flights.

A.2 **Methodology**

For analysis, data pre-processing involved converting Mean Sea Level (MSL) altitudes into AGL values using a third-party Application Programming Interface (https://api.open-elevation.com/api/v1/lookup?locations=<latitude>+<longitude>). The objective is to identify scenarios where agricultural aircraft have close encounters with powerlines by overlapping powerline maps with aircraft trajectories. This includes scenarios where the aircraft descends from above the powerline to the field and ascends from the field to above the powerline, ensuring a comprehensive understanding of potential collision risks.

The currently available powerline map (https://hifld-geoplatform.hub.arcgis.com/) is not up-to-date, with outdated information on domestic transmission lines. Additionally, variations in the width (number of lines) and height of powerlines further complicate the analysis. This necessitated manual identification of powerlines near agricultural aircraft trajectories. This was achieved by plotting trajectories on Google Maps and pinpointing close encounters with powerlines. Multiple scenarios of agricultural aircraft encounters with powerlines were identified, including aircraft flying from the field towards the powerline, descending to the field from above the powerline, and flying underneath the powerline from one field to another.

Figure A1 shows the scenario of an agricultural aircraft descending into the field from above a powerline. This was identified through close examination of the trajectory of data points. Similarly, the scenario of aircraft ascending and descending can be identified by manually examining trajectories and pinpointing the location of the powerline.

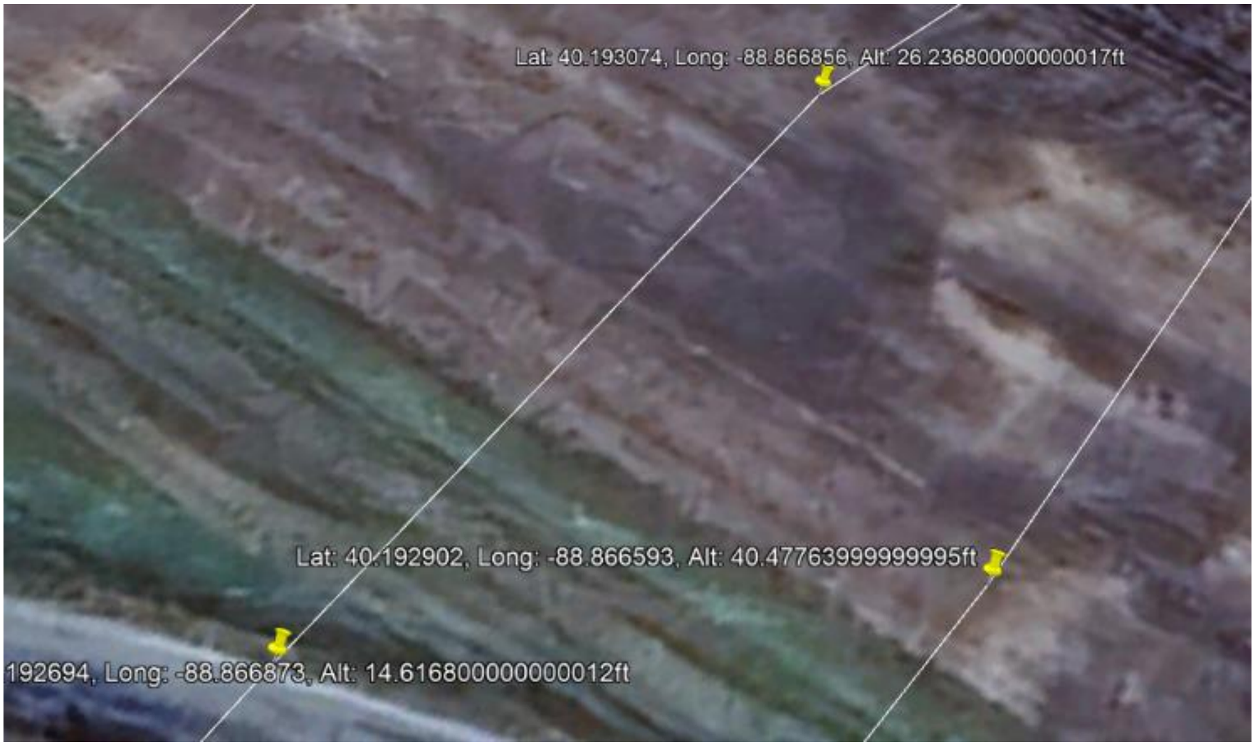


Figure A1. Example of descent-into a field near a powerline.

Figure A2 shows the scenario of a very low-altitude aircraft flying underneath a powerline. A similar scenario is shown in Figure A3, where a crop duster is shown flying under a high-power transmission line.

Figure A2. Example of an aircraft flying under a powerline.

Figure A3. Example of an aircraft flying under a high-power transmission line.

For this analysis, the team considered the first scenario where an aircraft flies above the powerline (either descending-into or climbing-from a field). Multiple data points for cases of ascending and descending were identified. These were categorized as either descend-into or climb-from and combined into one set of data for each. This compositing was performed because the time between data points was typically 1 s, which resulted in poor flight path resolution for any one encounter with a powerline.

Over 200,000 geo-locations were used as input. After converting from MSL to AGL, data points having altitudes less than 100 ft were considered. A thorough manual analysis was conducted to identify powerlines near the aircraft trajectories, specifically focusing on scenarios where agricultural aircraft cross powerlines. A detailed analysis of the trajectories with time instances was done to distinguish scenarios where the agricultural aircraft were either ascending towards or descending from the powerline. Multiple instances were identified. The data points were then separated into two datasets and analyzed individually. For each data point, the latitude, longitude, and altitude of the agricultural aircraft, as well as the locations of the powerlines, were recorded. One datapoint was used as the reference location. For the remaining data points from each set, the relative geo-location from the powerline (in ft) was calculated. The third step involved merging multiple relative locations with the initially identified reference location.

A.3 **Results**

Figure A4 shows the result of merging multiple data points into a single reference location in three dimensions for aircraft flying towards powerlines after a spraying operation. Different viewing angles are provided in Figure A4.

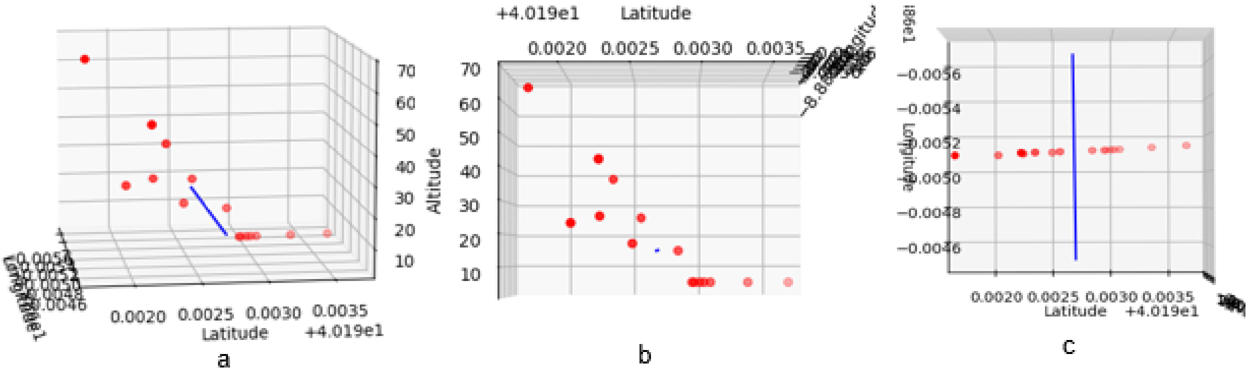


Figure A4. Multiple views for composited climb-from field agricultural operator data. Perspectives are (a) from above and at an angle relative to the powerline, (b) along the powerline, and (c) from above the powerline. Red dots indicate aircraft locations and the blue line indicates the powerline.

Similarly, Figure A5 shows the same for descend-into field from above the powerline. In both scenarios, the powerline is assumed to be at an altitude of 15 ft above the ground, In reality, the height of a powerlines varies depending upon the transmission line it carries.

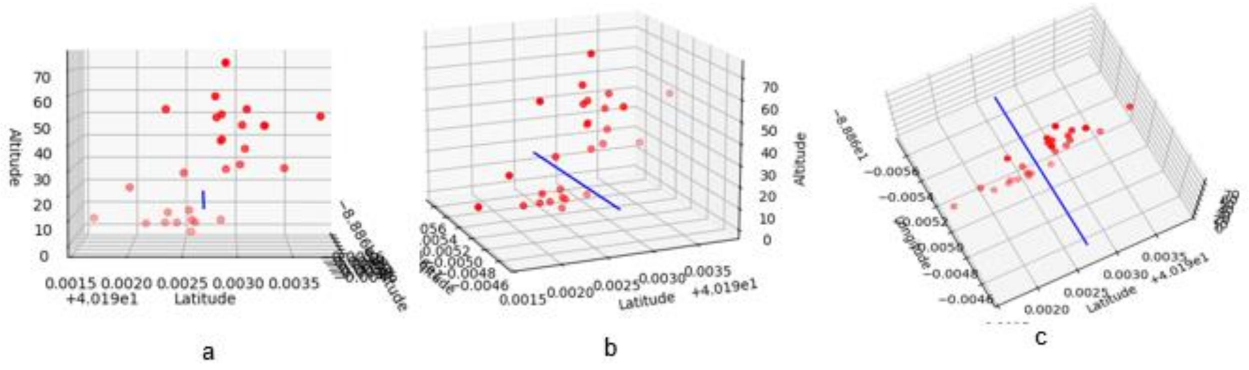
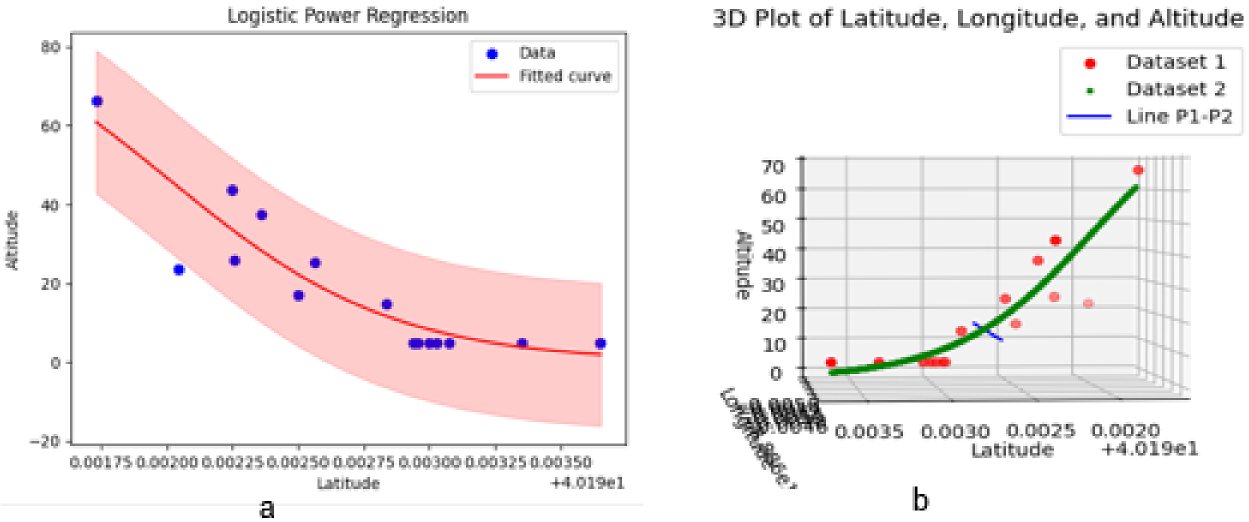


Figure A5. Multiple views for composited descend-into field agricultural operator data. Perspectives are (a) from above and along the powerline, (b) above and at an angle relative to the powerline, and (c) from above the powerline. Colors are as in Figure A4.

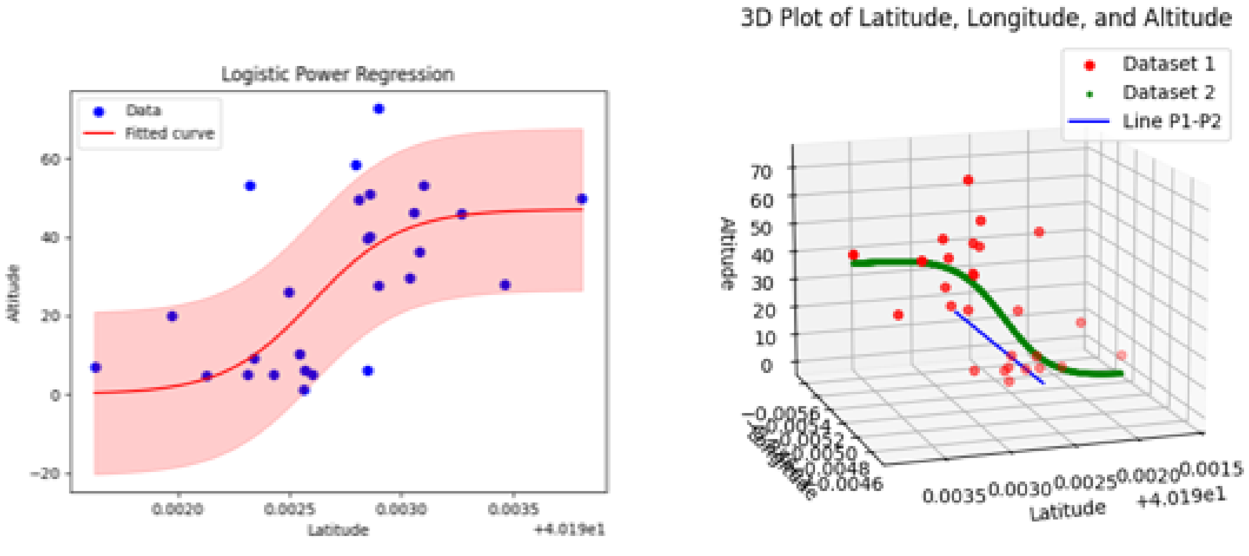
The next step of the analysis was to calculate a curve representing average aircraft trajectory based on the multiple identified data points. Various curve fitting algorithms, such as a Gaussian curve, logistic regression, polynomial regression, lowess smoothing, and linear regression, were used to find the best fit. The results, presented in Figures A6 and A7, illustrate the best curves captured after performing multiple analyses with different curve fitting algorithms. A logistic regression-based curve provided the best fit.



a

b

Figure A6. Resultant curve for climb-from field data. The two-dimensional curve fit is provided in (a) and a three-dimensional perspective is provided in (b). In (a) blue dots represent aircraft locations and the red line indicates the fitted curve. In (b) the red dots indicate aircraft locations, the green line indicates the fitted curve, and the blue line indicates the powerline.



a

b

Figure A7. Resultant curve for descend-into field data. The two-dimensional curve fit is provided in (a) and a three-dimensional perspective is provided in (b). Colors are an in Figure A6.

Estimates of horizontal and vertical distances for the average trajectory for climb-from field data are on the order of 3-6 ft. These are likely too small, and may be driven by GPS altitudes that have a low bias. Given that for standard GPS systems vertical height errors are commonly < ~15 ft (e.g., FAA William J. Hughes Technical Center 2023), even with the assumption of altitudes having a low bias clearance distances for the average curve for climb-from field data are small (< 25 ft). For the average trajectory for descend-into field data, estimated horizontal and vertical distances from the powerline are on the order of 10-15 ft. Thus, for both climb-from and descend-into, horizontal and vertical distances from powerlines are estimated to regularly be < 25 ft. This is consistent with survey results, which indicated that agricultural operators regularly fly within 25 ft of powerlines (Askelson et al. 2023).