DOT/FAA/TC-23/67

Federal Aviation Administration
William J. Hughes Technical Center
Aviation Research Division
Atlantic City International Airport
New Jersey 08405

Evaluation of Unmanned Aircraft Systems for Airport Perimeter Inspections and Surveillance

September 2023

Final Report

U.S. Department of Transportation
Federal Aviation Administration

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/TC-23/67		

4. Title and Subtitle EVALUATION OF UNMANNED AIRCRAFT SYSTEMS FOR AIRPORT PERIMETER INSPECTIONS AND SURVEILLANCE	5. Report Date September 2023 6. Performing Organization Code ANG-E26
7. Author(s) Jonathan Sheairs* and Garrison Canter	8. Performing Organization Report No.
9. Performing Organization Name and Address GDIT* 600 Aviation Research Boulevard Egg Harbor Township, NJ 08234	10. Work Unit No. (TRAIS) 11. Contract or Grant No. 692M15-22-D-00005
12. Sponsoring Agency Name and Address Department of Transportation Federal Aviation Administration Office of Airports Safety and Standards 800 Independence Avenue, S.W. Washington, DC 20591	13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code AAS-300

15. Supplementary Notes

The Federal Aviation Administration Airport Technology R&D Branch COR was Michael DiPilato. Woolpert Inc. conducted UAS flight operations and provided technical support during this research effort.

16. Abstract

Federal Aviation Administration (FAA) Airport Technology Research and Development Branch personnel conducted a research effort to evaluate the use of unmanned aircraft systems (UASs) for airport perimeter inspections and surveillance. The purpose of this effort was to develop minimum recommended performance specifications and technical/operational considerations for the use of UASs to conduct airport perimeter inspections.

This research effort was conducted in two phases. Phase 1 included tests of various flight parameters, UAS platforms, and payloads at Cape May County Airport to develop performance specifications and best practices on conducting perimeter inspections using UASs. During Phase 1, UAS flights were conducted during daylight and night conditions. Phase 2 consisted of validation testing at three airports with varying environments, Savannah/Hilton Head International Airport, McGhee Tyson Airport, and Cincinnati/Northern Kentucky International Airport, to further evaluate the findings regarding the use of UASs for perimeter inspections in daylight, twilight, and night conditions. During testing, researchers collected feedback from airport and perimeter security stakeholders to determine the flight parameters, use cases, and technologies that provided the greatest benefit.

This report summarizes the testing conducted and recommended UAS platform and payload specifications. FAA researchers found that UASs equipped with thermal and visual cameras provided a significant benefit for inspecting hard-to-reach or inaccessible areas and detecting unauthorized persons or vehicles. However, because the detail visible during UAS inspections of fencing is limited by payload resolution and the elevated viewing angle, it is recommended that UASs be used to supplement, rather than replace, current methods of conducting visual inspections of airport perimeters. FAA researchers also set minimum performance specifications, including minimum recorded resolutions of 1080p (1920x1080) for recorded visual camera footage, 720p (1280x720) for live-streamed visual camera footage, and 640x512 for thermal camera footage.

17. Key Words	18. Distribution Statement
Unmanned Aircraft Systems, UAS, Drone, Perimeter inspections, surveillance, fence line	This document is available to the U.S. public through the National Technical Information Service (NTIS), Springfield, Virginia 22161. This document is also available from the Federal Aviation Administration William J. Hughes Technical Center at actlibrary.tc.faa.gov.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	144	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

ACKNOWLEDGEMENTS

The Federal Aviation Administration Airport Technology Research and Development Branch would like to thank the following organizations for their participation in this outreach effort:

- Cape May County Airport (WWD), New Jersey
- Delaware River & Bay Authority
- National Safe Skies Alliance
- Cincinnati/Northern Kentucky International Airport (CVG), Kentucky
- Savannah/Hilton Head International Airport (SAV), Georgia
- McGhee Tyson Airport (TYS), Tennessee

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LIST OF ACRONYMS

AC	Advisory Circular
AOA	Air operations area
AGL	Above ground level
ATC	Air traffic control
CFR	Code of Federal Regulations
CONOP	Concept of Operation
CVG	Cincinnati/Northern Kentucky International Airport
DJI	Da-Jiang Innovations
FAA	Federal Aviation Administration
FOV	Field of view
FPS	Frames per second
GCS	Ground control station
GNSS	Global navigation satellite system
GPS	Global positioning system
IEC	International Electrotechnical Commission
IP	Ingress protection
LWIR	Long wave infrared
M210	Matrice 210 RTK v2
M2ED	Mavic 2 Enterprise Dual
mK	Millikelvin
MP	Megapixel
MSL	Mean sea level
PARAS	Program for Applied Research in Airport Security
PTF	Perimeter Test Facility
RPIC	Remote pilot in command
SAV	Savannah/Hilton Head International Airport
SM	Statute mile
SME	Subject matter expert
TFR	Temporary Flight Restriction
TSA	Transportation Security Administration
TYS	McGhee Tyson Airport
UA	Unmanned aircraft
UAS	Unmanned aircraft system
VO	Visual observer
WWD	Cape May County Airport

EXECUTIVE SUMMARY

Perimeter inspections are a critical responsibility of all airport operators, particularly airports certificated under Title 14 Code of Federal Regulations (CFR) Part 139. These airports are required to conduct daily inspections of perimeter fencing. Often these patrols can take several hours, representing a significant time burden on airport staff, particularly when the airport has a large perimeter. At some airports rough terrain, dense vegetation, or wetlands can prevent ground vehicles from accessing certain segments of the perimeter fence line. This can necessitate airport staff completing the inspection on foot or by boat, making the task significantly more difficult, dangerous, and time-consuming.

To address these challenges, the Federal Aviation Administration's (FAA) Airport Technology Research and Development Branch conducted a research effort to explore the use of small unmanned aircraft systems (UASs) for conducting perimeter inspection activities in the airport environment. The purpose of this effort was to develop recommended minimum performance specifications and technical/operational considerations for the use of UASs for airport perimeter inspections and surveillance.

This research effort was conducted in two phases. Phase 1 consisted of testing various flight parameters, UAS platforms, and payloads at Cape May County Airport (WWD) to develop preliminary performance specifications and best practices. During Phase 1, a total of 168 UAS flights were conducted in daylight and night conditions. Phase 2 consisted of validation testing at three airports with varying environments and sizes, McGhee Tyson Airport (TYS), Savannah/Hilton Head International Airport (SAV), and Cincinnati/Northern Kentucky International Airport (CVG), to further evaluate the benefits and limitations of UASs and to validate the recommended performance specifications and technical/operational considerations of using UASs for airport perimeter inspections. Phase 2 consisted of 50 UAS flights conducted in daylight, twilight, and night conditions. Both during and following Phase 2 testing, FAA researchers collected feedback from airport operations personnel and airport security stakeholders to determine the flight parameters and technologies that provided the most benefit.

FAA researchers found that UASs equipped with thermal and visual cameras provided a significant benefit for inspecting hard to reach or inaccessible areas and detecting unauthorized persons or vehicles. However, it was found that the detail visible of fencing during UAS inspections is limited by payload resolution and the elevated viewing angle, making it difficult to see certain types of security concerns, such as gate locks, erosion under the fence, and damage to chain links. Due to this inability to see certain details, it is recommended that UASs be used to supplement, rather than replace, current methods of conducting visual inspections of airport perimeters. Additional limitations of utilizing UAS for perimeter inspections and surveillance include weather, airspace restrictions, line-of-sight requirements, and the increased time required to deploy UASs versus performing a ground inspection.

Minimum recommended performance specifications were also identified to ensure the effectiveness of the payload video, including a minimum resolution of 1080p (1920x1080) for recorded visual camera footage, 720p (1280x720) for live-streamed camera footage, and 640x512 for thermal camera footage.

FAA researchers also developed technical and operational guidance to maximize the benefits of UASs for airport perimeter inspections. This guidance addresses technical aspects, such as the UASs, ground control stations, and payloads, and technical/operational considerations for using UASs to conduct perimeter inspections and surveillance.

This report summarizes the testing conducted, and provides benefits and limitations, recommended performance specifications, and technical and operational considerations for using UASs to conduct airport perimeter inspections and surveillance.

1. INTRODUCTION

The Federal Aviation Administration (FAA) Airport Technology Research and Development Branch conducted a research effort to explore the feasibility of using small unmanned aircraft systems (UASs) for conducting perimeter inspections (i.e., public protection inspections and inspecting for unauthorized entry by individuals/ground vehicles). This research focused solely on small UASs, which are defined in Title 14 Code of Federal Regulations (CFR) Part 107.3, *Definitions*, as unmanned aircraft weighing less than 55 pounds on takeoff, including everything that is on board, or otherwise attached to the aircraft (Definitions, 2022). This report summarizes the research conducted and provides recommended minimum performance specifications and technical/operational guidance for the use of UASs for perimeter inspections.

1.1 BACKGROUND

Perimeter inspections are a critical responsibility of all airport operators, particularly airports certificated under 14 CFR Part 139, *Certification of Airports*. Under Title 14 CFR Part 139.327, *Self-Inspection Program*, airports are required to conduct daily inspections of perimeter areas (Self-Inspection Program, 2004). Advisory Circular (AC) 150/5200-18, *Airport Safety Self Inspection*, specifies the following perimeter inspection practices for airports certificated under Title 14 CFR Part 139:

> During the public protection inspection, check gates, fencing, locks, and other safeguards are in place and functioning properly to prevent inadvertent entry to movement areas by unauthorized persons and vehicles and offer protection from jet blast. Report and monitor any safeguards that are damaged or missing. In accordance with the airport's security plan, report unauthorized persons or vehicles in the movement area (airports regulated by the Transportation Security Administration may have additional requirements for reporting and responding to unauthorized persons and vehicles). (FAA, 2004)
>
> Title 49 CFR Part 1542, *Airport Security,* provides additional security regulations that are administered by the Transportation Security Administration (TSA). The most pertinent section of Title 49 CFR Part 1542 related to perimeter security is in Title 49 CFR Part 1542.203, *Security of the Air Operations Area*. This section states that airport operators are responsible for establishing and protecting the air operations area (AOA), which is an area containing the areas of the airport used for landing, takeoff, or surface maneuvering of aircraft (i.e., runways, aprons, and taxiways).

This section also states that airport operators must "…prevent and detect the unauthorized entry, presence, and movement of individuals and ground vehicles into or within the AOA" (Security of the Air Operations Area, 2002).

Depending on the size of the airport, perimeter inspections and security patrols are often time-consuming, particularly when the airport has a large perimeter. At some airports, rough terrain, dense vegetation, and/or wetlands can sometimes prevent ground vehicles from accessing segments of the perimeter at some airports. This can necessitate airport staff to complete the inspection on foot or by boat, making the task significantly more difficult and potentially dangerous.

UAS platforms equipped with high-definition visual and thermal cameras could provide several potential benefits to enhance airport perimeter inspections and surveillance. UASs can be used for inspecting hard-to-reach sections of fence that might be time-consuming or dangerous to access. The UAS's elevated vantage point can also increase the ability of airport operations and security personnel to detect unauthorized vehicles and intruders, particularly at night when equipped with a thermal camera payload. These benefits have the potential to improve the efficiency and efficacy of airport perimeter inspections and surveillance.

1.2 PURPOSE

The purpose of this research effort was to develop minimum performance specifications and technical/operational considerations for the use of UASs to conduct airport perimeter inspections.

1.3 OBJECTIVES

The objectives of this research effort were to:

1. Evaluate the benefits and limitations of using UASs to conduct airport perimeter inspections.
2. Develop and validate recommendations for UAS platform and payload minimum performance specifications.
3. Provide technical and operational considerations for the use of UASs to conduct airport perimeter inspections.

1.4 RELATED DOCUMENTS

1. FAA AC 107-2A, *Small Unmanned Aircraft System (Small UAS)*
2. Program for Applied Research in Airport Security (PARAS) 0012, *Guidance for Integrating Unmanned Aircraft Systems into Airport Security*
3. PARAS 0021, *Utilization of Autonomous Vehicles for Security at Airports*

1.5 RESEARCH APPROACH

This research effort was conducted in two phases. Phase 1 consisted of initial testing of multiple combinations of UAS platforms, payloads, and flight parameters at Cape May County Airport (WWD), New Jersey, to begin to develop minimum performance specifications and technical/operational considerations. Phase 2 consisted of validation testing at three airports of varying environments and size: McGhee Tyson Airport (TYS), Tennessee; Savannah/Hilton Head International Airport (SAV), Georgia; and Cincinnati/Northern Kentucky International Airport (CVG), Kentucky. Phase 2 testing further evaluated the benefits and limitations of UASs and validated the recommended minimum performance specifications and technical/operational considerations of using UASs for airport perimeter inspections in various environments. Both phases consisted of testing in daylight, twilight, and night conditions.

2. UAS PERIMETER INSPECTION CONCEPT OF OPERATIONS

In the initial stage of this research effort, FAA researchers developed an overall concept of operations (CONOPs) for the use of UASs to conduct airport perimeter inspections. Sections 2.1 through 2.4 provide details regarding the CONOPs.

2.1 USE CASES EVALUATED

For this research effort, two use cases for UASs were identified relating to airport perimeter inspections:

1. Conducting inspections of perimeter fencing. This would include inspecting gates, fencing, locks, and other safeguards to ensure these are in place and functioning properly to prevent inadvertent entry to movement areas by unauthorized persons and vehicles, as required under Title 14 CFR Part 139.
2. Conducting perimeter surveillance for the purpose of detecting unauthorized individuals and vehicles, as required under Title 49 CFR Part 1542.

2.2 CORE REQUIREMENT

The core requirement for UASs used for perimeter inspections at airports is that they provide live and/or recorded visual and thermal video camera feeds of the perimeter fence line and surrounding area.

The purpose of live video is to allow the remote pilot in command (RPIC) to conduct the inspection in real time. The purpose of the video recording functionality is to preserve the video evidence of the perimeter inspection that can be used to document the inspection and any anomalies of interest.

The purpose of the visual camera is to allow for a public protection inspection of perimeter infrastructure, and to conduct surveillance of the airport perimeter in daylight or certain twilight conditions. The purpose of the thermal camera is to conduct surveillance in low-light or low-visibility conditions where a visual camera would not be as effective. In certain circumstances, the thermal camera could be used to conduct an inspection of the fence in low-light conditions. However, the detail visible in the thermal footage will be significantly less effective for a thorough perimeter inspection versus visual camera footage captured in the daylight.

2.3 SYSTEM OVERVIEW

As defined in 14 CFR Part 107.3, *Definitions*, a UAS includes the "the unmanned aircraft and its associated elements (including communication links and the components that control the small unmanned aircraft) that are required for the safe and efficient operation of the small unmanned aircraft in the national airspace system" (Definitions, 2016).

FAA researchers determined that UASs operated for perimeter inspections should be multirotor rather than fixed-wing models. Multirotor UASs provide more precise flight plans than fixed-wing UASs and are also capable of flying at slower speeds while maintaining flight stability. In addition, multirotor UASs offer more flexibility during flight than fixed-wing UASs due to their ability to hover or quickly backtrack along the flight path to allow for further inspection of anomalies detected during an inspection.

For perimeter inspections, the UAS would be equipped with both visual and thermal camera sensors. Depending on the UAS model, these camera sensors might be permanently integrated with the unmanned aircraft (UA) or mounted as external payloads. The ground control station (GCS) is used by the RPIC to control the UA. The GCS will often include a mounting bracket for a touch screen smartphone or tablet. These devices are used for displaying the live video feeds; viewing battery status; adjusting settings; and displaying flight telemetry data, such as altitude, speed, and location. The live payload video feed could also be viewed remotely by additional personnel using streaming software.

2.4 OPERATIONAL DESCRIPTION

Depending on the airport's organizational structure, the personnel deploying the UAS might be part of the airport operations department, airport security, law enforcement, or another department or entity. It is expected that each airport will develop and adopt standard operating procedures for UAS operations. Third-party operators must receive approval from the airport sponsor prior to conducting operations. In addition, all UAS operations in controlled airspace must be conducted with air traffic control (ATC) approval, which is typically obtained through an airspace authorization received in advance of the operation.

The UAS must be operated in compliance with all applicable FAA regulations by a trained and certified RPIC. The UAS should be operated within the visual line-of-sight of the RPIC and any visual observers (VOs). The RPIC operates in accordance with all provisions of the airspace authorization, such as contacting the ATC facility prior to conducting UAS operations, monitoring the local ATC frequency during the operation, and ensuring the UAS remains within the approved airspace volume. Throughout the operation, the RPIC is responsible for giving way to manned aircraft that might be present.

Before launching the UAS, the RPIC would perform a brief preflight checklist and verify that there are no aircraft or obstructions above, or in the immediate vicinity of, their location. In most cases, the UAS would be stored in a case that would be removed from a vehicle and require some amount of assembly prior to flight.

For routine inspections, UASs would use preprogrammed flight plans to ensure safety and consistency and to allow the RPIC to focus more attention on the live payload feed during flight. The flight plans would need to be created in advance of UAS operations using global positioning system (GPS) coordinates of the fence line to be inspected. The parameters of these flight plans are dependent on the operating environment and the objective of the UAS operation (fence inspection or surveillance). If the UAS is operated for the purpose of conducting an inspection of the fence condition, it is recommended that the flight plan specify that the UAS fly along the fence at a lateral offset of no more than 30 ft. This is consistent with guidance within the TSA document, *Security Guidelines for General Aviation Airport Operators and Users*, which suggests that airports maintain clear areas of 10 ft to 30 ft on both sides of perimeter fencing (TSA, 2017). For flights intended to be conducted at an offset, the fence line GPS coordinates should be adjusted in the flight plan to account for the lateral distance from the fence.

In certain cases where flight planning cannot take place in advance of UAS operations, such as during a response to a perimeter breach or an unplanned nonstandard spot inspection, preprogrammed flight plans are unable to be created. In these situations, manual flight might be necessary.

The method by which the payload video footage is evaluated depends upon personnel availability, the urgency of the inspection, and whether the operating entity has the capability to remotely view the live payload video feed. The simplest and most immediate means would be to have the RPIC view and evaluate the live payload feed in real-time on the GCS screen. If the operating entity has the capability to stream the live video feed and additional staff availability, the live feed could be viewed and evaluated by another individual at a remote location, such as a security operations center. As an alternative, the recorded payload video could also be evaluated at a later time following the flight. Once the flight operations are complete, the RPIC would land the UAS and transfer the video footage from the physical memory card for evaluation and/or archival purposes.

3. PHASE 1 TESTING: CAPE MAY COUNTY AIRPORT

Phase 1 testing took place at WWD, located near Rio Grande, New Jersey. WWD is a non-towered, public use airport located in Class G airspace from the surface to 700 ft above ground level (AGL). During this phase, contracted personnel conducted test flights over and adjacent to perimeter and AOA fencing in three areas at WWD with a variety of UASs while collecting video with visual and thermal camera payloads. Each piece of video footage was reviewed and evaluated regarding its respective quality and usefulness for fulfilling the requirements stated in Title 14 CFR Part 139 and Title 49 CFR Part 1542.203, *Security of the Air Operations Area (AOA)*. This analysis identified initial findings regarding minimum recommended performance specifications and technical and operational considerations for UAS platforms, payloads, and GCS when conducting airport perimeter inspections and surveillance.

Phase 1 UAS testing at WWD consisted of two test efforts, referred to as Phase 1A and Phase 1B. Phase 1A UAS testing focused on evaluating a variety of preprogrammed flight plan parameters and their effect on the quality and usefulness of the footage captured. In total, 73 test flights were conducted to evaluate various UAS platforms, payloads, and flight parameters. Following Phase 1A testing, the footage collected during each flight was evaluated to identify the most effective flight parameters and payloads.

Phase 1B UAS testing used the most effective flight parameters identified during Phase 1A to evaluate additional UAS platforms and payloads in three test areas that each presented a unique environment. Eighty-four test flights were conducted during follow-up testing, and the footage was evaluated to develop initial minimum technology performance specifications.

3.1 TEST AREAS

Testing was performed within three test areas along the AOA perimeter fence. Each test area was selected to provide a unique environment to evaluate each combination of UAS, payload, and flight parameters. Figure 1 shows the locations of these test areas. The fencing in each test area was 10-ft galvanized steel, chain-link fence topped with barbed wire. In addition to existing features in each test area (such as AOA gates, locks, burrowing, or vegetation), additional test targets were placed within each test area to assess the ability to detect and identify anomalies with various flight plans, UAS platforms, and payloads.

Figure 1. Test Areas at WWD

Test Area 1 included an AOA fence line bordering wooded areas and featured an AOA access gate (with a lock to prevent inadvertent entry by unauthorized personnel) that was inspected as part of the testing. This allowed for testing and evaluation of various flight parameters, UAS platforms, and payloads when performing perimeter inspections in easily accessible locations. In addition, an instance of burrowing underneath the fence was present and used as an additional point of comparison. Figure 2 shows a portion of the fence line in Test Area 1.

Figure 2. Example of Fencing in Test Area 1

Test Area 2 was located adjacent to an internal AOA fence line that directly abutted a densely wooded area. The fence featured a trench running along the interior with thick vegetation growing out of it. This vegetation partially obscured the view of the fence and prevented a thorough inspection using ground vehicles while also making access by foot difficult. This allowed for testing and evaluation of UAS platform and payload performance when inspecting a fence line in a hard-to-access area. Figure 3 depicts the fence line, as well as the trench and vegetation.

Figure 3. Fencing in Test Area 2 Obscured by Trench and Vegetation

Test Area 3 was located on the southeast corner of the airport property and included an AOA fence line with trees on both sides. This allowed for testing and evaluation of UAS platform and payload performance when inspecting a fence line in a remote, densely wooded environment. Figure 4 shows the fence line in Test Area 3.

Figure 4. Fencing in Test Area 3

3.2 UNMANNED AIRCRAFT SYSTEM PLATFORMS AND PAYLOADS

Sections 3.2.1 through 3.2.3 describe the UAS platforms, payloads, and additional equipment used to conduct Phase 1 testing.

3.2.1 Unmanned Aircraft System Selection Criteria

Prior to testing, FAA researchers developed basic UAS selection criteria to adequately perform airport perimeter inspections, including airframe type, payload compatibility, safety, cybersecurity, deployment type, deployment speed, ease-of-use, and cost-effectiveness. These criteria, which are described in Sections 3.2.1.1 through 3.2.1.8, were used to select the UASs and payloads included in this testing effort.

3.2.1.1 Unmanned Aircraft System Airframe Type

The vast majority of UASs, much like manned aircraft, are either fixed-wing or rotorcraft. Only multirotor UASs were included in this research effort to allow for slow and precise patrols that can follow along potentially complex, nonlinear perimeters. In addition, multirotor UASs were selected because they have the capability to stop and hover, allowing for detailed inspections of anomalies spotted during flight. Multirotor UASs also increase safety when operating in the airport environment due to their enhanced maneuverability versus fixed-wing UASs.

3.2.1.2 Payload Compatibility

To provide the greatest versatility for conducting perimeter inspections and surveillance in a variety of lighting conditions, the UASs selected for this research program were capable of carrying both visual and thermal camera payloads.

3.2.1.3 Safety

Safety is the top priority for all activity in the airport environment. Therefore, the UASs selected for this research effort included safety features such as a lost link return-to-home failsafe mode and geofencing capability (software restricting the ability of the UAS to leave its designated airspace limits) to minimize hazards with aircraft, people, and property. Other safety features included an anti-collision beacon for safely conducting twilight and night operations.

3.2.1.4 Cybersecurity

Cybersecurity measures must prevent outside persons from knowingly or unknowingly accessing or interrupting data communications. This includes data used for command and control of the aircraft as well as payload footage. The UASs selected for this research program featured secure, encrypted connections between the aircraft, GCS, and any other devices that receive data.

3.2.1.5 Deployment Type

Security-focused UAS manufacturers are currently developing autonomously deployed "drone-in-a-box" systems that can be remotely deployed from a covered base station permanently installed on the airport property. These systems can automatically deploy to conduct routine patrols or to respond to alarms along the perimeter. While these UASs could provide time and efficiency savings versus traditional manually deployed UASs, their operation would require operations beyond visual line-of-sight. In addition to this concern, due to the immature nature of these emerging autonomously deployed UAS technologies, only manually deployed UASs were included in this research effort.

3.2.1.6 Deployment Speed

To provide the greatest efficiency benefit for airport operations and security personnel, the UAS must be launched and begin recording and transmitting data as quickly as possible. The speed of deployment is the primary consideration that affects the ability of UASs to provide a time-saving benefit for perimeter inspections. For this reason, FAA researchers tested systems that were capable of rapid deployment.

3.2.1.7 Ease-of-Use

UASs that were as simple as possible to operate were selected to minimize potential delays in launching the aircraft and reduce the chance of user error.

3.2.1.8 Cost Effectiveness

Airports vary significantly in the resources that can be used to purchase equipment. Therefore, UAS platforms ranging in price from $3,850 to $28,000 were included in testing to find solutions that could be effective for different organizational budgets.

3.2.2 Unmanned Aircraft System Platforms

FAA researchers selected the following three commercial-off-the-shelf multirotor UAS platforms that met the selection criteria in Section 3.2.1 for this research effort. The selected UAS platforms represent varying sizes, payload capabilities, and price points:

- Da-Jiang Innovations (DJI) Matrice 210 RTK v2 (M210)
- DJI Mavic 2 Enterprise Dual (M2ED)
- Parrot ANAFI USA*

*Used in Phase 2 only.

During Phase 1A testing at WWD, all tests were conducted using the M210. The M210 was selected for initial testing due to its capability to use a variety of interchangeable payloads of varying capabilities. The M2ED was used along with the M210 during Phase 1B testing. The M2ED was selected for testing due to its smaller form factor and considerably reduced price point versus the M210. In addition, its lower resolution thermal camera allowed for further development of payload minimum performance specifications. The ANAFI USA was not available for use during Phases 1A and 1B but was incorporated in Phase 2 to provide a more comprehensive assessment of varying performance specifications due to this UAS's dual visual cameras and zoom capability.

These UASs are pictured in Figure 5. Table 1 provides an overview comparison of key specifications for each UAS. Additional specifications for each platform are presented in Appendix A.

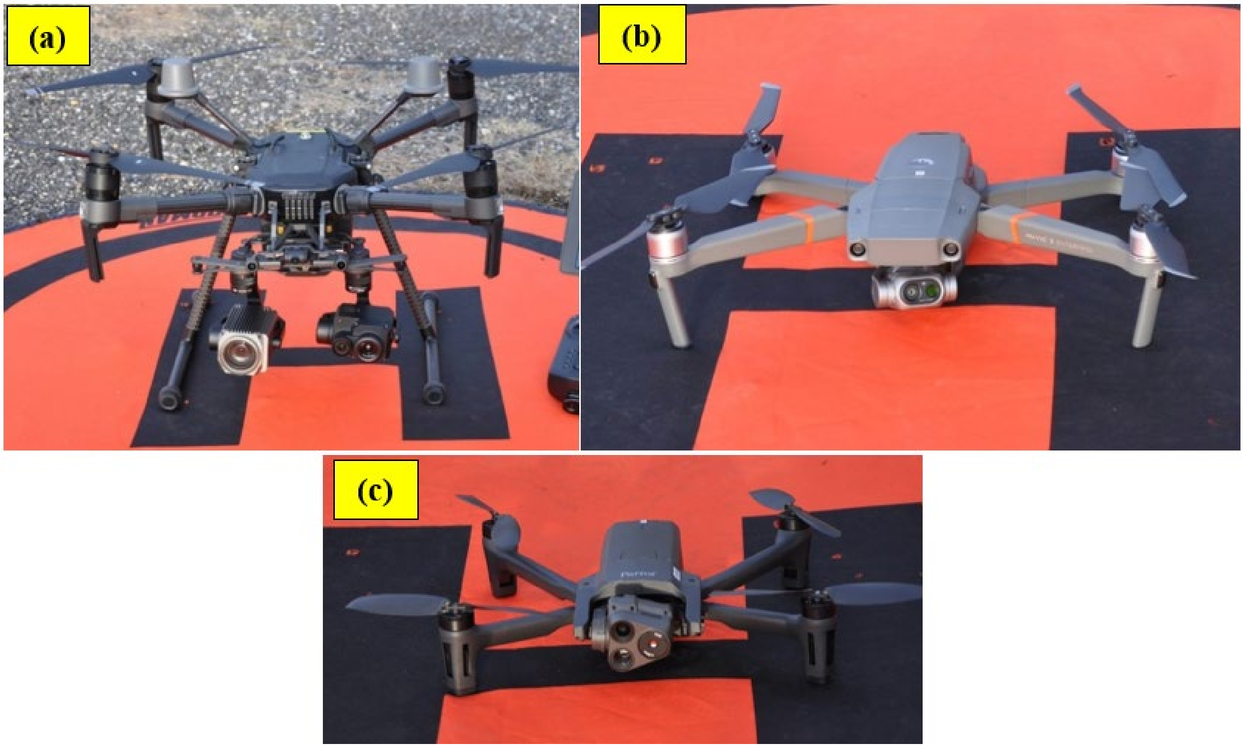

Figure 5. Unmanned Aircraft System Platforms: (a) DJI M210, (b) DJI M2ED, and (c) Parrot ANAFI USA

Table 1. Phase 2 Unmanned Aircraft System Platform Specifications (DJI, 2020; DJI, 2021a; Parrot, 2020)

	DJI M210	DJI M2ED	Parrot ANAFI USA
Maximum takeoff weight	13.5 lb	2.4 lb	1 lb
Airframe dimensions	34.8″ x 34.9″ x 16.8″	12.7″ x 9.5″ x 3.3″	11.1″ x 14.7″ x 3.3″
Endurance	24 min	31 min	32 min
RF Range	5 miles	5 miles	2.5 miles
Data Encryption	AES 256-bit encryption	AES 256-bit encryption	AES 128-bit encryption
3-axis Gimbal	Yes	Yes	Yes
IP rating	IP43	N/A	IP53
Operating temperature range	-4 °F to 122 °F	14 °F – 104 °F	-32 °F to 110 °F
Maximum wind resistance	26 mph	23 mph	32.88 mph
Interchangeable payloads	Yes	No	No
Estimated cost	UAS: $28,000 (with XT2 and Z30 payloads)	$3,850	$7,000

RF = Radio frequency

Each UAS used during this research effort utilized a different GCS to evaluate varying specifications with regard to form factor, screen size, and screen brightness. The GCSs used during Phase 1 testing were the DJI Cendence controller and CrystalSky Tablet, and the DJI Smart Controller. Screen brightness is traditionally measured in candelas per square meter, also known as *nits*. The Parrot SkyController 3 and iPad Mini were used during Phase 2 testing. All three GCSs are pictured in Figure 6. A comparison of key specifications for these GCSs is presented in Table 2.

Figure 6. Ground Control Stations: (a) DJI Cendence Controller and CrystalSky Display, (b) Parrot Skycontroller 3 and iPad Mini®, and (c) DJI Smart Controller

Table 2. Phase 1 GCS Specifications (DJI, 2018a; DJI, 2021b, Apple, 2022)

	DJI M210	DJI M2ED	Parrot Anafi USA
GCS controller	DJI Cendence	DJI Smart Controller	Parrot Skycontroller 3
GCS screen	DJI CrystalSky Tablet		Apple iPad Mini® (5^{th} generation)
Screen size	7.85″	5.5″	7.9″
Screen brightness	2,000 nits	1,000 nits	500 nits
Integrated screen and controller	No	Yes	No

3.2.3 Payloads

FAA researchers tested the following eight visual and thermal camera payloads to determine minimum performance requirements for perimeter UAS inspections.

- DJI Zenmuse X5S (visual camera)
- DJI Zenmuse Z30 (visual camera with 30x optical zoom)
- DJI Zenmuse XT2 9mm (dual visual and thermal camera)
- DJI Zenmuse XT2 13mm (dual visual and thermal camera)
- DJI Zenmuse XT2 19mm (dual visual and thermal camera)
- DJI Zenmuse XT2 25mm (dual visual and thermal camera)
- DJI M2ED Integrated Camera (dual visual and thermal camera)
- Parrot ANAFI Triple Integrated Camera (two visual cameras and one thermal camera)*

*Used in Phase 2 only.

These payloads are pictured in Figure 7. Table 3 compares key specifications of each payload used. The Parrot ANAFI Triple is included in Figure 6 and Table 3 for comparison purposes but was only used during Phase 2 testing. Additional specifications for each payload are presented in Appendix B.

Figure 7. Unmanned Aircraft System Camera Payloads: (a) DJI Zenmuse XT2, (b) DJI Zenmuse Z30, (c) Zenmuse X5S, (d) M2ED Integrated Camera, and (e) Parrot ANAFI Triple

Table 3. Camera Payload Specifications (DJI, 2017; DJI, 2018b; DJI, 2019; DJI, 2021a; Parrot, 2020)

	Zenmuse X5S	Zenmuse XT2	Zenmuse Z30	M2ED Integrated Camera	ANAFI Triple
Compatible UAS Platform	DJI M210			DJI M2ED	Parrot ANAFI USA
Visual Camera Resolution Recorded	3840 x 2160 (4K); 1920 x 1080 (1080p)	4K/1080p	1080p	4K	4K
Visual Camera Resolution Streamed	1080p	1080p	1080p	1080p	720p
Visual Camera Zoom	N/A	1x, 2x, 4x, 8x digital	30x optical continuous; 6x digital continuous	N/A	1x to 5x optical continuous; 5x to 32x digital continuous
Visual Camera FOV	72°	57.12° × 42.44°	63.7° (max)–2.3° (min)	85°	Wide: 84° Zoom: up to 75.5°
Visual Camera Sensor Size	4/3” 20.8 MP	1/1.7″, 12 MP	1/2.8″, 2.13 MP	1/2.3″, 12 MP	Wide: 1/2.4″, 21 MP Zoom: 1/2.4″, 16 MP
Thermal Camera Resolution	N/A	9mm: 336 x 256 13mm: 640 x 512 19mm: 640 x 512 25mm: 640 x 512	N/A	160 x 120	320 x 256
Thermal Camera FOV	N/A	9mm: 35° x 27° 13mm: 45° x 37° 19mm: 32° x 26° 25mm: 25° x 20°	N/A	57°	50° horizontal
Thermal Camera Zoom (Digital)	N/A	336: 1x, 2x, 4x 640: 1x, 2x, 4x, 8x	N/A	N/A	N/A
Thermal Camera Sensitivity	N/A	< 50 mK	N/A	Not Specified	< 60 mK
Additional Features		Thermal/ Visual Image Blending, Temperature measurement	N/A	Thermal/ Visual Image Blending	Thermal/ Visual Image Blending
Approximate Cost	$1,240	$6,000 (336 x 256) $10,000 (640 x 512) (Payload only)	$3,000 (Payload Only)	$3,850 (with UAS)	$7,000 (with UAS)

FOV = Field of view
mK = millikelvin
MP = megapixel

In addition to camera payloads, researchers also evaluated the effectiveness of the Wingsland Z15 Gimbal Spotlight payload when used on the M210 in conjunction with camera payloads during test flights in low-light conditions. The Wingsland Z15 spotlight has a brightness of 10,200 lumens and a working distance of 492 ft (Shenzhen BOOY Technology, 2019). The Wingsland Z15 Gimbal Spotlight is pictured in Figure 8.

Figure 8. Wingsland Z15 Gimbal Spotlight

3.3 TEST METHODS AND PROCEDURES

Sections 3.3.1 through 3.3.5 describe the site setup, test procedures, data collection, data analysis, and safety and coordination procedures employed during Phase 1 testing at WWD.

3.3.1 Site Setup

To evaluate the performance of each payload and the efficacy of the various flight parameters, test targets were placed throughout each test area prior to data collection. These targets were used to evaluate the capabilities of various visual and thermal camera payloads. These test targets included the following:

- Vehicle
- Human
- Bolt cutters
- Ladder and blanket

The vehicle and human were selected as test targets to simulate a potential attempted breach of the perimeter. In addition, because these targets emit heat radiation, they could be used to evaluate thermal camera payloads during flights in low-light conditions. The bolt cutters, ladder, and blanket were selected to simulate leftover evidence of a past perimeter breach. The human and vehicle test targets were used during Phases 1A and 1B, while the bolt cutters, ladder, and blanket were only used during Phase 1B. Figure 9 shows examples of these test targets.

Figure 9. Test Targets: (a) Vehicle, (b) Human, (c) Bolt Cutters and AOA Gate, and (d) Ladder and Blanket

In addition, the following existing features of each test area were used to evaluate the capabilities of the UAS payloads and flight parameters:

- AOA gate locks and latches
- Erosion underneath fencing
- Fallen tree lying on fencing

These existing features are pictured in Figure 10.

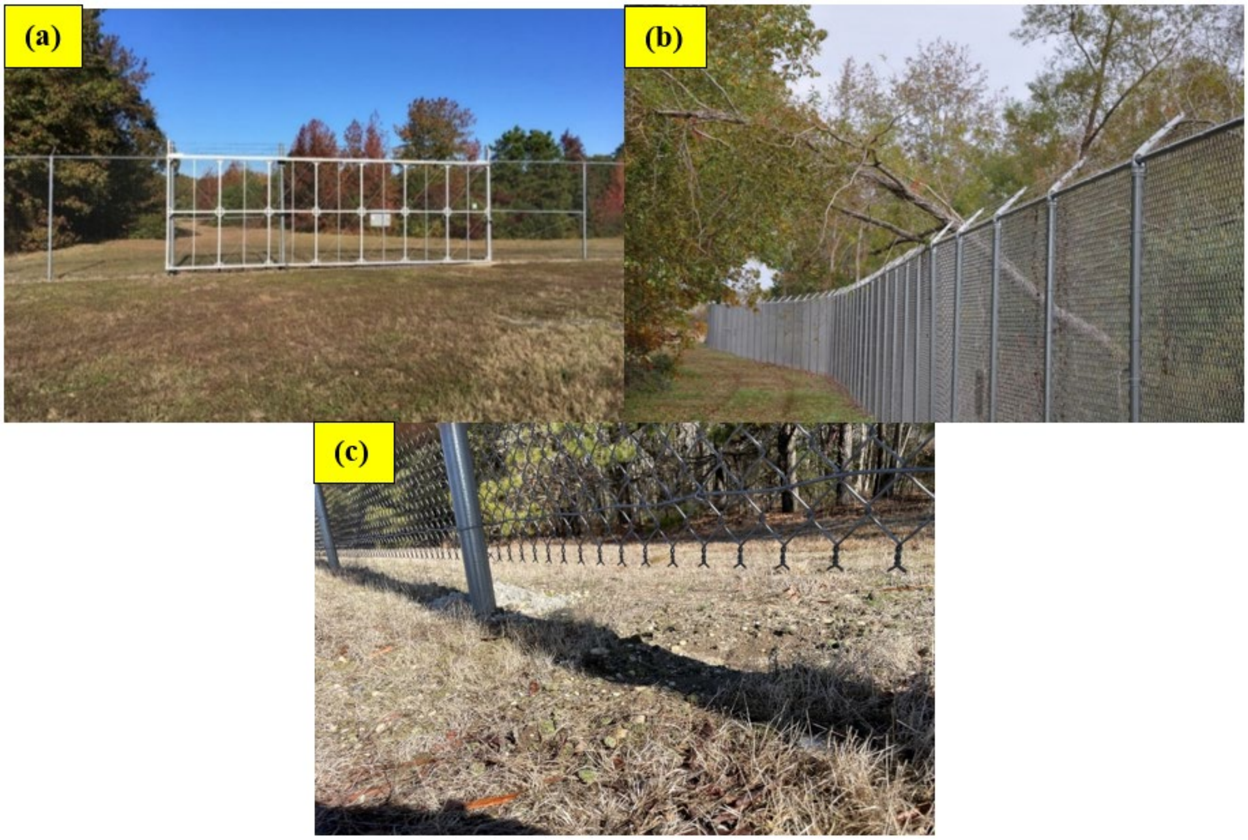

Figure 10. Existing Features: (a) AOA Access Gate, (b) Fallen Tree, and (c) Erosion Underneath Fence

In Test Area 1, a vehicle, a human subject, AOA access gate, bolt cutters, and preexisting erosion under the fence were used as test targets. The fence line observed during testing in Test Area 1 and the locations of these targets are shown in Figure 11.

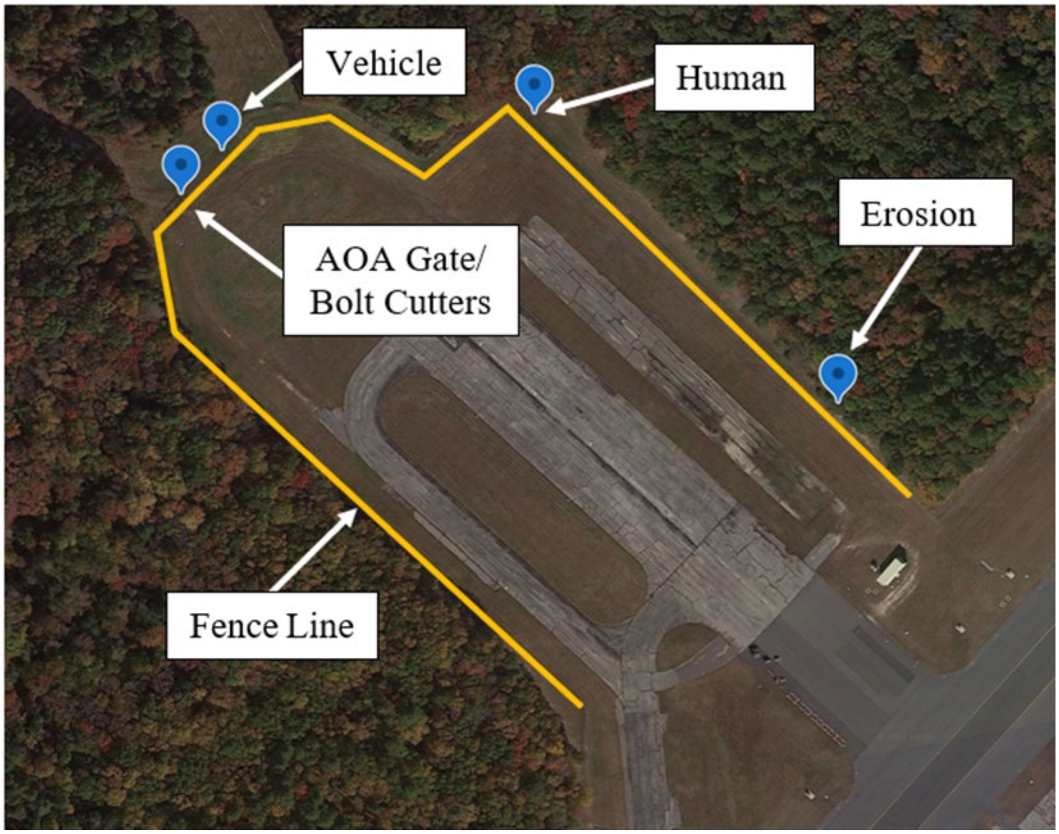

Figure 11. Test Area 1 Fence Line and Target Locations

In Test Area 2, a ladder, a blanket placed over the fence, and a human subject served as targets for evaluating flight parameter and payload performance. Figure 12 shows the fence line observed in Test Area 2 and the location of these targets.

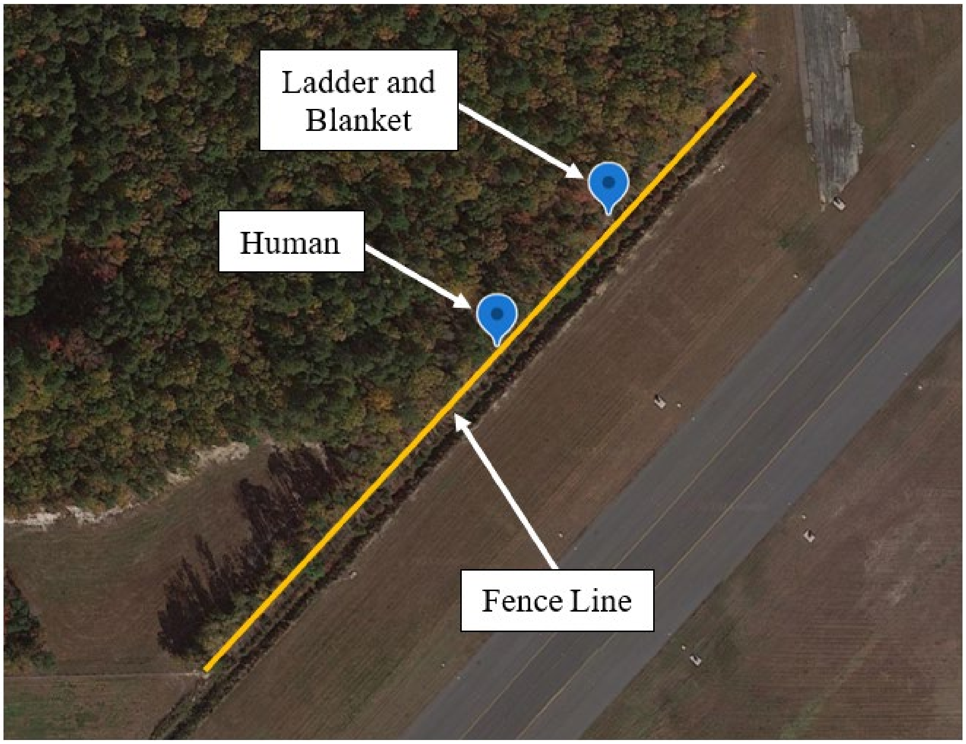

Figure 12. Test Area 2 Fence Line and Target Locations

In Test Area 3, a vehicle, a human subject, a ladder and blanket, and bolt cutters were used to evaluate payload performance, in addition to a downed tree that was already lying on the fence prior to testing. Figure 13 shows the fence line observed in Test Area 3 and the locations of these targets.

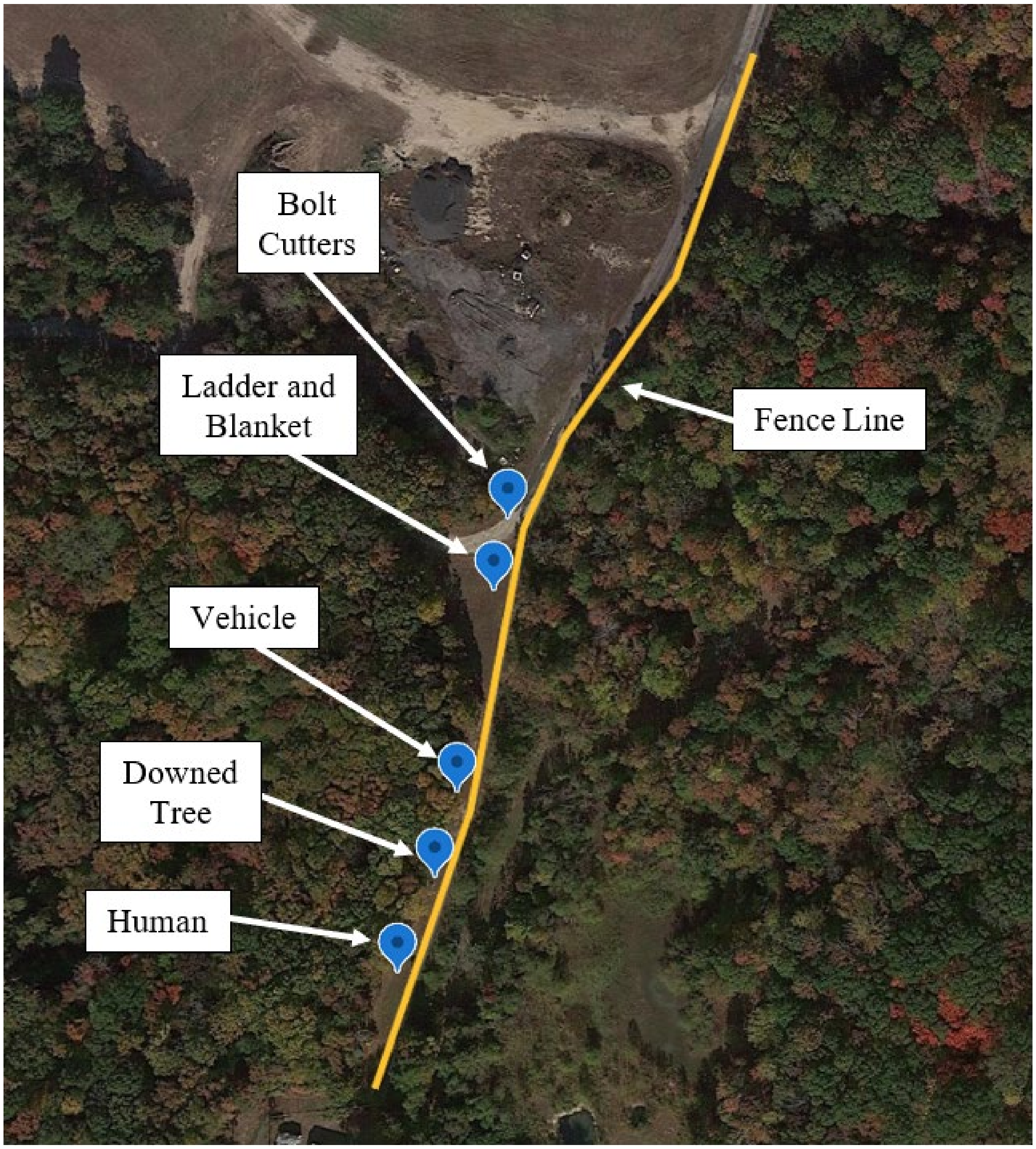

Figure 13. Test Area 3 Target Locations

3.3.2 Test Procedures

Phase 1 testing at WWD consisted of two test efforts, Phase 1A and Phase 1B. Sections 3.3.2.1 and 3.3.2.2 provide more detail on the test procedures used during these test efforts.

3.3.2.1 Phase 1A UAS Testing

Phase 1A UAS testing consisted of a total of 73 test flights, 51 conducted during daylight and 22 at night. To ensure consistency when evaluating the video collected, flights were conducted using preprogrammed flight plans. All test flights during Phase 1A testing took place in Test Area 1.

The primary objective of Phase 1A testing was to evaluate a variety of flight plans to assess the best methods of flying UASs to conduct perimeter inspections and surveillance. These parameters included the UAS flight path's offset from the fence line, horizontal camera angle, and altitude. Since evaluating flight parameters was the focus, all tests were conducted using the M210 UAS. Since the M210 has interchangeable payloads, various visible and thermal camera payloads were used to assess their capabilities and limitations and to begin to develop minimum performance specifications.

Three primary types of flight plans were used during Phase 1A testing to evaluate flight parameters. In two of these flight plans, the UAS was flown parallel to the perimeter fence at a 30 ft offset from the inside of the fence line, while in the third configuration the UAS was flown directly over the fence line. The 30 ft offset flight plans were created to fulfill the first-use case presented in Section 2.1, the conducting of fence line inspections. The 30-ft offset value was chosen to allow the camera to get an adequate angle to inspect the fence while remaining within the 10- to 30-ft "clear areas" adjacent to the fence recommended in the TSA's *Security Guidelines for General Aviation Airport Operators and Users* (TSA, 2017). Each flight plan was flown at multiple altitudes, ranging from 10 ft AGL to 100 ft AGL.

In the first 30-ft offset flight plan, the payload faced at a constant horizontal angle of approximately 30 degrees relative to the direction of motion, as shown in Figure 14. In the second 30-ft offset flight plan, the payload faced directly towards the fence at a 90-degree angle, as shown in Figure 15.

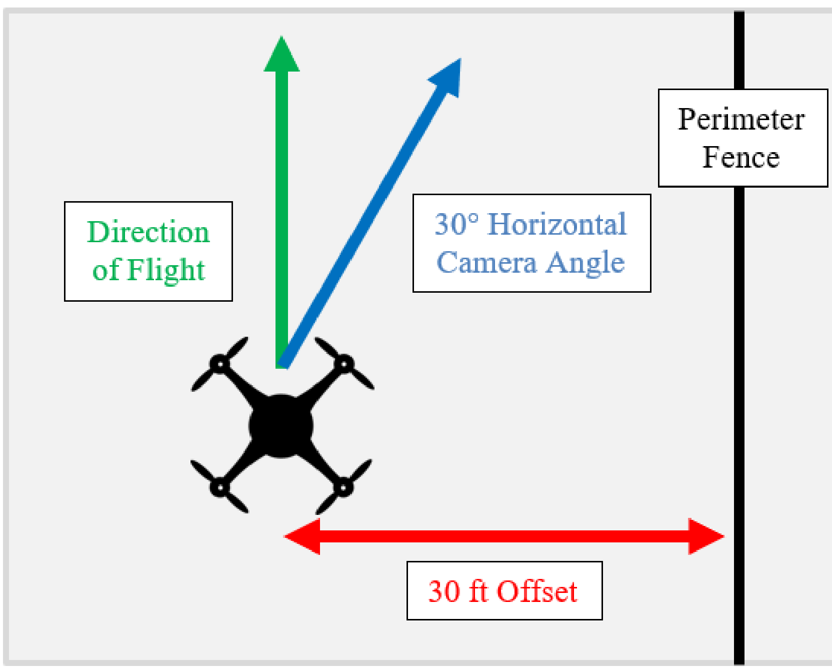

Figure 14. Overhead View of 30 ft Offset, 30-degree Horizontal Camera Angle Flight Plan (Not to Scale)

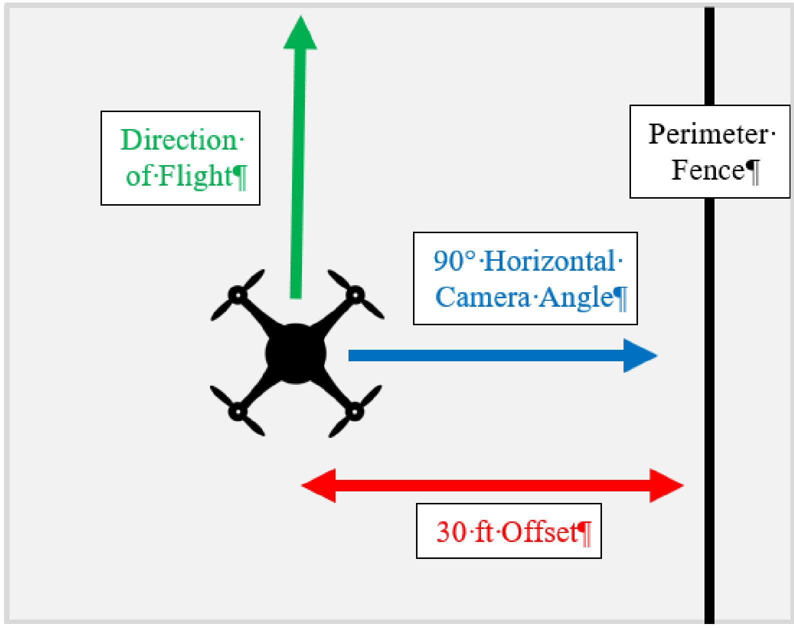

Figure 15. Overhead View of 30-ft Offset, 90-degree Horizontal Camera Angle Flight Plan (Not to Scale)

The third flight plan was developed to satisfy the surveillance use case presented in Section 2.1, or to allow for an inspection of perimeter areas where obstacles on either side of the fence prevent the UAS from flying at an offset. This flight plan consisted of the UAS flying directly above the fence at a 0-ft offset with the camera facing forward. This flight plan is depicted in Figure 16.

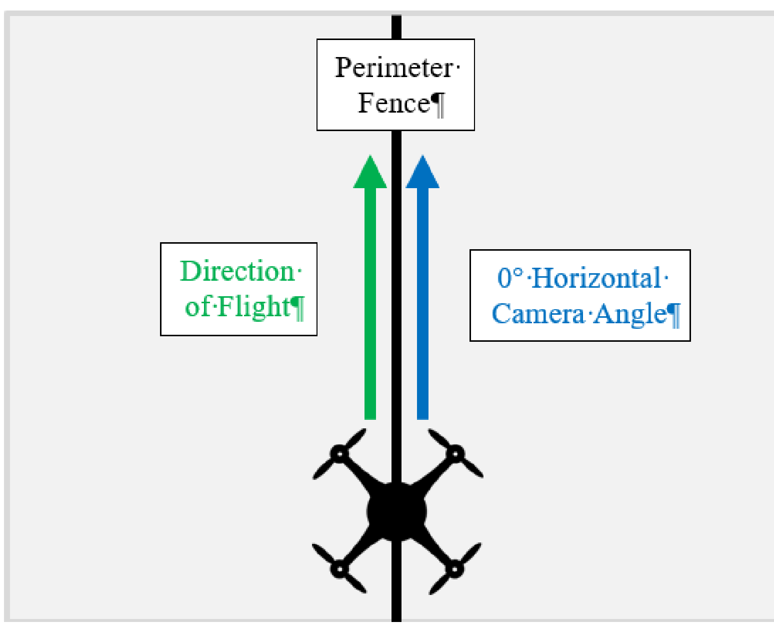

Figure 16. Overhead View of 0-ft Offset, 0-Degree Horizontal Camera Angle Flight Plan (Not to Scale)

A complete list of test parameters used during Phase 1A testing at WWD is shown in Appendix C.

3.3.2.2 Phase 1B UAS Testing

Phase 1B UAS testing consisted of a total of 84 test flights, all conducted during daylight conditions. The objective of Phase 1B testing was to further assess initial findings from Phase 1A regarding flight parameters and payloads by conducting testing in additional test areas (Test Areas 2 and 3) with varying environments and by using additional UAS platforms and payloads.

Phase 1B testing leveraged the findings from Phase 1A by significantly narrowing down the flight parameters used. All tests with a 90-degree horizontal camera angle were eliminated, as well as flights with a 30-degree horizontal camera angle and an altitude above 20 ft AGL. For tests conducted with a 0-degree horizontal camera angle at a 0-ft offset, only altitudes of 40 ft and 100 ft AGL were used to evaluate the difference between high and low altitudes. In addition, each test was conducted one additional time while flying in the opposite direction to evaluate the effect of sun angle on each payload. Appendix C presents the test flights and parameters employed during this test effort.

With regard to UAS platforms and payloads, Phase 1B expanded on Phase 1A by including two additional thermal payloads sensors for the M210, and an additional UAS platform with integrated thermal and visual payloads to compare various resolutions. In addition to Test Area 1, two additional testing locations, Test Areas 2 and 3, were used to assess the capabilities and limitations of the technology and flight parameters in various environments.

3.3.3 Data Collection

Two types of data (video footage) were recorded for subsequent analysis. These included the full-resolution payload video footage recorded directly onboard the UAS to a secure digital memory card, and recordings of the live payload video feed as displayed on the GCS. These types of video were distinguished from each other due to their varying resolutions and their projected use with regard to airport perimeter inspections. Payload video recorded onboard the UAS is of higher resolution and experiences less compression than live-streamed video, resulting in higher quality data. Live-streamed footage, however, can be viewed in real-time during the inspection, whereas recorded video can only be viewed after the UAS has landed. Depending on the UAS platform in use, the live feed was recorded either by a screen recording program installed on the GCS display or by an external video recording device connected to the GCS. The external video recording device, shown in Figure 17, was used to record the live payload feed while using the M210 via a high-definition, multimedia-interface cable connection with the GCS display. This external recording device stored footage on a USB media drive at a resolution of 1080p. The live video feed was also displayed on a 23.8 in. external monitor with a brightness of 250 nits. This external monitor is shown displaying the live payload feed during Phase 1 testing in Figure 18.

Figure 17. External Video Capture Device

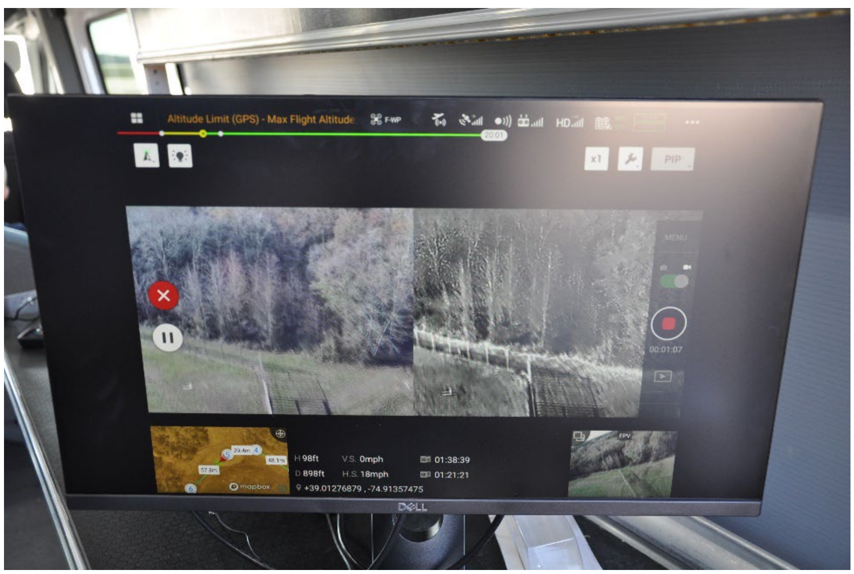

Figure 18. External Monitor Displaying Live Video Feed

<u>3.3.4 Data Analysis</u>

During each test flight, FAA researchers viewed the live payload feed on the GCS and external monitor to verify the capture and quality of footage in real-time. Following Phase 1A testing, the video footage was collected and analyzed by FAA researchers with prior experience conducting airport perimeter inspections on foot and in ground vehicles. The purpose of this analysis was to determine the flight parameters that provided an effective vantage point from which to collect data fulfilling each perimeter inspection use case.

Once the flight parameters that produced the most useful, high-quality footage were identified, FAA researchers evaluated the recorded video footage and provided feedback regarding the quality of the video from each payload. Separate analyses were performed for the visual and thermal camera payloads and the recordings of the live video feeds and the full-resolution footage recorded onboard each UAS. These analyses helped to determine the capabilities and limitations of the payloads, and to develop payload minimum performance specifications for perimeter inspections and surveillance.

Visual camera payload footage was evaluated based on the amount of detail visible when viewing the video, including the condition of the chain links and general fence structure; the presence of any people, vehicles, or objects near the fence; and status of the AOA gate and locks. Thermal camera payloads were evaluated for their ability to detect and identify the human and vehicle targets during each test.

3.3.5 Safety and Coordination

Prior to conducting UAS operations, the contracted flight team conducted a site survey, walking the fence line and observing each test area to identify any obstructions or hazards that could impact testing, such as structures or trees. They also verified that the planned flight parameters (offset and altitude) would be safe and effective and identified adequate emergency landing locations, the optimal return-to-home sequence altitude, and optimal locations for the ground station and visual observers.

Since WWD is located in uncontrolled airspace, a Part 107 airspace authorization was not required to operate UASs on the premises. Comprehensive coordination was conducted with WWD management and airport operations personnel prior to each phase of testing to ensure the UAS operations would be executed safely and have no impact on airport operations. This included the submission of a "Notice of Proposed UAS Operations" form to WWD management, which described the dates, times, and locations of testing.

In preparation for working at WWD, evaluations were completed to check for potential flight restrictions enforced by DJI. WWD is in a locked geo zone, and authorization is required to conduct operations. FAA researchers submitted credentials and unlocked the zone prior to commencing operations.

All UAS operations were conducted in accordance with the regulations of Title 14 CFR Part 107, including strict observance of the requirement to operate the UASs within visual line-of-sight of the RPIC. This included radio communication between the RPIC and visual observers, and constant crew monitoring of the appropriate ATC frequencies. In addition, all members of the flight crew were FAA-certificated RPICs experienced in the operation of UASs at airports.

To mitigate the risks associated with operating UASs in the airport environment, additional safety protocols were enacted, including establishing lost communications procedures if any crew members lost contact with one another, and emergency procedures in the event of an incident. Prior to UAS operations, the RPIC presented a safety briefing to all those present during testing, informing them of relevant federal regulations, internal safety protocols, and emergency procedures. During pre- and post-flight procedures, crew members used established internal checklists to ensure safety. During operations, all flight crew members maintained a sterile cockpit, and wore high-visibility reflective safety vests to aid in identifying members of the UAS team and enhancing visibility to other airport operations.

3.4 RESULTS AND DISCUSSION

Sections 3.4.1 through 3.4.2 summarize the results from Phase 1 UAS testing at WWD.

3.4.1 Phase 1A

Sections 3.4.1.1 through 3.4.1.6 present the results from Phase 1A UAS testing. The results address evaluations of flight parameters, payload performance, live-streamed video performance, and additional considerations.

3.4.1.1 Flight Parameter Analysis

For the fence inspection use case, the flight parameters were evaluated based on their ability to provide a detailed view of the face of the fence. For the surveillance use case, the flight parameters were evaluated based on their ability to provide a vantage point that allowed for footage to be collected that maximized the situational awareness of people, vehicles, or wildlife in the area surrounding the fence.

3.4.1.1.1 Flight Path Offset and Horizontal Camera Angle

- 0-ft Offset, 0-Degree Horizontal Camera Angle

  Flights conducted directly over the fence (0-ft offset) with a 0-degree horizontal camera angle were the most effective in providing situational awareness of both sides of the perimeter fence. This flight configuration is particularly useful for patrolling unauthorized persons or vehicles.

  While this vantage point provides a limited view of the perimeter fence itself, it can verify that the fence is upright and has not sustained major structural damage. Figure 19 shows an example of a screenshot from a 0-ft offset flight. While the condition of the face of the fence cannot be seen, the footage allowed evaluators to detect the human subject near the perimeter.

Figure 19. 0-ft Offset, 0-Degree Horizontal Camera Angle, 40 ft AGL Flight

- <u>30-ft Offset, 90-Degree Horizontal Camera Angle</u>

  Tests conducted at a 30-ft offset with the camera aimed towards the fence at an approximate 90-degree horizontal camera angle did not produce video footage that was useful for fence inspections. The limited field of view at this camera angle significantly reduced the amount of perimeter fence visible at any given time, as well as the time a given section of fence was visible in the frame, limiting the ability to perform a thorough inspection while using this flight plan. For example, Figure 20 shows a screenshot taken from footage captured at an approximate 90-degree horizontal camera angle in which only three complete fence sections are visible in the frame. In addition, pointing the camera directly at the fence caused an increase in the sense of motion (when viewing the video), causing a blurring of the imagery and making it difficult to focus on or properly assess any particular part of the fence.

Figure 20. 30-ft Offset, 90-Degree Horizontal Camera Angle, 10 ft AGL Flight

- 30-ft Offset, 30-Degree Horizontal Camera Angle

  Tests conducted at a 30-ft offset with an approximate 30-degree horizontal camera angle were found to produce video footage that was acceptable for fence inspections. The 30-degree horizontal camera angle allowed the camera to see the face of the fence with enough detail for operators to make assessments regarding its general condition. This camera angle provided the operator with a vantage point similar to what they might see during a traditional ground vehicle-based inspection. However, they were less effective for surveillance because viewing the chain link fence from an angle causes a masking effect. This masking effect prevents the camera from detecting targets until they get sufficiently close, as shown in Figure 21.

Figure 21. Example of Masking Effect of Human Subject

3.4.1.1.2 Altitude

For all tests, lower altitudes provided a better vantage point than high altitudes for performing detailed inspections. Low altitudes allowed the fence to remain centered in the field of view while allowing the camera pitch to remain high enough to see the horizon. This maximized the length of the perimeter fence in the frame and minimized the blind spot below the camera's vertical field of view.

Figure 22 compares screenshots taken from recorded footage collected with the Zenmuse X5S at a variety of altitudes during tests conducted with a 0-ft offset. During these tests, the best results were achieved at altitudes of 60 ft AGL or lower. Figure 23 compares screenshots taken from recorded footage collected with the Zenmuse XT2 13mm at a variety of altitudes during tests conducted with a 30-ft offset and 30-degree horizontal camera angle. Tests conducted at a 30-ft offset produced the best results at altitudes of 40 ft AGL or lower to allow for a more direct view of the fence, thus capturing more detail needed for these inspections.

Figure 22. 0-ft Offset and 0-Degree Horizontal Camera Angles at Different AGL Altitudes from Zenmuse X5S

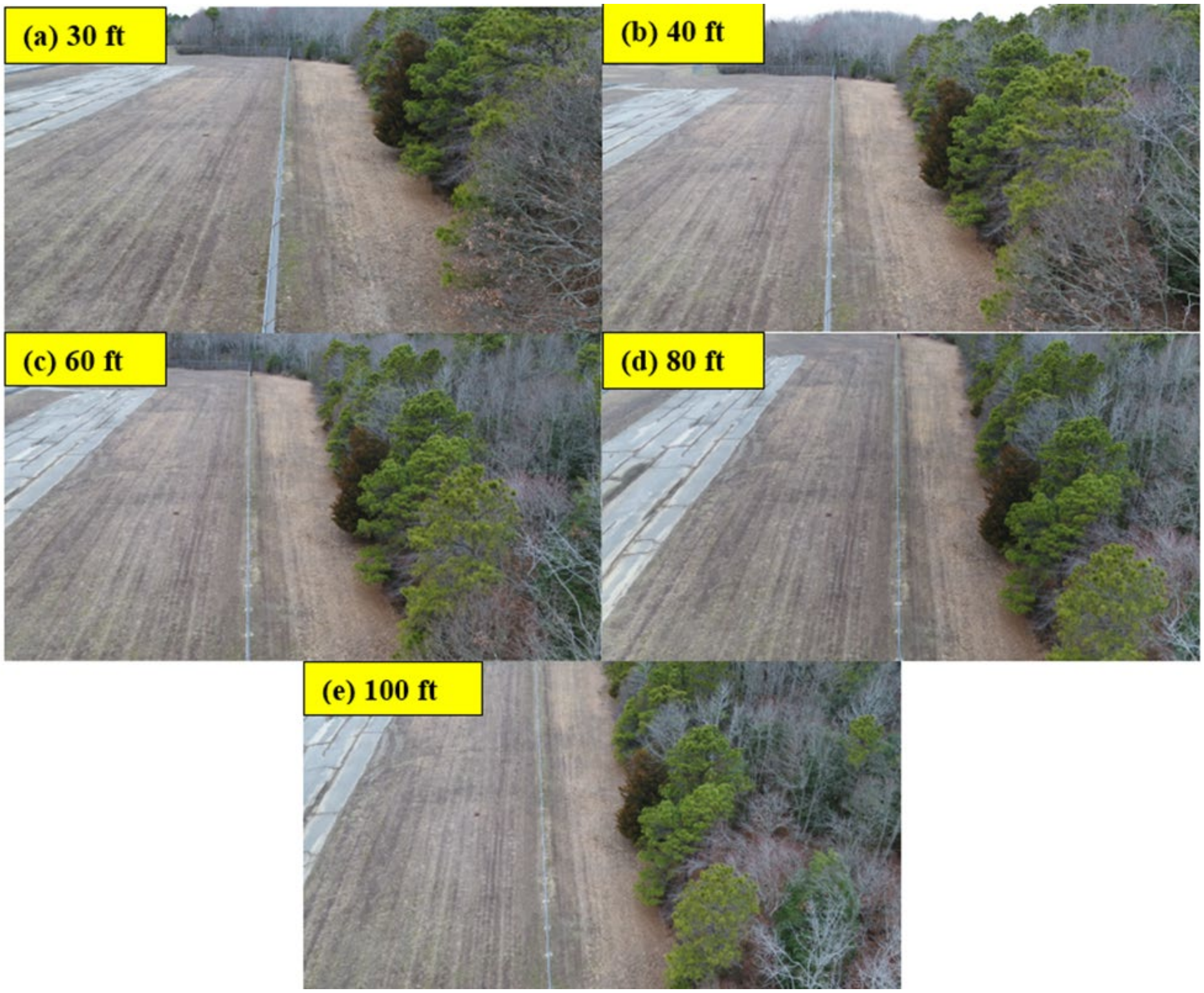

Figure 23. 0-ft Offset and 30-Degree Horizontal Camera Angle at Different AGL Altitudes from Zenmuse XT2 13mm

3.4.1.1.3 Camera Pitch

Shallow camera pitch angles (i.e., angles closer to the horizon) produced a better perspective of the fence than steeper camera angles, allowing the camera to see farther down the fence line. Situational awareness is maximized when either the horizon or the end of the fence line is in view. Steep camera angles have a similar effect on the footage as flights with a 90-degree horizontal camera angle, increasing the sense of motion and significantly reducing the amount of time any given object is in the frame. This would inherently minimize the opportunity for operations personnel to identify any anomalies. Figure 24 compares two screenshots taken with different camera pitches.

Figure 24. Camera Pitch Angles: (a) -5° Pitch from 10 ft AGL and (b) -40° Pitch from 60 ft AGL

3.4.1.1.4 Speed

All flights were conducted at a speed of 11.2 mph (5 meters per second). This speed was selected because DJI products use metric units, and typical perimeter inspections conducted from a ground vehicle are driven at a speed of 10 to 15 mph. This speed was found to be acceptable to allow UAS operators to balance the competing priorities of performing thorough inspections and completing the patrols in a timely manner.

3.4.1.2 Onboard Recorded Visual Camera Video Analysis

Figures 25 and 26 compare screenshots taken from full-resolution camera footage recorded onboard the M210 using each payload tested during Phase 1A. Each of these flights was conducted with a 30-ft offset and 30-degree horizontal camera angle at an altitude of 10 ft AGL.

Figure 25 compares screenshots of footage showing the fence and human subject. The human subject is outlined in red in each screenshot. All recorded visual camera payload videos, including those recorded at resolutions of 1080p and 4K, were acceptable for inspecting the general condition of the fence and detecting the human subject. However, due to optical limitations of the cameras, none of the footage collected provided enough detail to reliably inspect fine detail such as the individual chain links.

Figure 26 shows screenshots comparing each payload's ability to confirm that the AOA gate is closed and locked. The AOA gate latch and lock are outlined in red in each screenshot. While each video, including those recorded in resolutions of 1080p and 4K, was able to confirm that the gate was closed, none of them provided enough detail to confirm whether the gate was locked.

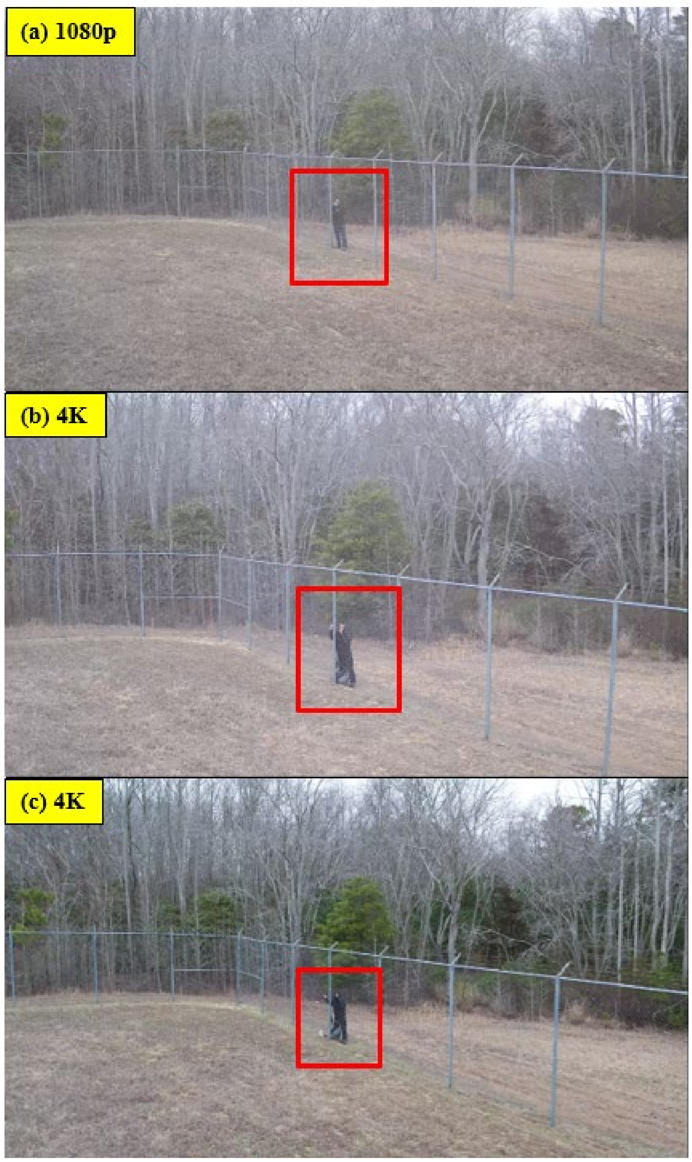

Figure 25. Recorded Visual Camera Footage of Human Subject from 10 ft AGL: (a) XT2 9mm, (b) XT2 13mm, and (c) X5S

Figure 26. Recorded Visual Camera Footage of AOA Gate from 10 ft AGL: (a) XT2 9mm, (b) XT2 13mm, and (c) X5S

3.4.1.3 Thermal Camera Analysis

Figures 27 and 28 compare screenshots taken from onboard recorded video footage from both thermal camera payloads included in Phase 1A testing in the daylight and at night. Each flight was conducted with a 0-ft offset at an altitude of 40 ft AGL. No zoom was employed during these test flights, and any perceived difference in zoom between the images is a product of differences between each camera's lens and field of view (FOV). Lighting condition does not affect thermal camera performance. The ground appears warmer during the day (higher concentration of white in the images) due to solar loading, which dissipated after dark due to the colder ambient temperature (~34 degrees Fahrenheit).

The human subject and the vehicle were used as targets and outlined in red in each of the screenshots presented in Figures 27 and 28. It should be noted that in Figure 28b, two human subjects can be seen—one on each side of the fence. Evaluators found that both thermal cameras provided adequate detail for perimeter surveillance and were able to clearly identify both the human and the vehicle in both daylight and night conditions. While the 336x256 resolution footage captured by the XT2 9mm was acceptable, evaluators agreed that the 640x512 resolution of the XT2 13mm captured more detail, particularly in the background of the scenes.

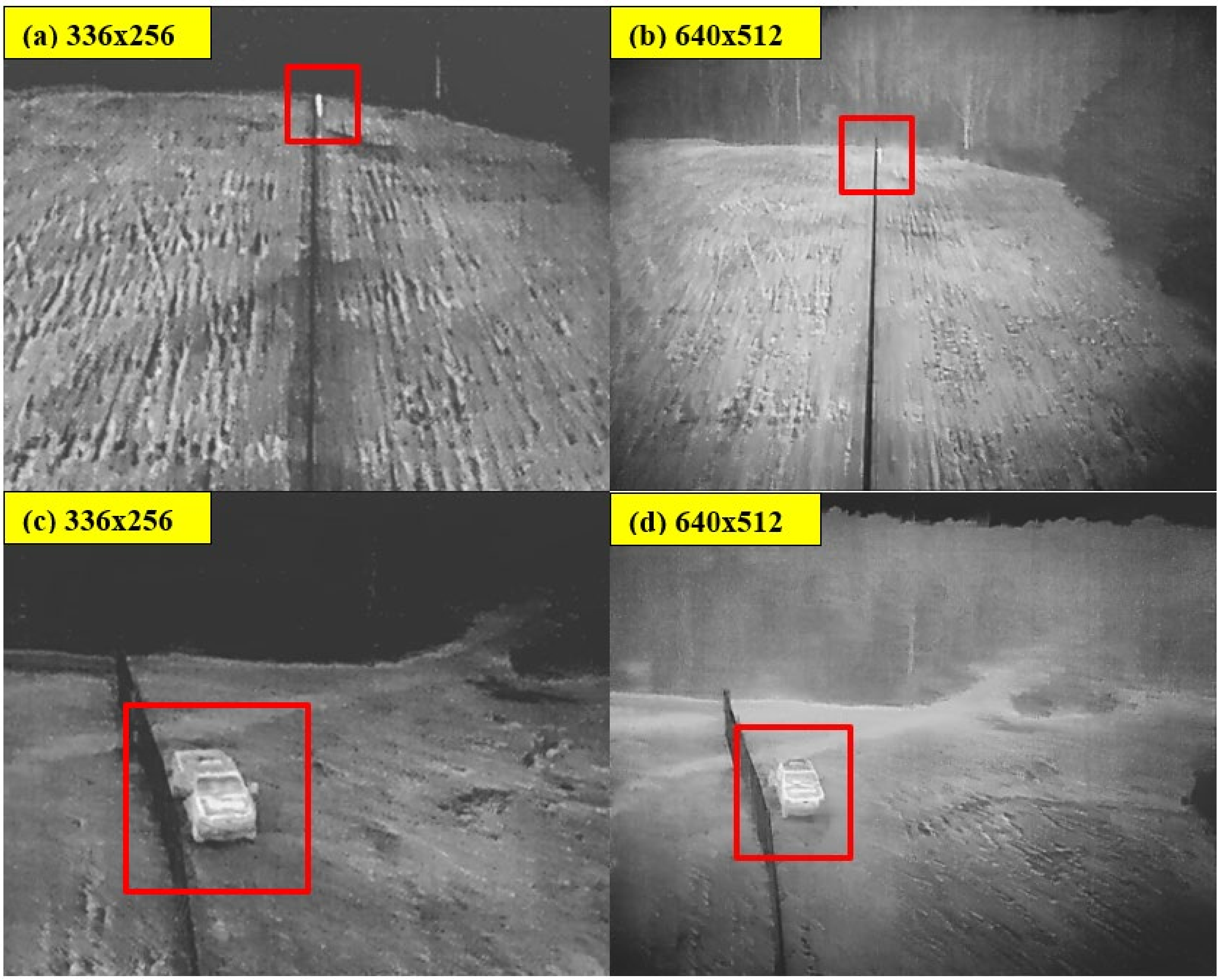

Figure 27. Daylight Thermal Camera Footage of Vehicle and Human from 40 ft AGL: (a) XT2 9mm, (b) XT2 13mm, (c) XT2 9mm, and (d) XT2 13mm

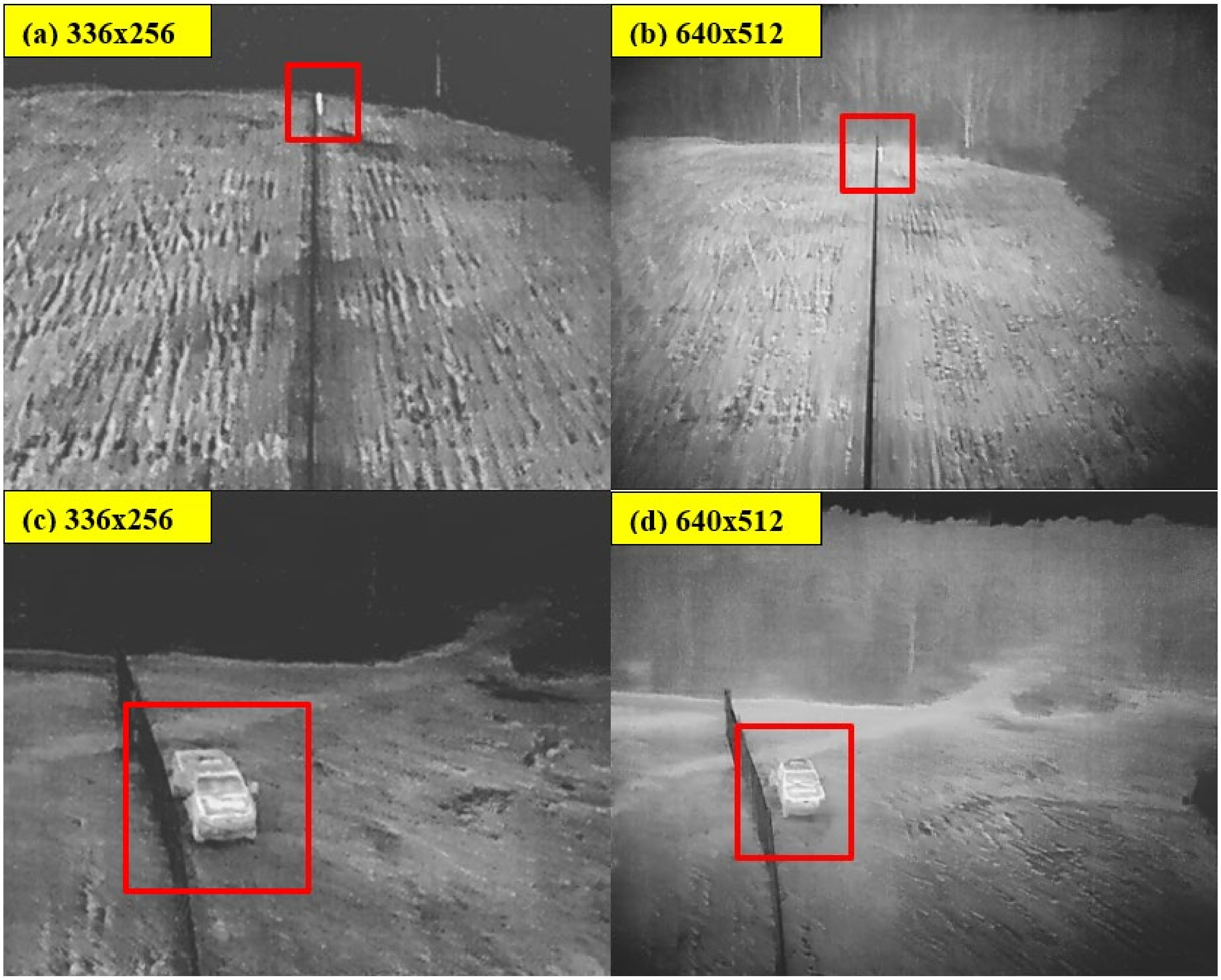

Figure 28. Night Thermal Camera Footage of Vehicle and Human from 40 ft AGL: (a) XT2 9mm, (b) XT2 13mm, (c) XT2 9mm, and (d) XT2 13mm

3.4.1.4 Live Payload Video Feed Analysis

Figures 29 and 30compare screenshots taken from live camera footage recorded on the CrystalSky GCS with the X5S and XT2 13mm payloads. Though the cameras recorded footage at a resolution of 4K, the M210 and CrystalSky displayed the live-streamed video at a resolution of 1080p. It should be noted that the live-streamed video collected using the XT2 13mm payload used a split-screen mode that simultaneously displayed both the visual and thermal camera feeds to test the usefulness of this feature and determine whether it had a negative effect on the ability to see details in the visual camera image.

Tests shown in Figure 29 were conducted with a 0-ft offset at an altitude of 30 ft AGL. As shown in these screenshots, the human subject (outlined in red) and fence line are clearly identifiable in both live streams, including the XT2 13mm side-by-side view. The split screen mode did not affect the level of detail visible in the live stream from the XT2 13mm. Both of these live-streamed videos were found to be sufficient for conducting perimeter surveillance. As expected, however, the live-streamed footage did not provide an equivalent level of clarity or detail to the onboard recorded visual camera footage.

Figure 29. Live-Streamed Footage of Human from 30 ft AGL: (a) XT2 13mm and (b) X5S

Tests shown in Figure 30 were conducted with a 30-ft offset and 30-degree horizontal camera angle at an altitude of 30 ft AGL. Both videos provided an equivalent level of detail, and the split screen mode used by the XT2 did not affect its usefulness. As shown in these screenshots, the general condition of the fence and the status of the AOA gate latch and lock (outlined in red) are visible in both live streams; however, the amount of detail in the video is limited. While both videos can provide a general view of the fence condition and can confirm that the AOA gate is closed, they do not provide enough detail to confirm that the gate is locked.

Figure 30. Live-Streamed Footage of AOA Gate from 10 ft AGL: (a) XT2 13mm and (b) X5S

3.4.1.5 Spotlight Analysis

Figure 31 shows screenshots taken from footage collected by the visual camera on the XT2 13mm payload when used in conjunction with the Z15 spotlight when observing the human subjects and vehicle. These targets are outlined in red in each screenshot. In Figure 31a, the human subject on the left was wearing a reflective vest, while the human on the right was wearing a black outfit. These tests were conducted with a 0-ft offset at an altitude of 30 ft AGL. The 10,200-lumen spotlight was effective in enhancing the visual camera's ability to detect targets in darkness, but it is not recommended in place of a thermal camera. The spotlight must be pointed almost directly at a target to adequately illuminate it, significantly limiting its usefulness in aiding target detection. In addition, using the spotlight decreased aircraft endurance by approximately 30% when compared to using the visual and thermal camera payloads alone due to power consumption. Despite this determination, FAA researchers believe the spotlight could be of use to provide illumination to airport staff on the ground if they are working in remote areas after dark.

Figure 31. Z15 Spotlight and XT2 13mm Visual Camera Performance from 40 ft AGL: (a) Human Subject and (b) Vehicle

3.4.1.6 Additional Considerations

Sections 3.4.1.6.1 through 3.4.1.6.3 provide results regarding additional technical and operational considerations for using UASs for perimeter inspections, including gimbal performance, frame rate, and data storage.

3.4.1.6.1 Gimbal Performance

During Phase 1A testing, each payload was stabilized with a 3-axis gimbal. This gimbal compensated for changes in aircraft pitch, roll, and yaw, ensuring the camera footage is smooth and level throughout the flight. This 3-axis gimbal consistently performed as expected, and all footage captured was smooth.

3.4.1.6.2 Frame Rate

Each camera captured footage at a frame rate of 30 frames per second (FPS). This is the standard frame rate used for many visual media and provided adequate clarity for both fence inspections and surveillance.

3.4.1.6.3 Data Storage

The average time to cover 0.43 SM (2,290 linear ft) was 2 minutes and 43 seconds for flights directly over the fence and 2 minutes 47 seconds for flights at a 30-ft offset from the fence. A ground vehicle traveling at the same speed would require 2 minutes and 12 seconds to complete a patrol of an equivalent length of fence. This difference was due to the extra time required by the autopilot to stop the UAS and reposition the camera gimbal at each turn in the fence line.

Table 4 shows the average file size for each type of video file. The XT2 4K video files were approximately 25% larger than the XT2 1080p HD video files. This increase in file size is caused solely by the increase in resolution; 4K video files from the X5S were 400% larger than 4K video files captured by the XT2. This is caused by the significantly larger sensor in the X5S.

Table 4. Recorded Video Resolutions and Corresponding File Sizes

File Type	Approximate File Size
Thermal Video Files	40 MB
XT2: 1920x1080 (1080p)	330 MB
XT2: 3840x2160 (4K) Resolution	415 MB
X5S: 3840x2160 (4K) Resolution	2,000 MB

3.4.2 Phase 1B

Sections 3.4.2.1 through 3.4.2.5 present the results from Phase 1B UAS testing. The results address evaluations of flight parameters, payload performance, live-streamed video performance, and additional considerations.

3.4.2.1 Flight Parameter Analysis

- 0-ft Offset, 0-Degree Horizontal Camera Angle

  Testing during Phase 1B validated the finding from Phase 1A that flights conducted directly over the fence (0-ft offset) with a 0-degree horizontal camera angle were most effective for providing situational awareness of both sides of the perimeter when patrolling for unauthorized persons or vehicles. Testing during Phase 1B also demonstrated this flight configuration's usefulness in locations where obstructions near the fence line (such as trees or structures) prevented the use of flight plans with a greater offset at low altitudes, such as in Test Area 3.

  Figure 32 shows an example screenshot from a 0-ft offset flight in Test Area 3. This flight was conducted at an altitude of 100 ft AGL due to the presence of tall trees adjacent to and directly over the fence line. While the condition of the side of the fence cannot be seen, the footage was able to allow evaluators to detect the human and vehicle targets and a fallen tree resting on the fence.

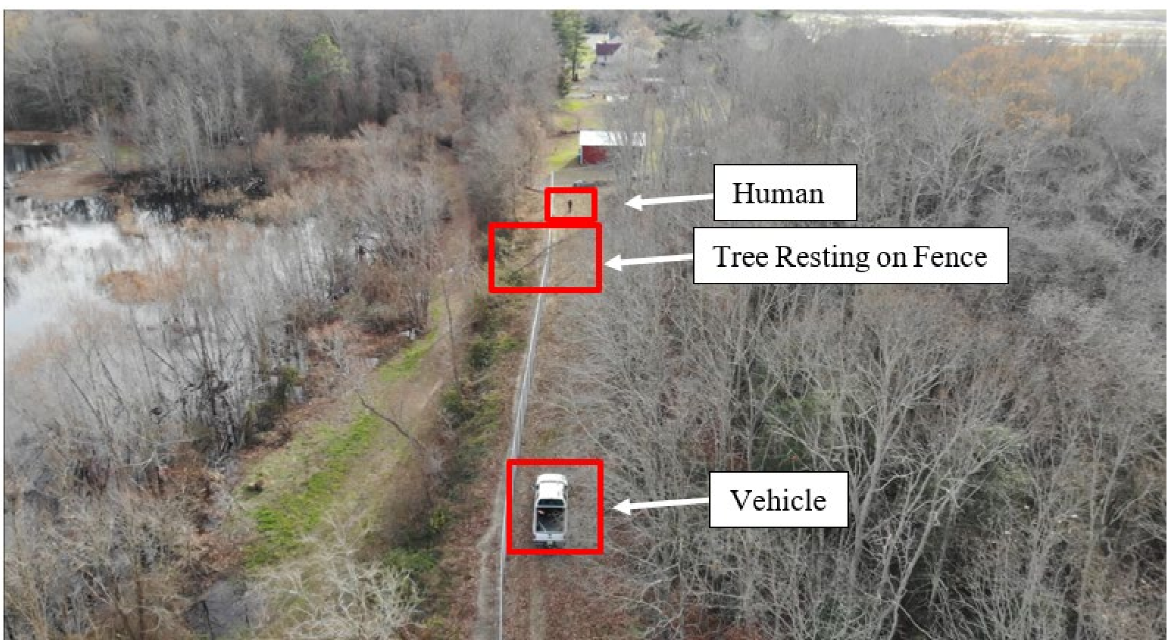

Figure 32. 0-ft Offset, 0-Degree Horizontal Camera Angle, 100 ft AGL Flight

- 30-ft Offset, 30-Degree Horizontal Camera Angle

  Phase 1B validated the finding that flights conducted at a 30-ft offset with a 30-degree horizontal camera angle are effective for conducting fence inspections and provide the greatest benefit when the fence cannot be easily viewed from the ground. Figure 33 compares the view of the fence line in Test Area 2 from the ground and from the UAS. This fence line cannot be easily viewed from the ground, as shown in Figure 33(a), due to the presence of dense vegetation and a trench on its immediate interior. Figure 33(b) shows this same section of fence as seen by the UAS payload at an altitude of 20 ft AGL with a 30-ft offset and a 30-degree horizontal camera angle. Evaluators found that the UAS greatly enhanced the ability of operations personnel to inspect the condition of the fence line.

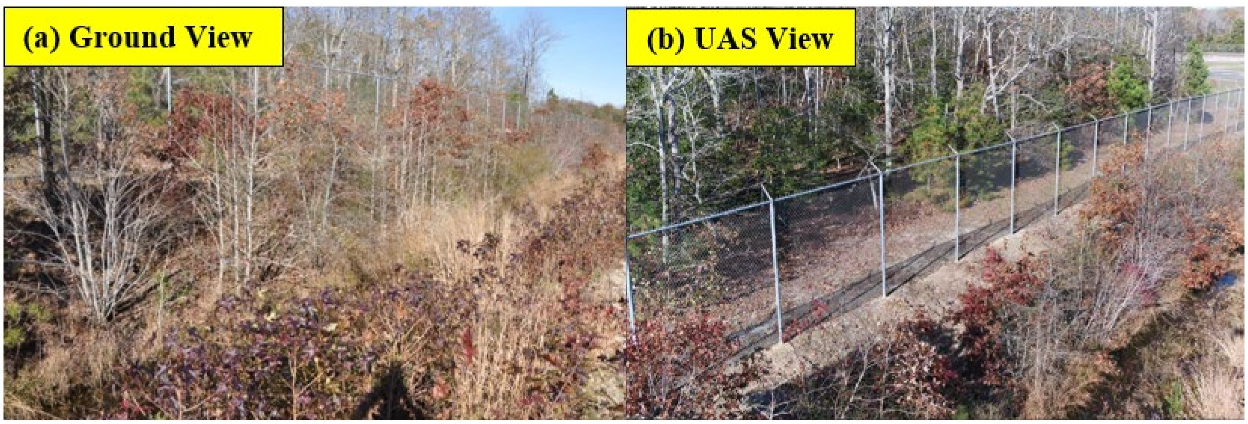

Figure 33. Test Area 2 Fence Line from a 30-ft Offset: (a) From the Ground and (b) From the UAS at 20 ft AGL

3.4.2.2 Onboard Recorded Visual Camera Analysis

Figures 34, 35, and 36 compare screenshots taken from full-resolution camera footage recorded using each payload tested during Phase 1B. Each flight was conducted with a 30-ft offset and 30-degree horizontal camera angle at an altitude of 20 ft AGL. All footage was collected without zoom; therefore, any perceived difference in zoom level is a product of differences between each camera's lens and FOV.

Figure 34 shows screenshots taken from footage captured in Test Area 1 to compare the ability of each payload to assess the state of the AOA gate and detect the bolt cutters. The AOA gate latch and bolt cutters are outlined in red in each screenshot. Evaluators found that all recorded visual camera payload videos, including those recorded at resolutions of 1080p and 4K, were able to identify the bolt cutters and confirm that the AOA gate was closed. However, none of the payloads collected footage with enough detail to confirm whether the gate was locked, only that it was closed.

Figure 35 compares screenshots taken from footage observing a ladder and blanket on the fence in Test Area 2. These items have been outlined in red in each screenshot. All recorded visual camera payload videos, including those recorded at resolutions of 1080p and 4K, were found to be acceptable to clearly detect and identify the ladder and blanket on the fence line.

Figure 36 compares screenshots taken from footage observing the erosion underneath the fence in Test Area 1. Each test was conducted at a 30-ft offset and 30-degree horizontal camera angle at 20 ft AGL. Upon reviewing the recorded video footage, evaluators found that none of the videos, including those recorded at resolutions of 4K and 1080p, were able to provide enough detail to reasonably expect those viewing the video to consistently identify areas with erosion. Evaluators concluded that this inability to clearly see the eroded area was due equally to the camera angle and the capabilities of the payloads. Because the erosion occurred at ground level, lower flight altitudes and shallower camera angles would be more effective to view the gap between the bottom of the fence and the ground. From an elevated view, the ability to discern the distance from the bottom of the fence to the ground is dependent on various factors, including lighting, the color of the fence, and the color of the ground.

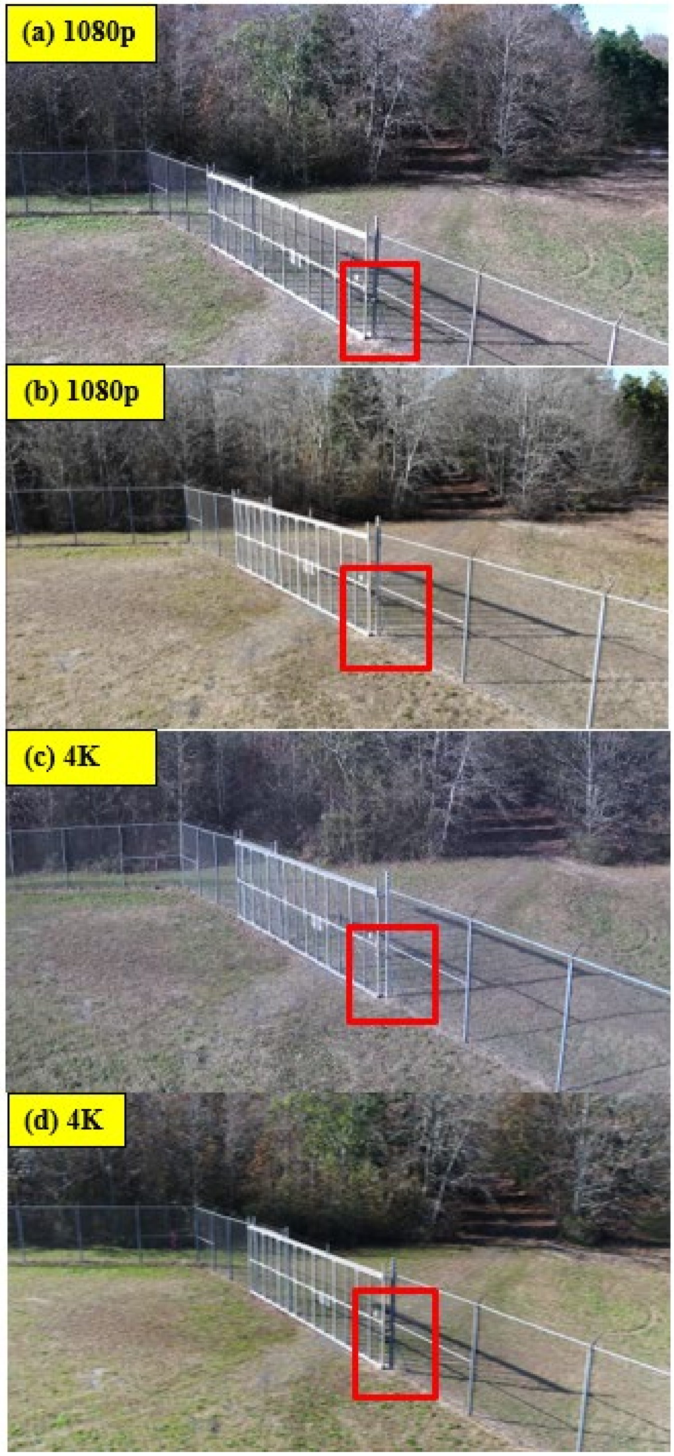

Figure 34. Recorded Visual Camera Footage of AOA Gate from 20 ft AGL: (a) Z30, (b) M2ED, (c) XT2 9mm, and (d) X5S

Figure 35. Recorded Visual Camera Footage of Ladder and Blanket from 20 ft AGL: (a) Z30, (b) M2ED, (c) XT2 9mm, and (d) X5S

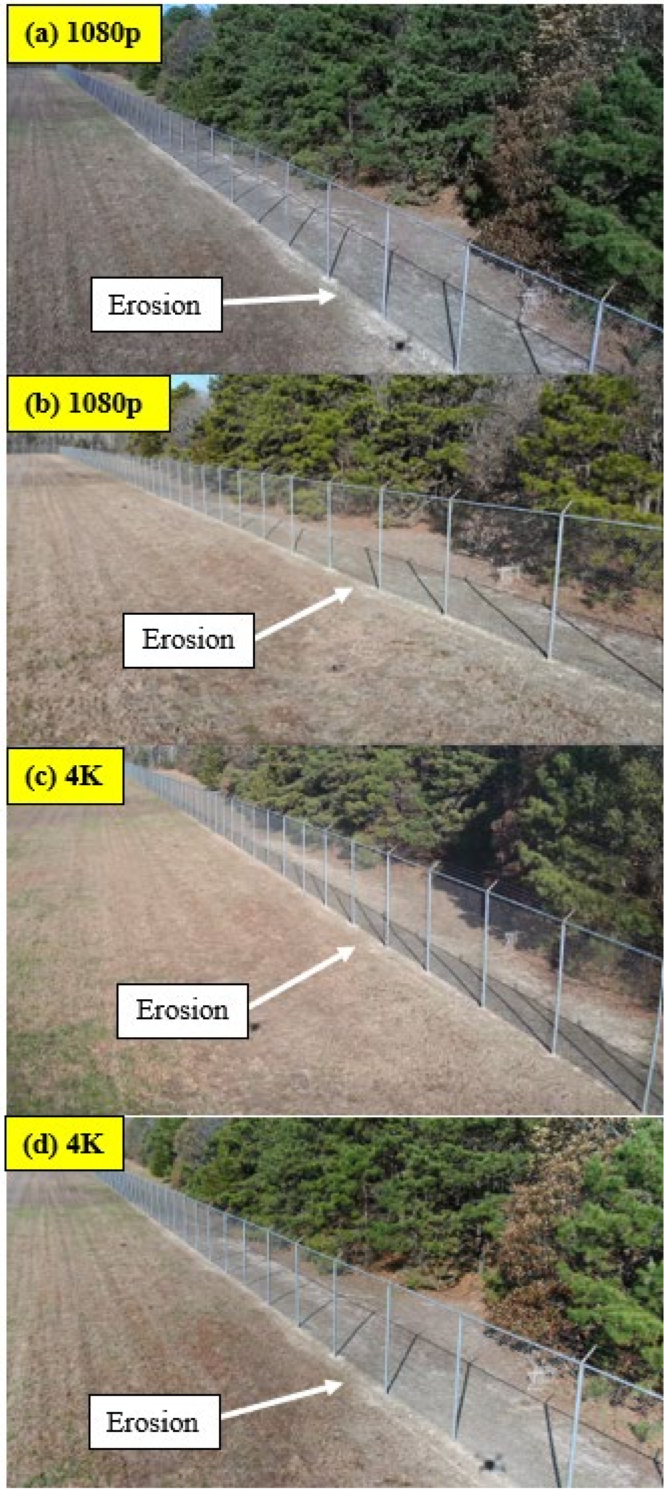

Figure 36. Recorded Visual Camera Footage of Erosion under Fence from 20 ft AGL: (a) Z30, (b) M2ED, (c) XT2 9mm, and (d) X5S

3.4.2.3 Thermal Camera Analysis

Figure 37 compares screenshots taken from recorded footage from each thermal camera payload used in Phase 1B testing when observing a vehicle target in Test Area 3. The vehicle is outlined in red in each screenshot. These tests were conducted at a 0-ft offset at an altitude of 100 ft AGL. This altitude was used to remain clear of the trees present on both sides of the fence in this test area. No zoom was employed during these test flights, and any perceived difference in zoom between the images in Figure 37 is a product of differences between each camera's lens and FOV.

Evaluators overwhelmingly agreed that the footage from the 160x120 thermal camera on the M2ED, shown in Figure 37(a), was not suitable for perimeter inspections. While the heat signature from the vehicle is present, it is not of sufficient resolution to clearly identify from where the heat signature is emanating.

Each of the XT2 sensors, including the XT2 9mm recording at a resolution of 336x256 (shown in Figure 37(b)), and the XT2 13mm, 19mm, and 25mm payloads recording at resolutions of 640x512 (shown in Figure 37(c-e)), were adequate to allow for the detection of the vehicle. However, the 640x512 resolution thermal cameras provided significantly more detail than the lower resolution sensors, especially in areas of dense vegetation and in the background of the scene. This increased resolution allowed for the quicker detection and identification of the vehicle, significantly more detail, and the ability to discern increased detail on the fence, including the vertical poles.

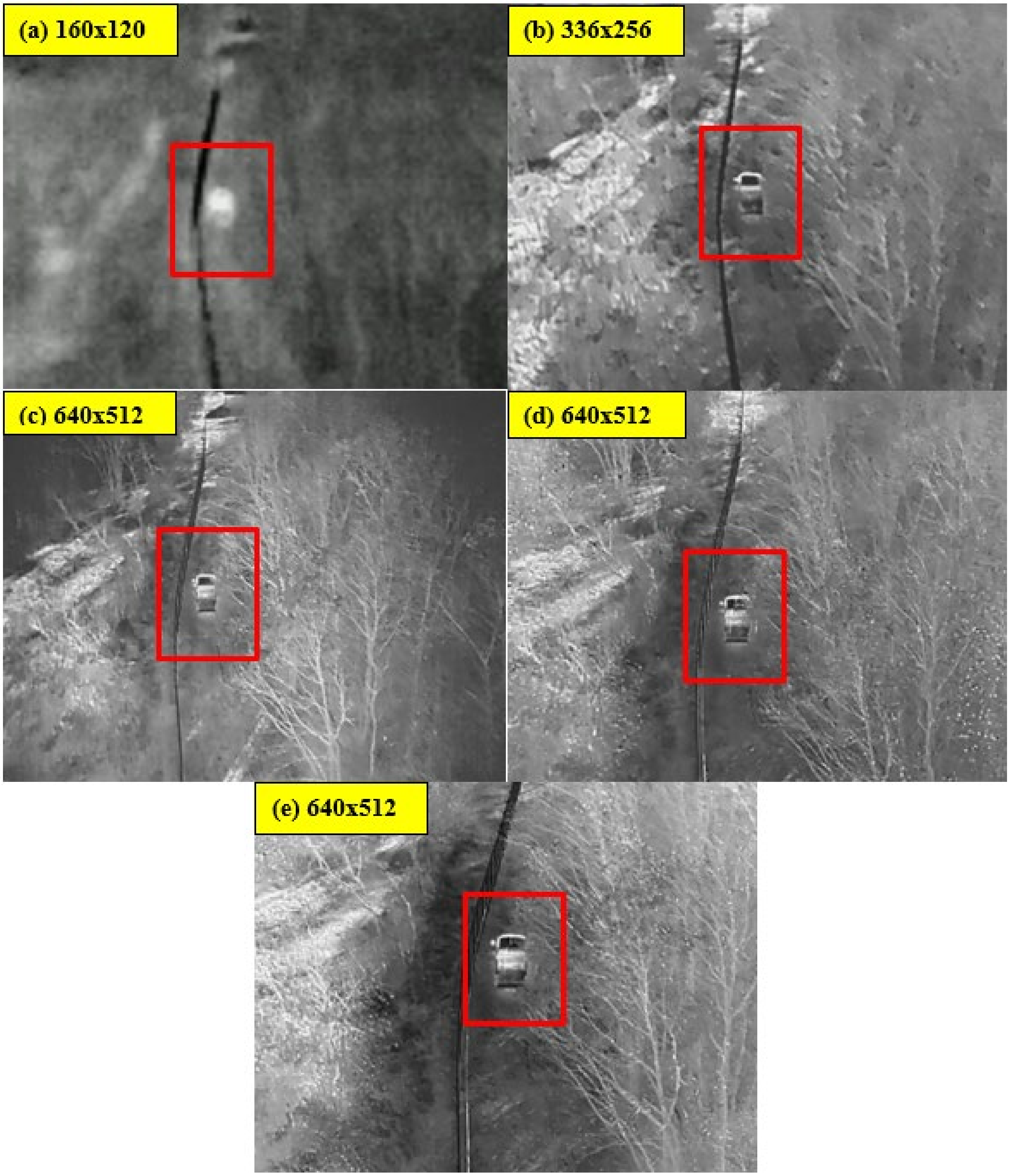

Figure 37. Thermal Camera Performance, 100 ft AGL: (a) M2ED, (b) XT2 9mm, (c) XT2 13mm, (d) XT2 19mm, and (e) XT2 25mm

Figure 38 compares screenshots taken from recorded footage from each thermal camera payload used in Phase 1B testing when observing a human subject in Test Area 2. The human subject is outlined in red in each screenshot. These tests were conducted with a 30-ft offset and 30-degree horizontal camera angle at an altitude of 100 ft AGL. No zoom was employed during these test flights, and any perceived difference in zoom between the images in Figure 38 is a product of differences between each camera's lens and FOV.

The results from the evaluation of these videos mirrored those of earlier comparisons. Evaluators again agreed that the footage from the 160x120 thermal camera on the M2ED, shown in Figure 38(a), was not suitable for perimeter inspections. Few details in the footage could be discerned, and the resolution was not sufficient to clearly identify the human subject.

Each XT2 sensor, including the XT2 9mm recording at a resolution of 336x256 (shown in Figure 38(b)), and the XT2 13mm, 19mm, and 25mm payloads recording at resolutions of 640x512 (shown in Figure 38(c–e)), provided enough detail to consistently detect the human subject. However, similar to results shown in Figure 37, the 640x512 resolution thermal sensors allowed for quicker detection and identification of the human subject, and greatly enhanced detail in the background of the scenes. FAA researchers found that this detail could be invaluable if attempting to locate an individual near the perimeter who might be attempting to evade detection. For these reasons, the 640x512 was found to be the recommended resolution for thermal camera payloads utilized for perimeter inspections and surveillance in low-light conditions.

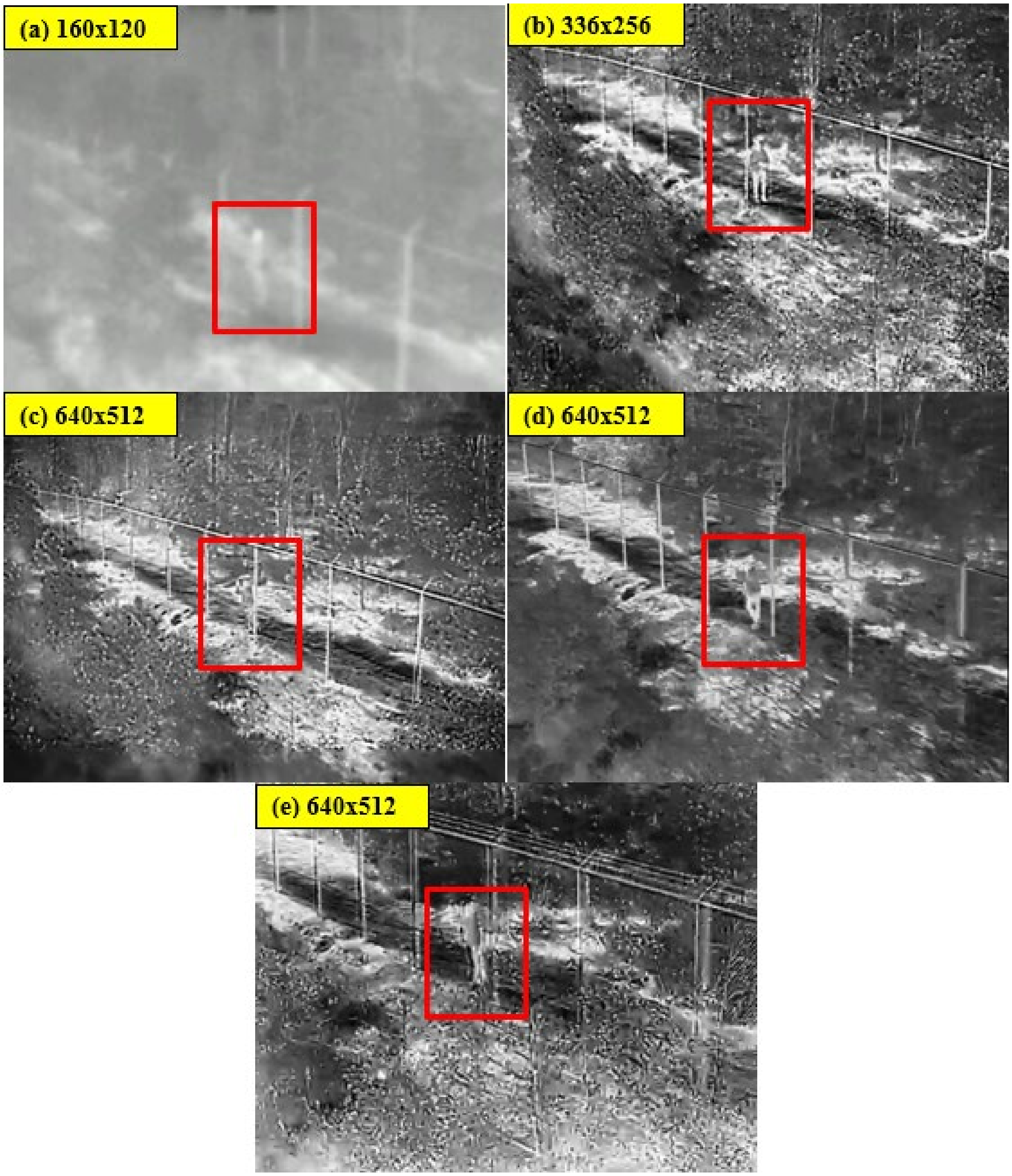

Figure 38. Thermal Camera Performance, 20 ft. AGL: (a) M2ED, (b) XT2 9mm, (c) XT2 13mm, (d) XT2 19mm, and (e) XT2 25mm

3.4.2.4 Live Payload Video Feed Analysis

Figure 39 compares screenshots taken from live camera footage of the eroded area beneath the fence recorded on the CrystalSky GCS with the Z30, XT2 13mm, and X5S payloads. Each test was conducted at a 30-ft offset and 30-degree camera angle at an altitude of 20 ft AGL. The eroded area is outlined in red in each screenshot. Though each live video was streamed at a maximum resolution of 1080p (actual resolution is variable based on signal strength between the UA and GCS), this comparison included the Z30, streamed at its native 1080p resolution (shown in Figure 39(a)); the X5S, which was downsized from its native 4K resolution (shown in Figure 39(c)); and the XT2 13mm, which was downsized from its native 4K resolution and further reduced to allow for split screen viewing (shown in Figure 39(b)). This split-screen mode was employed to test the usefulness of this feature and determine whether it had a negative effect on the ability to see details in either image. It should be noted that live-stream video files from the M2ED were corrupted prior to evaluation, preventing their inclusion in this comparison.

Figure 39. Live-Streamed Camera Footage of Erosion from 20 ft AGL: (a) Z30, (b) XT2 13mm, and (c) X5S

All live-streamed visual camera payload videos included in this comparison were found to be acceptable for general perimeter fence inspections, including those that were live-streamed at their native 1080p resolution (Z30), those that were downsized from a native resolution of 4K (X5S), and those that were downsized and viewed in split screen mode (XT2 13mm). Each video provided a near equivalent level of detail. However, despite being deemed acceptable for general inspection purposes, none of the videos provided sufficient detail to allow for the detection of the erosion beneath the fence.

3.4.2.5 Additional Considerations

Sections 3.4.2.5.1 through 3.4.2.5.3 address additional technical and operational considerations for using UASs for perimeter inspections, including sun angle, frame rate, and image blending technology.

3.4.2.5.1 Sun Angle

When the payload is pointed in the direction of the sun, it can become overexposed, washing out the image and significantly degrading the quality of the footage. Payloads collected higher quality footage when pointed away from the sun. Figure 40 shows a comparison of the same section of fence, as seen by the XT2 9mm payload, viewed from opposite directions to illustrate the effect of the sun on the footage.

Figure 40. Effect of Sun Angle: (a) Facing Away from the Sun and (b) Facing Toward the Sun

3.4.2.5.2 Frame Rate

Each camera captured footage at a frame rate of 30 FPS. This was acceptable and provided adequate clarity for both fence inspections and surveillance flights.

3.4.2.5.3 Image Blending

The M2ED offers the capability to augment the thermal camera footage by blending the thermal camera feed with the visual camera feed. Figure 41 compares the raw thermal footage with the blended thermal and visual footage while viewing a vehicle in Test Area 3. Figure 42 shows a similar comparison while viewing a human subject in Test Area 2. While this technology proved useful for increasing the M2ED payloads' ability to provide useful thermal camera footage, the video quality still lacks the detail of higher resolution thermal cameras.

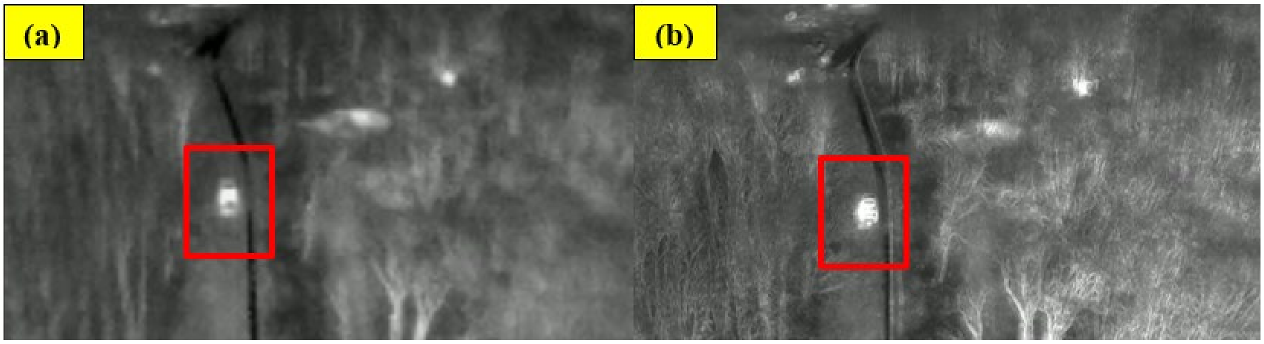

Figure 41. (a) M2ED Thermal and (b) Blended Thermal/Visual Footage of Vehicle Target

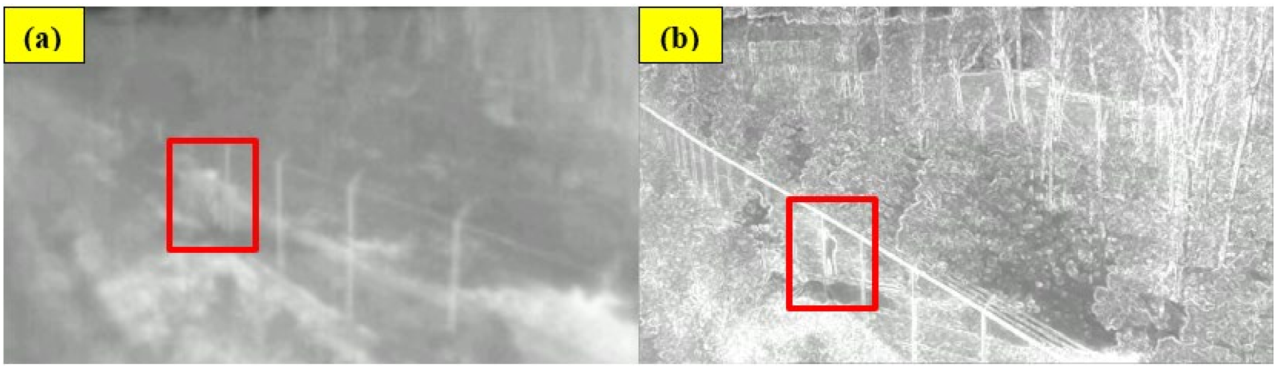

Figure 42. (a) M2ED Thermal and (b) Blended Thermal/Visual Footage of Human Subject

3.5 PHASE 1 FINDINGS SUMMARY

This section presents the findings from Phase 1 UAS testing at WWD. The findings address the overall use of UAS for airport perimeter inspections and surveillance, flight parameters, and payload performance.

Overall Findings:

- UASs were found to be capable of capturing footage that could be used to supplement a general inspection of airport perimeter fencing or surveilling for unauthorized persons and vehicles in daylight and twilight conditions. A general inspection of the fence includes observing the condition of the fence to ensure that there are no collapsed sections, that no objects or debris such as fallen trees are resting on the fence, and that the barbed wire is intact.
- UASs provided the most benefit for perimeter inspections when collecting video with a visual camera payload in hard-to-reach areas where the fence cannot be easily viewed using traditional ground-based techniques.
- UASs provided the most benefit for surveillance patrols when collecting video with a thermal camera payload after dark.
- The level of detail visible in both recorded and live payload feeds is limited and does not meet the level of detail that is visible when conducting an in-person inspection on foot or

in a vehicle. This limitation prevented UAS footage from discerning whether AOA gate locks were latched, erosion was present underneath the fence, or the chain links had minor damage.

Flight Parameters:

- For daylight fence inspections, flights with a 30-ft offset from the fence line and ~30-degree horizontal camera angle produced the most useful results. Altitudes of 30 ft AGL or lower provided the most useful footage in this flight configuration.
- UAS flights directly over the fence (0-ft offset) focused forward provided the greatest overall situational awareness for general surveillance purposes during daylight, twilight, and night conditions. This flight plan is also useful in areas where obstructions near the fence prohibit the use of flights at an offset. This flight configuration provided a limited view of the fence, however, and is not as suitable for fence inspections as flights conducted at an offset. Significant damage and major security concerns, such as trees resting on the fence, collapsed sections, and open gates could still be seen from this vantage point. Flights conducted at a 0-ft offset provided the most useful footage when conducted at altitudes of 60 ft AGL and lower.
- Tests conducted with a 30-ft offset and 90-degree horizontal camera angle were not found to be suitable for conducting perimeter inspections or surveillance. This flight configuration resulted in a significantly smaller portion of the perimeter visible in the camera frame at a given time when compared to the other flight plans tested. Due to the smaller portion of the fence visible in each frame, test targets were captured in the video for a shorter amount of time, decreasing the chance for those reviewing the footage to make a detection. In addition, the 90-degree horizontal camera angle resulted in an increased sense of motion that caused blurring of the video, therefore degrading the level of detail visible.
- Proper camera pitch is essential to situational awareness. The camera pitch should be positioned to keep the fence centered in the frame and the horizon in view at all times. This ensures that any targets, anomalies, or damage to the fence are detected as soon as possible, and remain in the frame for the greatest amount of time.
- Lower altitudes provided the greatest situational awareness. Low altitudes allow the camera pitch to remain high enough to see the horizon and center the fence within the frame while minimizing the blind spot below the camera's vertical FOV.
- All flights were conducted at a speed of 11.2 mph (5 meters per second). This was found to be an acceptable speed to allow UAS operators to balance the competing priorities of performing thorough inspections and completing the patrols in a timely manner.
- It is recommended to operate the UAS so that the sun is facing the rear of the aircraft to minimize glare and reduce the impact of shadows on the footage.

Payload Performance:

- Visual cameras with a minimum recorded resolution of 1080p (1920x1080) were acceptable for conducting fence inspections and provided the best combination of quality and file size. The 4K footage provided a greater amount of detail but resulted in much larger file sizes, and, therefore, should only be captured if the operator anticipates conducting analysis of the footage after the mission and has accounted for the increased file sizes.

- Thermal cameras with a minimum resolution of 640x512 are recommended for detecting people and vehicles near the fence.
- A live video-streaming resolution of 1080p (1920x1080) was acceptable for all payloads.
- Payloads capable of blending visual and thermal camera feeds improved the clarity of thermal camera footage, but this capability did not provide an adequate substitute for a higher-resolution thermal camera in low-light conditions.
- The 10,200-lumen spotlight payload was capable of adequately lighting the subject area in night conditions, providing some benefit for night operations when viewed with a visual camera; however, usage is only recommended for special cases (such as inspecting damage to a fence at night) because it significantly reduces battery life and does not provide as much situational awareness as a thermal camera payload.
- A frame rate of 30 FPS was acceptable for ensuring smooth and clear footage during UAS perimeter patrols.
- The 3-axis gimbals provided consistent and smooth video that compensated for aircraft changes in roll, pitch, and yaw during data collection.

4. PHASE 2 TESTING

Phase 2 testing leveraged the findings from Phase 1 at WWD and conducted additional UAS test efforts at three additional towered airports in controlled airspace: TYS, SAV, and CVG. The goal of Phase 2 was to further develop and refine the minimum technology performance specifications and operational recommendations for UAS platforms, payloads, and GCS when conducting perimeter inspections and surveillance.

Similar to Phase 1, Phase 2 UAS testing consisted of 57 UAS test flights along perimeter and AOA fence lines during daylight, twilight, and night conditions while collecting visual and thermal camera footage. Phase 2 UAS testing used the most effective flight parameters and payloads identified during Phase 1. Following data collection, the footage was internally reviewed by FAA researchers and was presented to subject matter experts (SMEs) and stakeholders at each airport for evaluation.

During data collection, airport operations and perimeter security SMEs viewed a deployment demonstration of each UAS platform to evaluate their portability and practicality. SMEs also observed each UAS platform during testing to evaluate various hardware characteristics such as GCS screen size and brightness.

Phase 2 UAS testing consisted of three test efforts conducted at TYS, SAV, and CVG. These airports were selected due to their varied environments and sizes, which facilitated the comprehensive analysis and validation of flight parameters, technical and operational considerations, and UAS and payload features and performance specifications for using UASs to conduct perimeter inspections.

4.1 UNMANNED AIRCRAFT SYSTEM PLATFORMS AND PAYLOADS

Sections 4.1.1 through 4.1.2 describe the UAS platforms, payloads, GCSs, and additional equipment used to conduct Phase 2 testing.

4.1.1 Unmanned Aircraft System Platforms

The following UAS platforms were used during Phase 2 testing:

- DJI M210
- DJI M2ED
- Parrot ANAFI USA

These UAS platforms are shown in Figure 5. A comparison of key specifications for each UAS used during Phase 2 testing is presented in Table 1. In-depth platform specifications are presented in Appendix A.

During Phase 2 testing, the DJI M210 and DJI M2ED were operated with the same GCSs as Phase 1. These are the DJI Cendence controller and CrystalSky display and the DJI Smart Controller. The Parrot ANAFI USA used the Parrot Skycontroller 3 with iPad Mini® display, which is pictured in Figure 6. Table 2 compares specifications for these GCSs.

4.1.2 Payloads

The following camera payloads were used to collect footage during Phase 2 UAS testing at ACY:

- DJI Zenmuse Z30 (visual camera)
- DJI Zenmuse XT2 9 mm (visual and thermal camera)
- DJI Zenmuse XT2 13 mm (visual and thermal camera)
- DJI Zenmuse XT2 19 mm (visual and thermal camera)
- DJI Zenmuse XT2 25 mm (visual and thermal camera)
- DJI M2ED Integrated Camera (visual and thermal camera)
- Parrot ANAFI Triple Integrated Camera (dual visual cameras and one thermal camera)

The DJI camera payloads included in this testing are pictured in Figure 7 in Section 3.2.3. Table 3 compares key specifications of each payload used during Phase 2. Detailed specifications for each payload are presented in Appendix B.

In addition to providing diversity beyond DJI products, the Parrot ANAFI USA platform was selected for testing due to the features of its ANAFI Triple payload. With the introduction of new models, UAS and thermal camera manufacturers are introducing their products in two resolutions:

640x512 and 320x256. The ANAFI Triple's thermal sensor, with its resolution of 320x256, allowed FAA researchers to evaluate this increasingly popular resolution.

To increase efficiency and reduce redundancy, the XT2 19mm and XT2 25mm payloads were not included in testing because they collect thermal and visual footage with the same sensors and at the same resolutions as the XT2 13mm payload.

4.2 TEST METHODS AND PROCEDURES

Phase 2 UAS testing followed a similar approach to Phase 1. UAS testing was conducted using preprogrammed flight plans while collecting recorded and live-streamed video. In addition, FAA researchers performed deployment demonstrations of each UAS platform while airport operations personnel and SMEs observed and evaluated various aspects of each UAS. Following each test effort, select video footage was presented to these SMEs for further evaluation. Sections 4.2.1 through 4.2.4 provide more detail on the test methods and procedures employed during Phase 2.

4.2.1 Unmanned Aircraft System Platform Evaluations

During each Phase 2 test effort, operations personnel from each airport accompanied FAA researchers to observe the flight operations. Deployment demonstrations of each UAS platform were conducted to allow airport security SMEs to observe and evaluate the hardware. These demonstrations included the entire preflight procedure, including unpacking and assembling the UAS and GCS. Once each UAS was ready for flight, participants were given an opportunity to handle the controller and view the payload feed on the GCS screen. The UASs remained on the ground while participants handled the controller. The demonstrations concluded with brief flights so SMEs could evaluate the flight stability of each platform. Following these demonstrations, each observer filled out an equipment evaluation questionnaire that addressed ease-of-use and practicality considerations such as GCS screen brightness, aircraft preflight preparation, manpower required, and deployment time.

4.2.2 Internal UAS Flight Testing Video Assessments

Following the completion of each test effort, recorded and live-streamed video from each test flight were collected and analyzed to determine and validate which combinations of factors provided the greatest situational awareness and detail for conducting perimeter inspections and surveillance in each airport's environment.

4.2.3 Post-Flight Questionnaires

Following the internal analysis by FAA researchers, selected footage was presented to SMEs and airport stakeholders for evaluation during onsite debriefs conducted at each Phase 2 airport. While viewing this footage, the SMEs and stakeholders responded to an additional post-flight questionnaire that asked participants to assess the overall quality and usefulness of each video sample and prompted them to provide additional comments that might be of use to researchers. Questionnaire data were compiled and analyzed to validate previous findings and to extract additional findings relating to technical and operational considerations that could not be inferred solely from the video.

4.2.4 Safety and Coordination

Phase 2 UAS testing followed all the safety and coordination procedures from Phase 1 described in Section 3.3.5. All UAS operations during Phase 2 were conducted in accordance with the regulations of Title 14 CFR Part 107 and FAA-approved airspace authorizations.

4.3 PHASE 2 TESTING: MCGHEE TYSON AIRPORT

Initial Phase 2 UAS testing was conducted at TYS near Knoxville, Tennessee. TYS is a towered public use airport located in Class C airspace. Certificated under 14 CFR Part 139, TYS services an average of more than 300 aircraft operations per day including commercial, military, air taxi, and general aviation traffic.

TYS was selected for UAS testing because it is the location of the National Safe Skies Alliance Perimeter Test Facility (PTF). The National Safe Skies Alliance is an FAA-funded nonprofit organization that has been conducting independent research regarding airport security technologies and procedures since 1997. To assist with their research, Safe Skies maintains a PTF at TYS, with a variety of mock AOA fencing types that provided an ideal location to perform perimeter inspections and UAS testing in controlled airspace. In addition, the Safe Skies staff at the PTF were available to provide key insights regarding airport perimeter inspections. An aerial photo of TYS showing the location of the PTF is pictured in Figure 43.

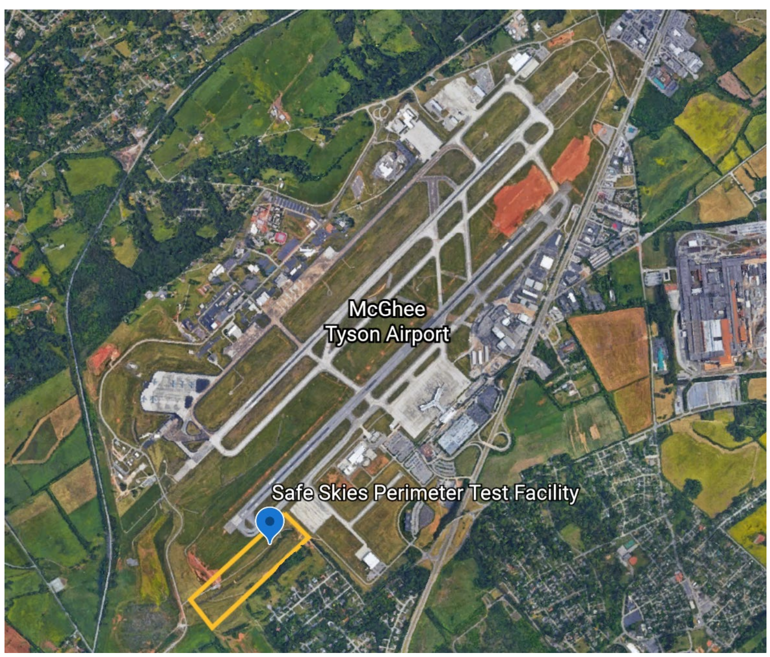

Figure 43. Safe Skies Perimeter Test Facility at TYS

4.3.1 Test Area

Testing at TYS was conducted at the PTF, located on the southwest corner of the property. The PTF includes approximately 1,000 ft of test fencing consisting of eight different lengths of fence with varying characteristics. This test fence is pictured in Figure 44.

Figure 44. Fence Line in the Safe Skies PTF

The perimeter test fencing in the PTF was constructed from galvanized steel, ranged in height from 7 ft to 12 ft tall, and included examples with existing intentional damage and with and without barbed wire and vinyl coating. Figure 45 shows examples of the PTF fencing.

Figure 45. Examples of Fencing in the PTF

4.3.1.1 Site Setup

To evaluate the performance of each payload and validate the efficacy of flight parameters, test targets were placed near the PTF fence line prior to data collection. These targets were used to evaluate the capabilities of various visual and thermal camera payloads. These test targets included:

- Vehicles, including a golf cart and pickup truck
- Human subjects
- Shovels

Similar to the approach used during Phase 1, the vehicle and human subjects were selected as test targets to simulate a potential attempted breach of the perimeter. Because these targets emit heat radiation, they were used to evaluate thermal camera payloads during flights in low-light conditions. The shovels were selected as targets to simulate leftover evidence of a past perimeter breach. Figure 46 shows examples of the test targets used at TYS.

Figure 46. McGhee Tyson Airport Test Targets: (a) Vehicles and (b) Shovels

In addition to the targets placed in the test area, the fence line observed during testing at TYS included a section of fence with two preexisting vertical cuts through the chain links. This section of fence is pictured in Figure 47. This damage was used to evaluate each UAS payload's capability to capture fine details during perimeter inspections.

Figure 47. Damaged Test Fence at TYS

Figure 48 shows an overview of the test layout used at TYS, including the locations of the various test targets and fence line.

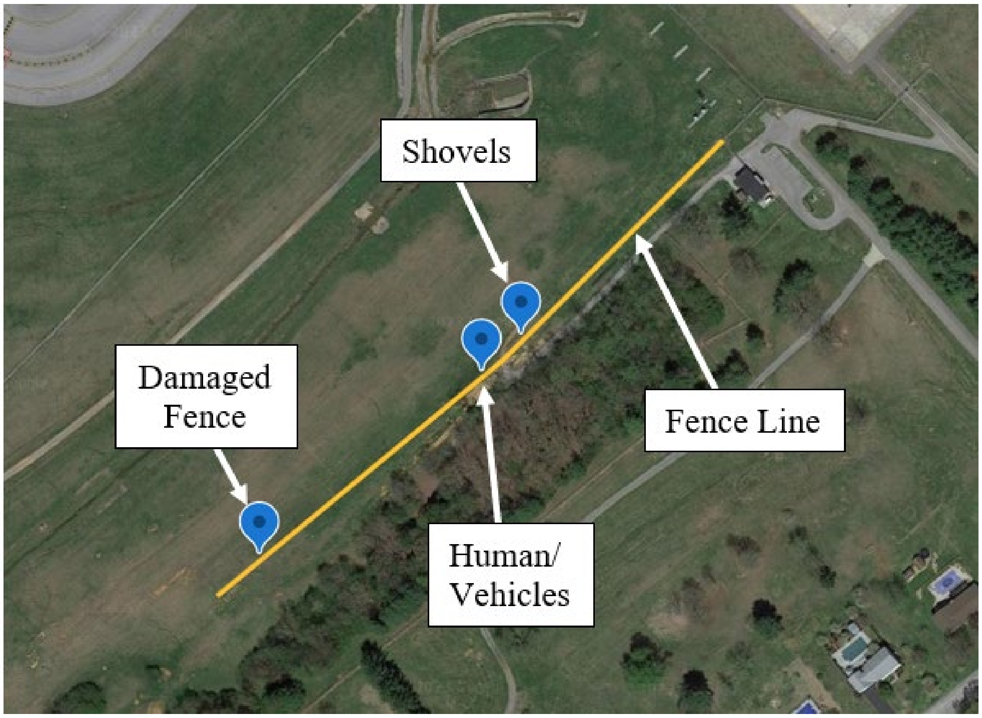

Figure 48. Overview of Test Layout

4.3.2 Test Parameters

Testing at TYS focused on evaluating minimum recorded video resolution requirements for visual and thermal cameras. In addition, this test effort sought to evaluate the performance of visual cameras in twilight conditions. Based on findings from Phase 1 UAS testing at WWD, the number of test flights completed at TYS weas significantly reduced. In total, 17 tests were conducted at TYS. These included one flight with each UAS in each lighting condition at a 0-ft offset and an altitude of 40-ft AGL, and one flight with each UAS at a 30-ft offset and an altitude of 20-ft AGL during daylight. The 30-ft offset flights were only conducted in the daylight because it is not feasible to conduct a thorough inspection of infrastructure after dark. Testing conducted at night focused on identifying unauthorized persons or vehicles near the perimeter using thermal camera payloads. Appendix D presents a complete list of test flights conducted at TYS.

4.3.3 Results and Discussion

Sections 4.3.3.1 through 4.3.3.4 present the results from UAS testing at TYS. The results address evaluations of recorded visual and thermal camera performance, and questionnaire responses provided by SMEs on site at TYS. These questionnaires evaluated various aspects of the UAS platforms and GCSs used during testing, as well as the quality and usability of footage collected.

4.3.3.1 Onboard Recorded Visual Camera Analysis

Figure 49 compares screenshots showing the damaged fencing taken from full resolution recorded camera footage captured during daylight using each payload tested at TYS. The red box in each photo identifies the location of the damaged fencing. Each flight was conducted with a 30-ft offset and approximately 30-degree horizontal camera angle at an altitude of 20 ft AGL. All footage was collected without zoom; therefore, any perceived difference in zoom level is a product of differences between each camera's lens and FOV.

Upon close inspection of the videos shown in the screenshots in Figure 49, the damage to the fence is visible in each, including those recorded at resolutions of 1080p and 4K. However, evaluators agreed that it is not reasonable to expect someone viewing the footage in real time to consistently identify this level of fine detail.

Figure 50 compares screenshots showing the shovels taken from full-resolution camera footage captured during daylight using each payload tested at TYS. The red box in each photo identifies the location of the shovels. Each flight was conducted with a 30-ft offset and 30-degree horizontal camera angle at an altitude of 20 ft AGL. All footage was collected without zoom; therefore, any perceived difference in zoom level is a product of differences between each camera's lens and FOV. Evaluators found that the shovels could be clearly seen in each of the videos shown in Figure 50, including those recorded at resolutions of 1080p and 4K.

Figure 51 compares screenshots showing the damaged fencing taken from full-resolution camera footage captured during twilight using each payload tested at TYS. The red box in each photo identifies the location of the damaged fencing. Each flight was conducted with a 30-ft offset and 30-degree horizontal camera angle at an altitude of 20 ft AGL. All footage was collected without zoom; therefore, any perceived difference in zoom level is a product of differences between each camera's lens and FOV. Evaluators found that the lower lighting had a negative effect on the quality of the footage collected. None of the payloads, including those recorded at resolutions of 1080p and 4K, were able to provide enough detail to identify the damage to the fence.

Figure 52 compares screenshots showing the shovel taken from full-resolution camera footage captured during twilight using each payload tested at TYS. The red box in each photo identifies the location of the shovel. Each flight was conducted with a 30-ft offset and 30-degree horizontal camera angle at an altitude of 20 ft AGL. All footage was collected without zoom; therefore, any perceived difference in zoom level is a product of differences between each camera's lens and FOV. Evaluators found that in each of the videos, including those recorded at resolutions of 1080p and 4K, the lower lighting also made it more difficult to distinguish the shovel next to the fence, although it is still visible.

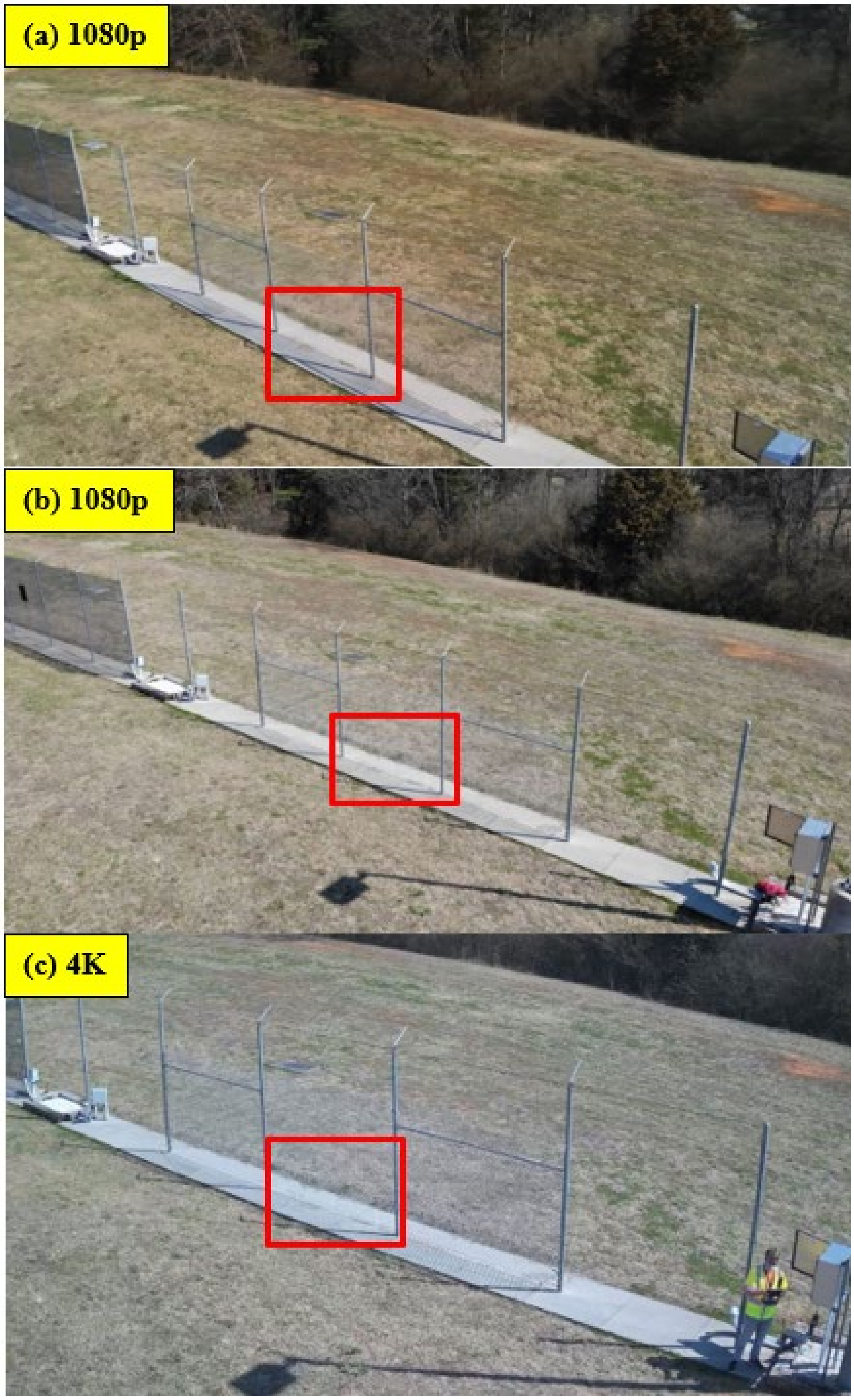

Figure 49. Daylight Recorded Visual Camera Footage of Damaged Fence from 20 ft AGL:
(a) ANAFI Triple, (b) M2ED, and (c) XT2 9mm

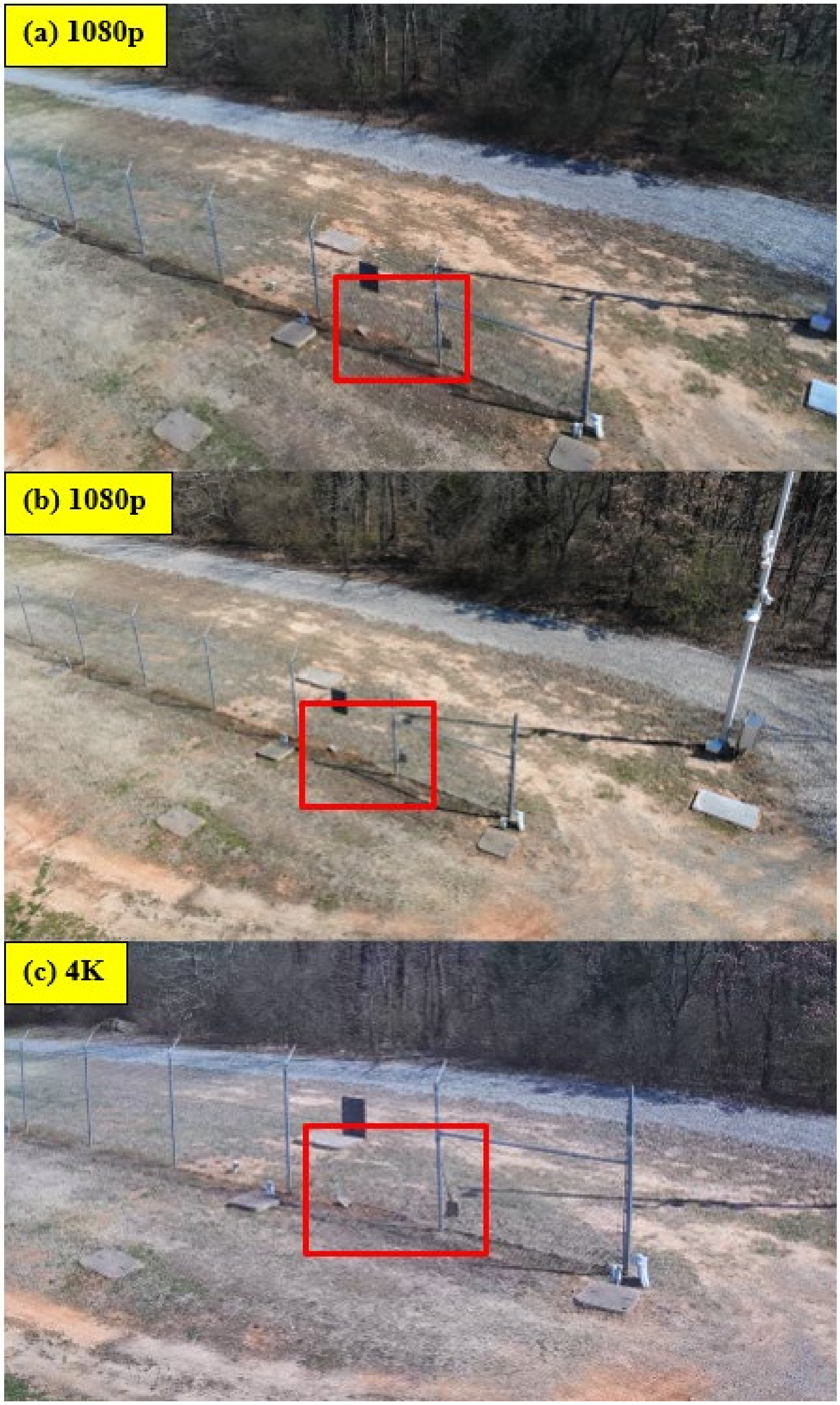

Figure 50. Twilight Recorded Visual Camera Footage of Shovels from 20 ft AGL:
(a) ANAFI Triple, (b) M2ED, and (c) XT2 9mm

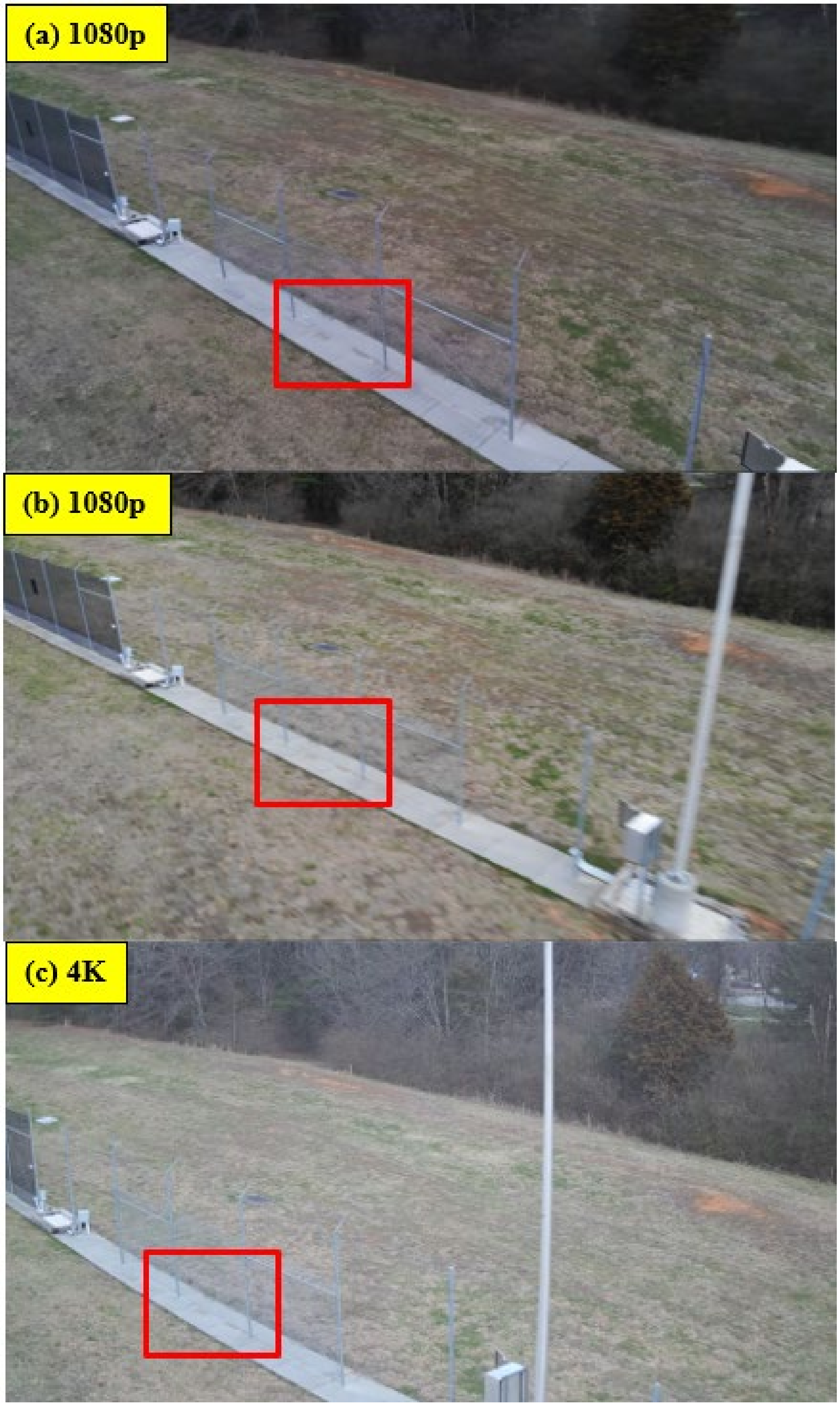

Figure 51. Twilight Recorded Visual Camera Footage of Damaged Fence from 20 ft AGL: (a) ANAFI Triple, (b) M2ED, and (c) XT2 9mm

Figure 52. Twilight Recorded Visual Camera Footage of Shovel from 20 ft AGL: (a) ANAFI Triple, (b) M2ED, and (c) XT2 9mm

4.3.3.2 Thermal Camera Analysis

Figure 53 presents a comparison of screenshots showing human and vehicle targets taken from footage from each of the thermal camera payloads tested at TYS. Both targets are outlined in red in each screenshot. Each flight was conducted at a 0-ft offset at an altitude of 40 ft AGL. No zoom was employed during these test flights, and any perceived difference in zoom between the images in Figure 53 is a product of differences between each camera's lens and FOV.

The M2ED standalone thermal camera footage with a resolution of 160x120, shown in Figure 53(a), proved ineffective at providing enough detail to identify the human or vehicle targets. This supported the analysis from Phase 1 that the M2ED 160x120 resolution thermal camera is not sufficient for conducting airport perimeter surveillance.

Figure 53(b) shows the Parrot ANAFI USA's 320x256 resolution thermal camera footage. This resolution was found to provide significant improvement when compared to the M2ED thermal footage but was still marginal with regard to its usefulness for perimeter surveillance. While the human subject is identifiable in the video, the vehicle heat signature lacks enough detail to allow for a clear detection.

The XT2 9mm 336x256 resolution footage, shown in in Figure 53(c), showed improvement over the Parrot ANAFI USA footage at 320x256. The human and vehicle heat signatures are shown with significantly greater contrast and detail, allowing for them to be quickly identified. Evaluators agreed that this footage is acceptable for airport perimeter surveillance.

The 640x512 resolution XT2 thermal cameras, shown in Figure 53(d–f), provided significantly greater clarity than the other payloads tested, especially in the background of the scenes. This improved performance allowed for faster identification of both the vehicle and human targets. In addition, the 640x512 resolution allowed for viewers to discern additional details on the fence itself, including the vertical poles and barbed wire. FAA researchers recommend this resolution due to its ability to provide for a general inspection of the fence condition (including ensuring the fence is standing and barbed wire is intact) in addition to surveillance.

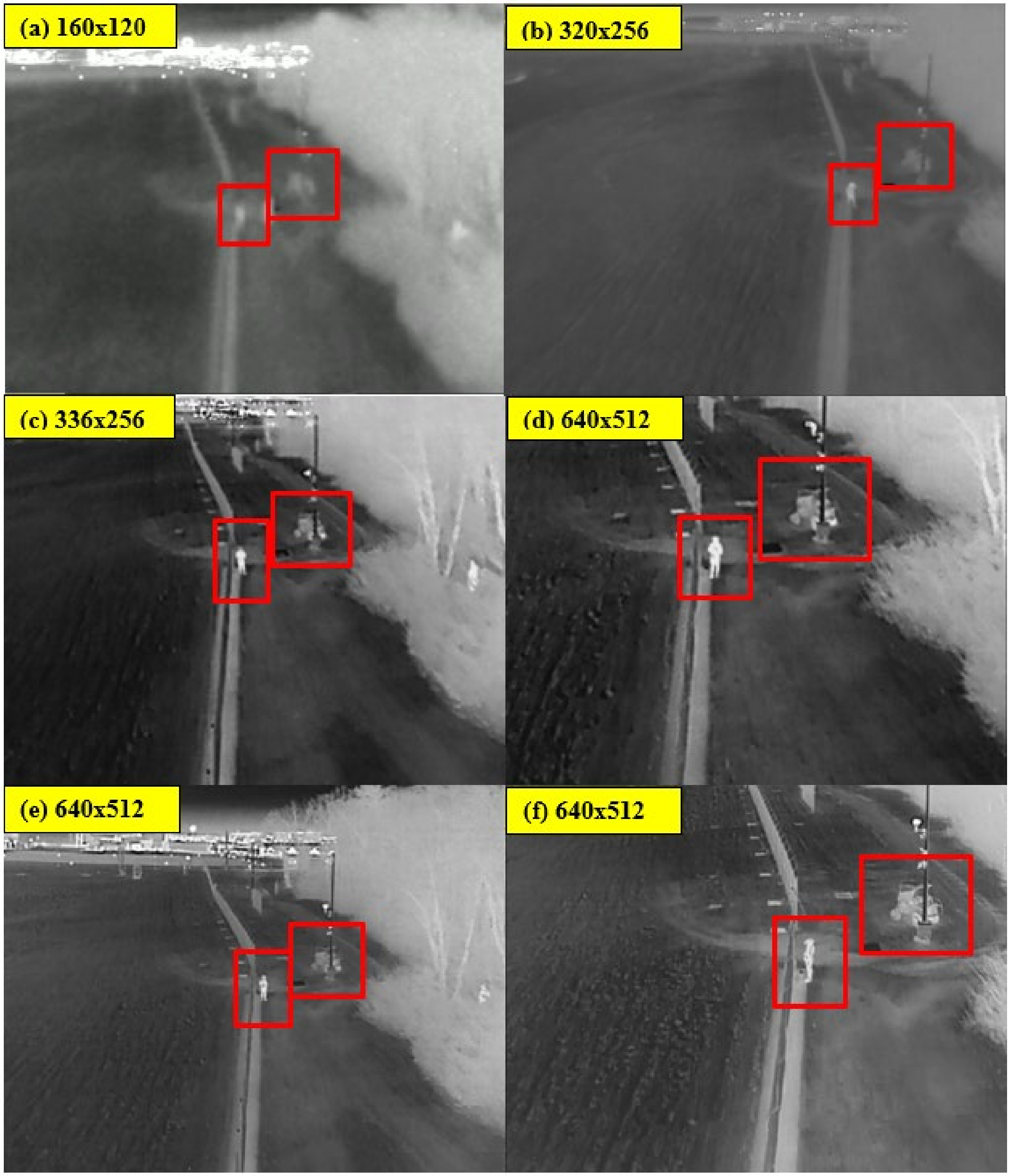

Figure 53. Thermal Camera Performance, 40 ft AGL: (a) M2ED, (b) ANAFI Triple, (c) XT2 9mm, (d) XT2 13mm, (e) XT2 19mm, and (f) XT2 25mm

4.3.3.3 Unmanned Aircraft System Platform Evaluations

During the deployment demonstrations, subjects evaluated each UAS platform regarding their deployment time, GCS screen size and brightness, and overall practicality for supporting airport perimeter inspections. Following the demonstrations, participants were given the option to provide comments regarding each UAS. Sections 4.3.3.3.1 through 4.3.3.3.3 summarize the feedback received during these evaluations.

4.3.3.3.1 Deployment Time

All subjects rated the deployment time of each of the three UAS platforms as "satisfactory" or better. Subjects gave the two foldable airframes (M2ED and ANAFI USA) the highest deployment time ratings.

Participants found the M2ED to be the simplest and the quickest to deploy. This can be attributed to its fold-out airframe that requires no assembly prior to flight. In addition, the M2ED used the DJI Smart Controller, which integrates the GCS screen and controller into a single unit, negating the need for assembly. When asked for comments regarding the M2ED, participants responded with:

- "Deployment time is practically nonexistent. Very quick to setup and get in the air."
- "For size and deployment time this seems like an excellent quick choice."

The Parrot ANAFI USA received the second-highest ratings for deployment time. Similar to the M2ED, participants found the Parrot ANAFI USA to be capable of rapid deployment due to its fold-out airframe that does not require any assembly prior to flight. However, they found its deployment to be more complicated than the M2ED due to the need to connect the iPad used for the GCS screen to the Parrot Skycontroller. No further comments were provided regarding the Parrot ANAFI USA's deployment.

Participants found the DJI M210 took longer than the other systems to deploy, due to the need to assemble the airframe and GCS prior to launch. This process included attaching the landing gear, propellers, and payload, and connecting the CrystalSky GCS display to the DJI Cendence controller. Participants provided the following comments regarding the deployment time of the M210:

- "Deployment time might not be fast enough."
- "With training and expertise, I think deployment in an airport environment is a viable option."
- "Very organized, well laid out case for assembly and disassembly."

4.3.3.3.2 Ground Control Station Screen Size/Brightness

All subjects rated the screen size of the M210 and M2ED monitors as "satisfactory" or better for viewing. By contrast, two subjects rated the ANAFI's USA iPad mini screen size as "marginal."

All subjects rated the M2ED and M210 monitor brightness as "satisfactory" or better. All subjects rated the DJI M210's high-brightness CrystalSky display as "excellent." However, four subjects rated the screen size of the ANAFI USA iPad display as "marginal." Generally, it seemed that subjects preferred a GCS screen that was developed by the UAS manufacturer specifically for the UAS in use, as was the case with the DJI platforms.

Overall, the CrystalSky display received the highest ratings due to its large size (7.85″) and significantly higher brightness (2,000 nits) versus the other displays. The M210 and CrystalSky received the following comments regarding its GCS screen size and brightness:

- "Very clear, large screen for viewing."
- "All [screen size and brightness] are acceptable for the end user."

The M2ED and Smart Controller were also received positively, though their ratings were lower overall when compared to the larger and brighter screen of the M210. Nevertheless, respondents rated the M2ED GCS as "satisfactory" or better for both screen size and brightness. The M2ED received the following comment regarding its GCS screen size and brightness:

- "The controller screen is adequate for an end user."

The Parrot ANAFI USA GCS received the lowest ratings for screen size and brightness; 50% of subjects rated its screen brightness (500 nits) as "marginal." The low screen brightness likely effected subjects' perception of the Parrot ANAFI USA GCS screen size as well, since 25% of responses regarding screen size were "marginal" despite the iPad in use having the largest screen of any GCS tested (7.9″). The Parrot ANAFI USA received the following comment regarding its GCS screen size and brightness:

- "The iPad viewing seemed a step behind other monitors."
- "Size and brightness dependent on a separate device, in this case an iPad."

4.3.3.3.3 Overall Rating

The majority of participants found each UAS to be satisfactory for use supporting airport perimeter inspections. All subjects rated the M210 and M2ED platforms as "good" or "excellent," with the M210 receiving slightly higher ratings. This was most likely due to its larger, brighter GCS screen and its more robust, enterprise-level construction. The M210 received the following comments regarding its overall suitability for airport perimeter inspections:

- "I would rate this drone as being good for an inspection scenario."
- "Drone is very stable and seems easy to control."
- "Looking forward to watching this technology enter the market."

The positive feedback for the M2ED was primarily due to its ease of use, quick deployment, and portability. The comments received regarding the overall performance of the M2ED during the demonstration included:

- "Rating this drone good for perimeter inspection scenarios."
- "With the speed, sound, and quick deployment time I foresee several deployment options."

While most found it to be satisfactory or greater for perimeter inspections, the Parrot ANAFI USA received the most critical feedback from subjects during the demonstration. Participants expressed concerns regarding its durability but were impressed by its payload's capabilities. The Parrot Anafi USA received the following comments during the demonstration:

- "Looking for a bulkier more redundant system."
- "It's a small, commercial off-the-shelf system but not what I would consider a candidate for implementation to an airport's daily operations."
- "Great zoom capability."
- "Impressive sensor"

4.3.3.4 Post-Flight Questionnaire Results

The post-flight questionnaire consisted of three sections: a flight parameter assessment, video footage quality assessment, and an overall assessment of using UASs for airport perimeter inspections and surveillance. The results from each of these sections are presented in Sections 4.3.3.4.1 through 4.3.3.4.3.

4.3.3.4.1 Flight Plan Assessment

In Section 1 of the TYS post-flight questionnaire, respondents were shown payload footage from the different flight plans used during testing. These configurations included the 0-ft. offset, an altitude of 40 ft AGL configuration and the 30-ft offset, 30-degree horizontal camera angle, and altitude of 20 ft AGL configuration. Respondents were asked to evaluate the usefulness of each flight plan for the fence inspection and surveillance use cases by rating how strongly they agree or disagree with a series of statements. Tables 5 and 6 present these statements and the results from Section 1 of the TYS post-flight questionnaire.

Table 5 shows the questionnaire results regarding the suitability of each flight plan for the fence inspection use case. Subjects preferred the 30-ft offset flight plan to the 0-ft offset flight plan for inspecting the condition of fencing, with five subjects agreeing or strongly agreeing that this flight path provided a suitable vantage point, and two disagreeing. By contrast, all subjects disagreed or strongly disagreed that the 0-ft offset flight configuration provided a suitable vantage point for inspecting the fence condition.

Table 5. McGhee Tyson Airport Flight Parameter Assessment Results: Inspection Use Case

Statement 1: "This view provides a suitable vantage point for inspecting the fence condition."						
	Number of Responses	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
30-ft Offset	10	0 (0%)	2 (20%)	3 (30%)	4 (40%)	1 (10%)
0-ft Offset	10	3 (30%)	6 (60%)	0 (0%)	0 (0%)	1 (10%)

Despite the respondents' preference for the 30-ft offset flight plan, they still expressed their concern regarding the level of detail the UAS could capture in the footage. Their comments validated the Phase 1 finding regarding the limited detail visible in UAS payload footage, and the sentiment that UASs could supplement, but not replace, ground-based inspections.

The respondents provided the following comments regarding the suitability of the 30-ft offset view for inspecting the fence condition:

- "Might be able to spot major issues, but more subtle problems are not visible; closer inspection would be necessary."
- "I think this works for looking for major damage. I'm not sure if it would be for compliance stuff like # of hot rings or post ties for a given section of fence."
- "It is plausible major damage to the fence could be seen. I think less cosmetic issues could go unseen and still yield high security threat potential. Example: Bracket ties and hog rings could be completely removed, so the damage would have to be an entire section."
- "Slightly difficult to see if damage or crawlspace open at bottom of fence."
- "Good for surveillance, cannot see bottom view of fence for inspection for holes/gaps, etc."
- "Great resolution. Very detailed."
- "Doubt you could see minor damage very well, but could be used to determine if more extensive damage (missing panel or significant damage) had occurred."

The respondents provided the following comments regarding the suitability of the 0-ft offset view for inspecting the condition of fencing:

- "Could barely see the fence at all."
- "I don't think you can tell much about fence condition outside of whether there is a section down. The other view (offset) was much better."
- "This FOV would not in assist in fence inspections. Only major damage could go noticed."
- "View from directly above makes it difficult to see if any holes may have been cut into fence, or if there is any damage at all."
- "Cannot see holes/gaps or other possible openings in fence material, only see overhead view.
- "Great resolution and detail."
- "Doesn't seem possible to determine if the fence has been damage from this angle, other than if entire panel has major damage."

Table 6 shows the questionnaire results regarding the suitability of each flight plan for the surveillance use case. The subjects generally agreed that both the 0-ft and 30-ft offset flight paths provided a suitable vantage point for conducting perimeter surveillance. Nine subjects agreed or strongly agreed that the 0-ft offset configuration was suitable for surveillance, while all ten agreed or strongly agreed that the 30-ft offset configuration was suitable. This indicates that the respondents felt that UASs are more suited to surveillance rather than detailed fence line inspections.

Table 6. McGhee Tyson Airport Flight Parameter Assessment Results: Surveillance Use Case

Statement 2 "This view provides a suitable vantage point for detecting vehicles, individuals, equipment, etc."						
	Number of Responses	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
30-ft Offset	10	0 (0%)	0 (0%)	0 (0%)	3 (30%)	7 (70%)
0-ft Offset	10	0 (0%)	0 (0%)	1 (10%)	2 (20%)	7 (70%)

The respondents provided the following comments regarding the suitability of the 30-ft offset view for detecting vehicles, individuals, and equipment:

- "The images easily captured human and vehicle sized targets."
- "Great view of detecting anyone near fence line."
- "Same as above. I could make out exact vehicle type and would be able to screenshot person's face for positive ID."
- "People and vehicles easily identifiable in the video."

The respondents provided the following comments regarding the suitability of the 0-ft offset view for detecting vehicles, individuals, and equipment:

- "This view gave better coverage of the area a potential intruder would hide in/approach fence."
- "Humans and vehicles are easily targeted approaching or stationary near the fence."
- "Great view for detecting people or animals near fence line."
- "Same as above."
- "People and vehicles easily identifiable in this video."

4.3.3.4.2 Video Footage Quality Assessments

In Section 2 of the TYS post-flight questionnaire, respondents were asked to provide ratings when viewing the recorded video footage from each payload in a variety of lighting conditions. Table 7 shows the results from the assessments of visual camera footage captured during daylight conditions. As shown in Table 7, the video quality of all visual cameras was rated as "satisfactory" or better by all subjects.

Table 7. McGhee Tyson Airport Daylight Visual Camera Payload Video Quality Assessments

Visual Cameras (Day)						
Payload	Number of Responses	Unsatisfactory	Marginal	Satisfactory	Good	Excellent
XT2 9mm	10	0 (0%)	0 (0%)	3 (30%)	5 (50%)	2 (20%)
ANAFI Triple	10	0 (0%)	0 (0%)	4 (40%)	3 (30%)	3 (30%)
M2ED	10	0 (0%)	0 (0%)	4 (40%)	2 (20%)	4 (40%)

The respondents provided the following comment regarding the quality of the visual camera footage captured during the day:

- “Very clear.”

Table 8 shows the results from the assessments of visual camera footage captured during twilight. These results indicate the respondents perceived a significant degradation of video quality during twilight when compared to video captured during the daylight. Only 10% of the total responses rated the video quality as “excellent” during twilight, versus 30% during daylight.

Table 8. Twilight Visual Camera Video Quality Assessments

Visual Cameras (Twilight)						
Payload	Number of Responses	Unsatisfactory	Marginal	Satisfactory	Good	Excellent
XT2 9mm	10	0 (0%)	0 (0%)	4 (40%)	5 (50%)	1 (10%)
ANAFI Triple	10	0 (0%)	0 (0%)	6 (60%)	3 (30%)	1 (10%)
M2ED	10	0 (0%)	0 (0%)	7 (70%)	2 (20%)	1 (10%)

The respondents provided the following comments regarding the quality of the visual camera footage captured during twilight:

- “Picture doesn’t seem as sharp as videos 1-3 [during the day].”
- “Picture seemed darker, a little jumpy and slightly blurry.”
- “Video seems grainy, not as clear as first 3 [videos captured during the day].”

Table 9 shows the results from the assessments of thermal camera footage captured at night.

Table 9. Nighttime Thermal Camera Video Quality Assessments

Thermal Cameras (Night)						
Payload	Number of Responses	Unsatisfactory	Marginal	Satisfactory	Good	Excellent
M2ED (160x120)	10	9 (90%)	0 (0%)	1 (10%)	0 (0%)	0 (0%)
ANAFI Triple (320x256)	10	3 (30%)	3 (30%)	3 (30%)	1 (10%)	0 (0%)
XT2 9mm (336x256)	10	0 (0%)	2 (20%)	4 (40%)	4 (40%)	0 (0%)
XT2 13mm (640x512)	10	1 (10%)	3 (30%)	2 (20%)	4 (40%)	0 (0%)
XT2 19mm (640x512)	10	0 (0%)	1 (10%)	1 (10%)	4 (40%)	4 (40%)
XT2 25mm (640x512)	10	1 (10%)	0 (0%)	6 (60%)	3 (30%)	0 (0%)

The three XT2 payloads with a 640x512 resolution received the best feedback, with 80% of their total combined responses rating their videos as “satisfactory” or greater. In particular, the XT2 19mm (640x512) had the highest overall ratings, with four “excellent” and four “good” ratings. In addition, the XT2 19mm was the only thermal payload to receive an "excellent" rating. The comments received regarding 640x512 resolution XT2 models included:

- "Smooth and sharp picture."
- "Sharper picture than previous thermals."
- "Better thermal image. Picture is cleaner and smoother."
- "Seems clearer."
- "Very detailed, great resolution."
- "Resolution and detail are good."

The XT2 9mm, which recorded thermal video at a resolution of 336x256, also received similarly high ratings, with 80% of responses rating its videos as "satisfactory" or greater. Respondents provided the following comments regarding the 336x256 resolution XT2 9mm payload video:

- "In reference for detecting intruders the thermal has a great display."
- "People/intruders are clearly visible."
- "Able to see people and vehicles."
- "Could make out 2 subjects and golf cart very easily, but resolution is okay."

Respondents were more critical of the video recorded by the ANAFI Triple, with only 40% of total responses rating its video quality as "satisfactory" or better. The ANAFI Triple received the following comments from respondents:

- "This image may be useful for intrusion detection but would not be the most reliable."
- "Not as bad as #11 [M2ED], but difficult to distinguish details; low contrast."
- "Not as clear."

Respondents overwhelmingly found the M2ED thermal video to be unsuitable for perimeter surveillance; 90% of responses rated the M2ED as unsatisfactory. Respondents provided the following comments regarding the M2ED's video quality:

- "Image is subpar. Can't distinguish much."
- "Not clear at all. Pretty much useless."
- "Worst one of them all."
- "No object is recognizable. A sound observation or judgement could not be made from this video."
- "Not good. Blurry, impossible to distinguish any detail."
- "Poor image quality. Everything blends together. Hard to make out what you are viewing."
- "Too blurry. Not enough detail or sharpness of image."

<u>4.3.3.4.3 Overall Assessment of UASs for Airport Perimeter Inspections</u>

In Section 3 of the post-flight questionnaire, subjects were asked to rate how strongly they agreed with a statement regarding UASs value for perimeter inspections and followed up with three open-ended questions regarding using UASs for airport perimeter inspections and surveillance. The statement and results for Section 3 of the TYS post-flight questionnaire are shown in Table 10.

Table 10. McGhee Tyson Airport Debrief Results

Statement 1: "Based on what you have seen, there is value in the use of UASs for performing perimeter fence inspections and surveillance."					
Number of Responses	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
10	0 (0%)	0 (0%)	2 (20%)	5 (50%)	3 (30%)

Overall, 80% of respondents agreed or strongly agreed that UASs provide potential value for airport perimeter fence inspections and surveillance. Five subjects agreed and three strongly agreed, and the remaining two subjects neither agreed nor disagreed.

The first open-ended question was: "What are the most significant benefits you see in this technology?" Based on their responses, subjects generally saw more benefit for responding to a potential security alarm or breach, increasing the situational awareness of responders. In addition, respondents noted that the UASs could enhance the ability to detect issues during inspections.

- "Increased situational awareness. Cuts time and cost of inspections/patrols. Faster response time."
- "Flexibility, I could see the potential in aiding fixed cameras and patrols."
- "Easy and fast. Getting eyes on a situation to see what is going on helps you prepare on how to handle the situation."
- "Being able to quickly launch a drone at fence line to immediately verify if alarm or other alert is authentic."
- "Vantage point is the most important aspect of using a drone. 4K and thermal cameras make it easy to spot issues on the fence line."

The second open-ended question in Section 3 was: "What do you see as the biggest limitations to implementing this technology?" Based on their responses, subjects were most concerned with UAS battery life and its impact on efficiently completing an inspection or patrol of an airport with a large perimeter.

- "Value depends on angle of flight and speed; may vary between pilots."
- "Battery life would be a factor on larger perimeters."
- "Finding its best application. I can see several options but finding one that justifies the cost and training may take time. I personally think response to an established perimeter intrusion system is the best for now."
- "Very large amounts of perimeter fencing. Battery life/flight time. Larger airports may have to spend a lot of money to get enough drones to cover the fence line. "
- "Weather (wind, snow, etc.) Battery power (time of flight) Fool-proof way to control UAS from losing control and flying outside of view of operator."
- "Battery life."
- "Shooting it down; losing it."

- "Possible risks to aircraft. Costs. Doesn't seem as effective for fence inspections as just having someone drive the perimeter and visually inspect it. Short battery could be an issue."

4.4 PHASE 2 TESTING: SAVANNAH/HILTON HEAD INTERNATIONAL AIRPORT

The second Phase 2 test effort was conducted at SAV in Savannah, Georgia. SAV is a towered, public-use airport located in Class C airspace extending from the surface to a ceiling of 4,100 ft Mean Sea Level (MSL). Certificated under 14 CFR Part 139, SAV services an average of more than 270 aircraft operations per day including commercial, military, air taxi, and general aviation traffic.

SAV was selected for Phase 2 UAS testing because of its largely rural perimeter that featured fence lines near wooded areas and swampland, which are either difficult to inspect via the ground or completely inaccessible. In addition, Test Area 2 identified in Section 4.4.1, provided the first opportunity for FAA researchers to conduct UAS operations along a fence line directly adjacent to a non-movement area taxiway used by an aircraft manufacturer at SAV.

4.4.1 Test Areas

Figure 54 shows the three areas where testing at SAV was performed. Each test area was selected to provide a unique environment to validate data collection technologies and methodologies.

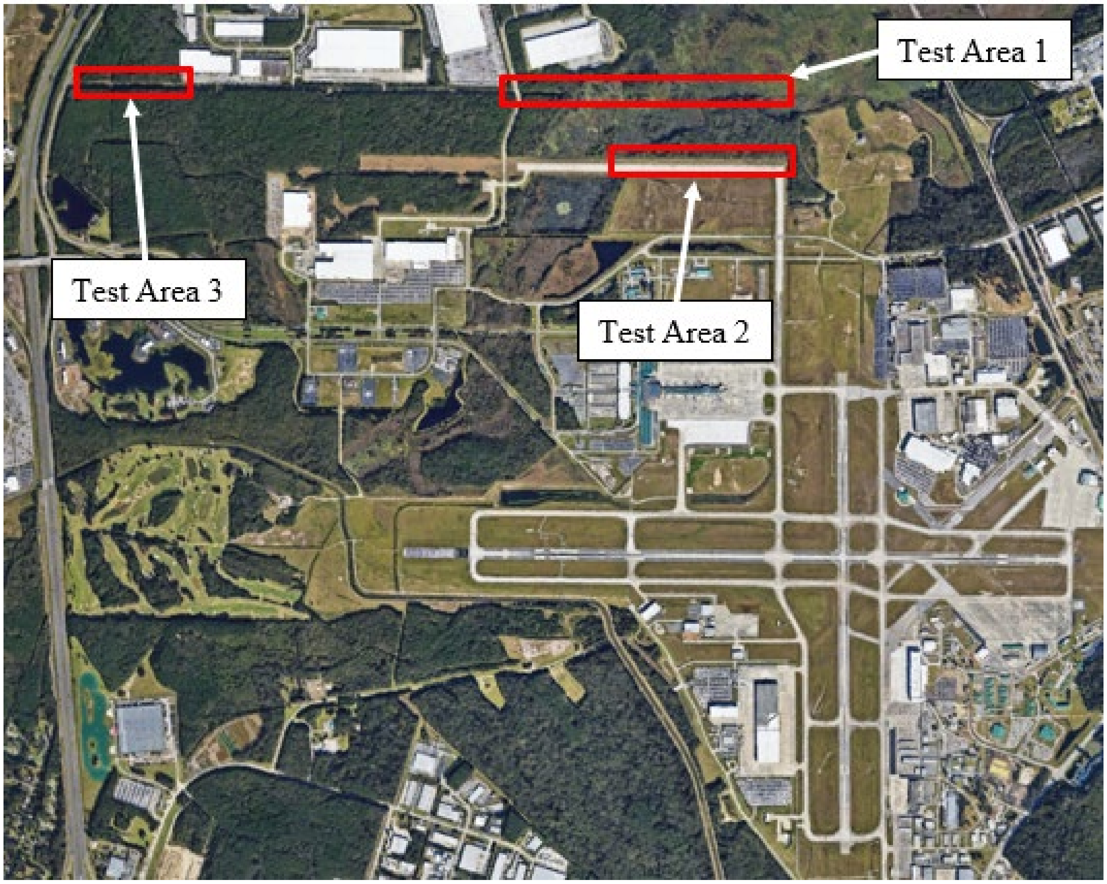

Figure 54. Savannah/Hilton Head International Airport Test Areas

Test Area 1, shown in Figure 55, featured 0.8 mile of non-AOA property boundary fencing that ran through a dense, wooded swamp. This fence line cannot be accessed on foot or by ground vehicles, making it an ideal case for using UASs to inspect the fencing. Due to the dense vegetation in this area, the fence cannot be seen at all from the ground. This fence was known to be damaged by downed trees in the swamp, providing visual targets for observation.

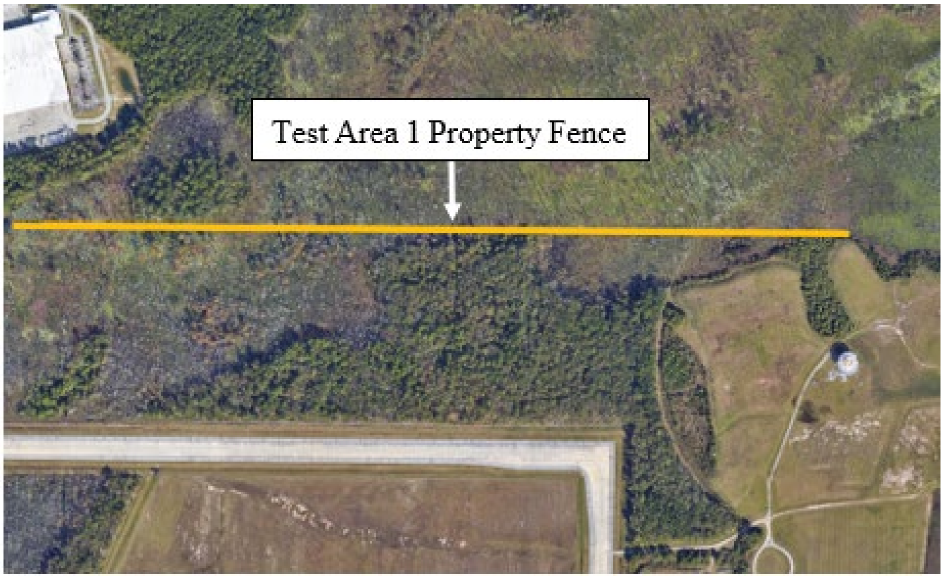

Figure 55. Fence Location in Test Area 1

Test Area 2 features 0.5 miles of AOA fencing that runs adjacent to a taxiway that is no longer part of the movement area. This taxiway connects to an aircraft manufacturing facility adjacent to SAV and is used to transport new aircraft to the airport. This AOA fence borders a densely wooded area to the north but is clear on the interior. This area was chosen because there is no perimeter road next to the fence line. The ground elevation at the fence is lower than the adjacent taxiway, resulting in this area holding water following rainstorms. This makes this area difficult to inspect when the ground is saturated, providing a potential use case for UASs. Test Area 2 is pictured in Figure 56.

Figure 56. Test Area 2

Test Area 3, pictured in Figure 57, was chosen due to its considerable elevation changes as the perimeter fence proceeds through a heavily wooded area. The eastern end is the highest point, and the elevation drops off considerably toward the western end. This provided a unique environment in which to validate previous findings from TYS regarding operating UASs along perimeters with varying terrain.

Figure 57. Test Area 3

4.4.2 Test Parameters

Testing at SAV continued the approach employed at TYS, which leveraged findings from Phase 1 testing at WWD. Identical flight plans as those used at TYS were executed at SAV, including a single test at a 0-ft offset and a single test at a 30-ft offset with a 30-degree horizontal camera angle with each UAS in each test area. In total, 18 test flights were conducted during Phase 2 testing at SAV. Appendix D presents a complete list of test cards conducted at SAV.

Because significant night testing of thermal cameras was conducted at WWD and TYS, testing at SAV included only daylight testing. The primary focus of this test effort was to assess the potential benefit UASs provide for inspecting fence lines in inaccessible areas. In addition, SAV provided FAA researchers the opportunity to evaluate the effectiveness of various payloads' zoom capabilities, validate findings from previous testing, and gain feedback from SMEs at an international airport in Class C airspace.

4.4.3 Results and Discussion

Sections 4.4.3.1 through 4.4.3.5 present the results from Phase 2 UAS testing at SAV. The results address evaluations of recorded visual camera performance and live-streamed payload video performance. A post-flight questionnaire was presented to SMEs on site; however, due to the limited number of responses received (two), the results are omitted. This questionnaire evaluated various aspects of the UAS platforms and GCSs used during testing, as well as the quality and usability of footage collected.

4.4.3.1 Onboard Recorded Visual Camera Analysis

Figure 58compares screenshots taken from full resolution recorded camera footage captured using each payload tested at SAV. Each flight was conducted in Test Area 1 with a 0-ft offset at an altitude of 100 ft AGL. These tests were conducted at an altitude of 100 ft AGL, rather than the 60 ft AGL or lower recommended from Phase 1 testing, due to the presence of tall trees on both sides of the perimeter fence. All footage was collected without zoom; therefore, any perceived difference in zoom level is a product of differences between each camera's lens and FOV.

As shown in Figure 58, a multitude of fallen trees are resting on the fence line in Test Area 1. Evaluators found that the fallen trees were clearly visible in each of the videos, and concluded that all recorded visual camera footage, including those recorded at resolutions of 1080p and 4K, were suitable for performing a general inspection of the perimeter fence.

Figure 59 compares screenshots taken from full resolution recorded camera footage captured using the Z30, ANAFI Triple, and M2ED payloads. The XT2 9mm is not included in this comparison due to a corrupted file discovered after the conclusion of testing. Each flight was conducted in Test Area 3 with a 30-ft offset and 30-degree horizontal camera angle at an altitude of 20 ft AGL. All footage was collected without zoom; therefore, any perceived difference in zoom level is a product of differences between each camera's lens and FOV.

Evaluators used a sign on the fence in Test Area 2 to assess the level of detail present in each payload video. This sign has the words "No Trespassing" in red lettering on a white background.

This sign is identified by a red box in each of the screenshots in Figure 59. While difficult to see in the compressed images in this report, the words on the sign are clearly visible in the full-resolution payload footage, and the word "No," which is considerably larger than the word "Trespassing," can be easily read. This was true for videos recorded in resolutions of 1080p and 4K.

In addition to the sign, evaluators found that pertinent aspects of the fence line, including the chain links and barbed wire, could be assessed in each of the videos. Based on this assessment, evaluators found that each of the payload videos were suitable for conducting a perimeter fence line inspection.

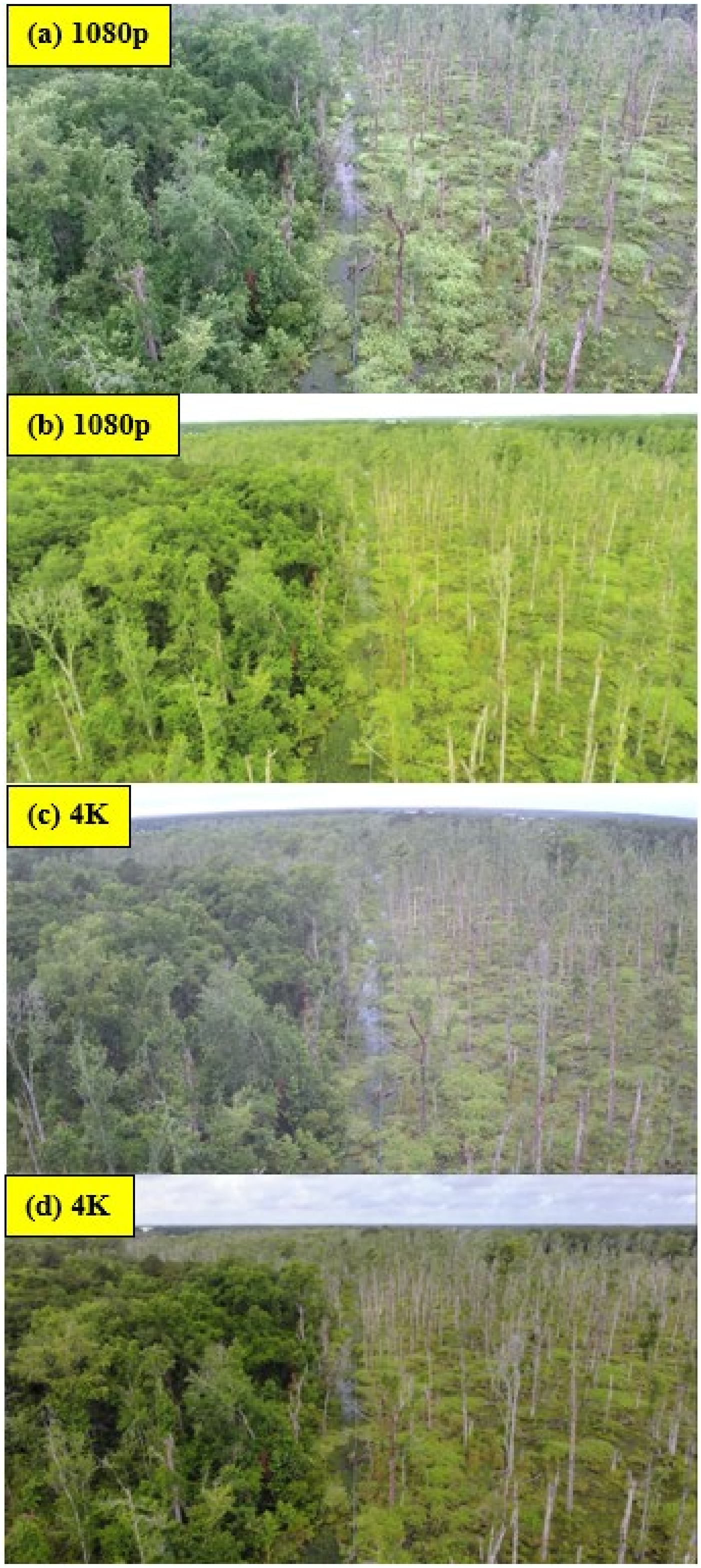

Figure 58. Recorded Visual Camera Footage of Test Area 1 from 100 ft AGL: (a) Z30, (b) ANAFI Triple, (c) XT2 9mm, and (d) M2ED

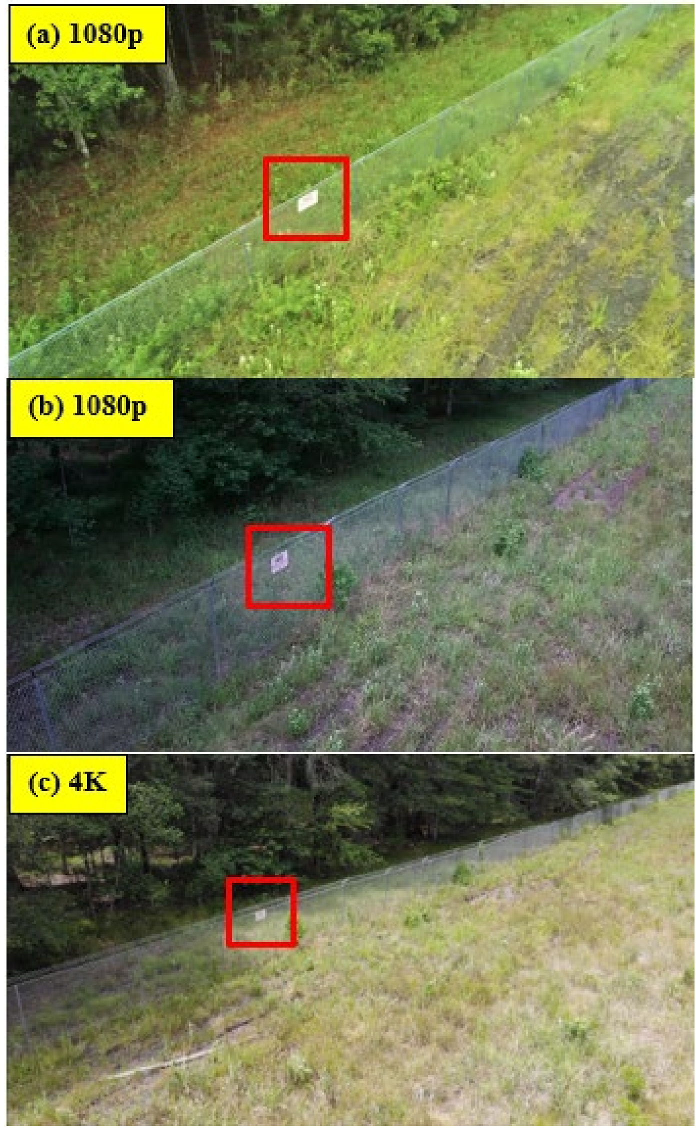

Figure 59. Recorded Visual Camera Footage of Test Area 3 from 20 ft AGL (a) ANAFI Triple, (b) Z30, and (c) M2ED

4.4.3.2 Live Payload Video Feed Analysis

Figures 60 and 61 compare screenshots taken from live-streamed payload camera feeds from the ANAFI Triple, Z30, and M2ED. All footage was collected without zoom; therefore, any perceived difference in zoom level is a product of differences between each camera's lens and FOV.

For these comparisons the ANAFI Triple, shown in Figures 60(a) and 61(a), was downsized from its native 1080p resolution and streamed in 720p (1280x720). The Z30, shown in Figures 60(b) and 61(b), was both recorded and streamed at 1080p, and the M2ED, shown in Figures 60(c) and 61(c), was recorded in 4K and streamed at 1080p. It should be noted that live-stream video files from the XT2 were corrupted prior to evaluation, preventing their inclusion in these comparisons.

Figure 60 compares screenshots taken from live-streamed footage of Test Area 1. Each flight was conducted at a 0-ft offset at an altitude of 100 ft AGL. When compared to each payload's equivalent recorded camera footage (shown in Figure 58), there is a slight drop in clarity, particularly for the live-streamed footage that was downsized from their native resolutions. Despite this reduction in quality, all three live payload feeds, including those streamed at 720p and 1080p, were found to be suitable for conducting a general, high-level fence line inspection. All trees resting on the fence that can be seen in the recorded videos are visible in the live-streamed videos, indicating that this drop in quality is not significant enough to affect the usefulness of the footage for this use case.

Figure 61 compares screenshots taken from live-streamed footage of Test Area 3. Each flight was conducted with a 30-ft offset and 30-degree horizontal camera angle at an altitude of 20 ft AGL.

Similar to the comparison of recorded payload footage shown in Figure 59, evaluators used a sign on the fence in Test Area 2 to assess the level of detail present in each payload video. This sign is identified by a red box in each of the screenshots in Figure 61.

Evaluators found that, compared to each payload's equivalent recorded camera footage (shown in Figure 59), there is a slight drop in clarity. This is particularly true for the live-streamed footage that was downsized from their native resolutions. The word "No" on the sign is still readable in the live-streamed footage from the Z30 and M2ED; however, it is marginal when viewed in the ANAFI Triple live feed. Despite this reduction in quality, all three of these live payload feeds, including those streamed at 720p and 1080p, were found to be suitable for conducting a general, high-level fence line inspection. Evaluators found that pertinent aspects of the fence line, including the chain links and barbed wire, could be assessed in each of the videos, although not with the same level of detail visible in the recorded videos, nor with the detail that would be seen by conducting the inspection in person from the ground.

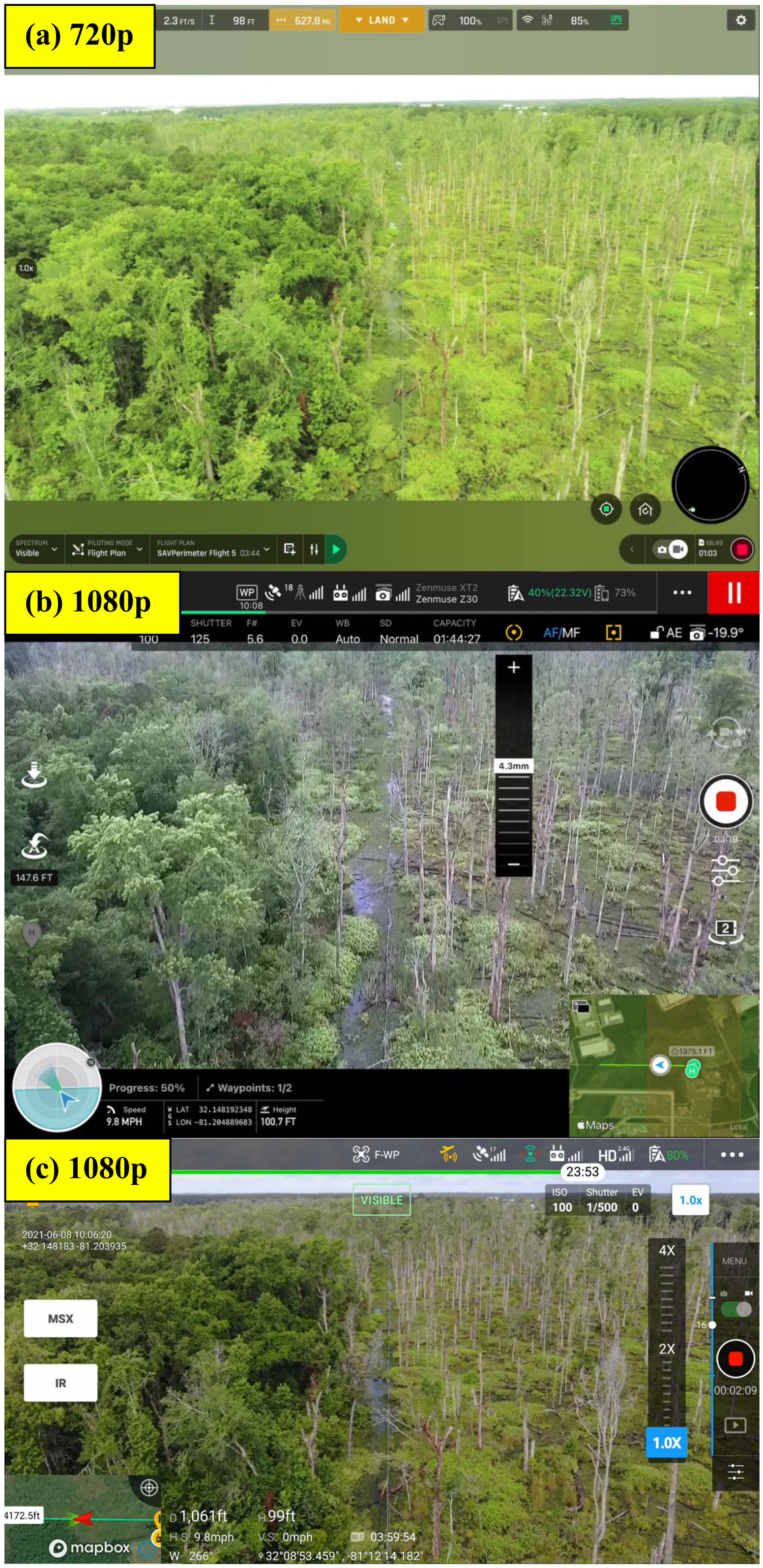

Figure 60. Live-Streamed Camera Footage of Test Area 1 from 100 ft AGL: (a) ANAFI Triple, (b) Z30, and (c) M2ED

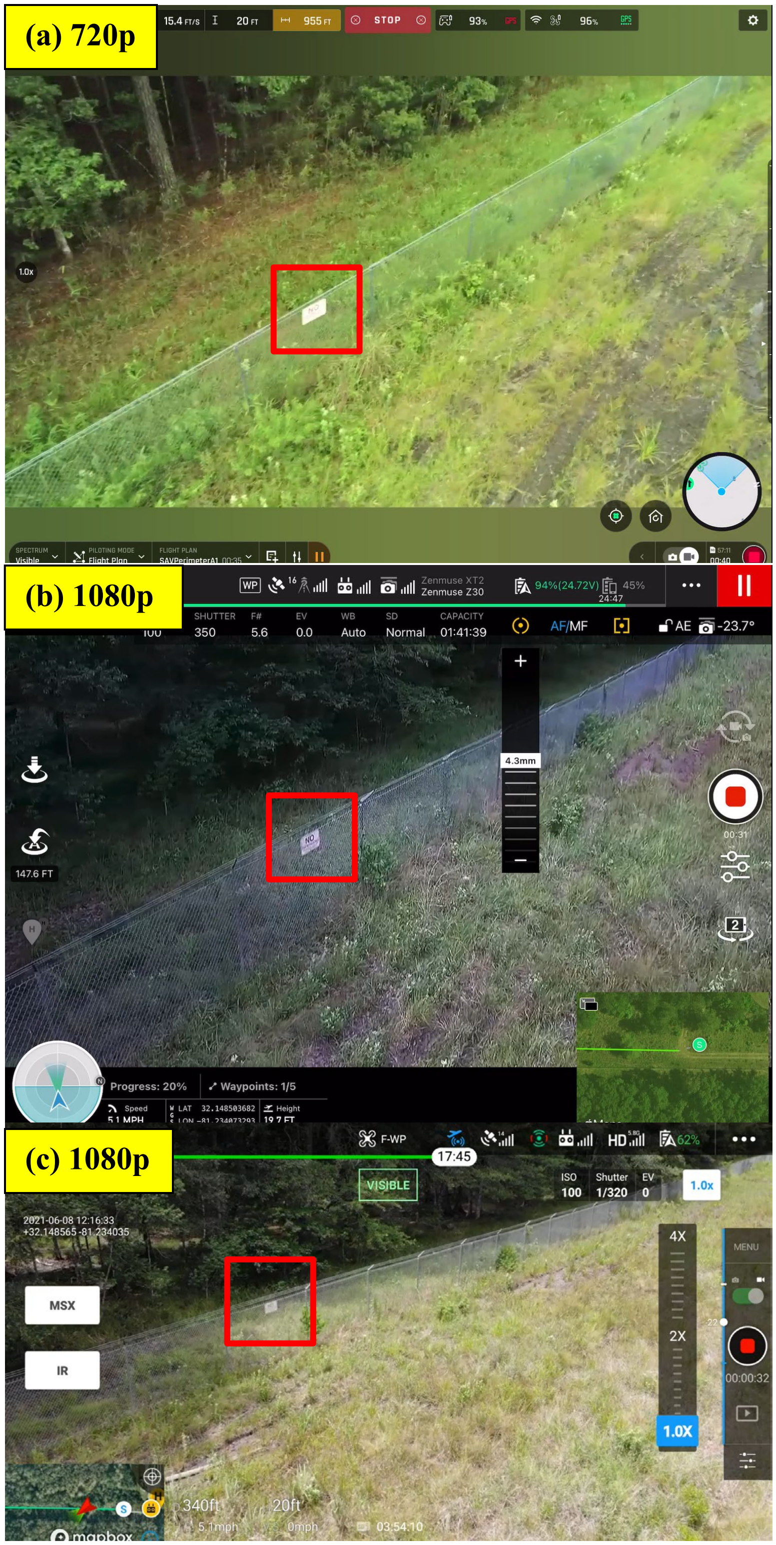

Figure 61. Live-Streamed Camera Footage of Test Area 1 from 20 ft AGL: (a) ANAFI Triple, (b) Z30, and (c) M2ED

4.4.3.3 Payload Zoom Capability

During UAS testing at SAV, FAA researchers evaluated the effectiveness of the zoom capabilities of three of the payloads to enhance one's ability to view fine details. Figure 62 shows the ability of these payloads, the ANAFI Triple, Z30, and M2ED, to enhance one's ability to view damage to the fence line. The screenshots in Figure 62 were taken from footage collected in Test Area 1 at SAV at a 0-ft offset and altitude of 100 ft AGL.

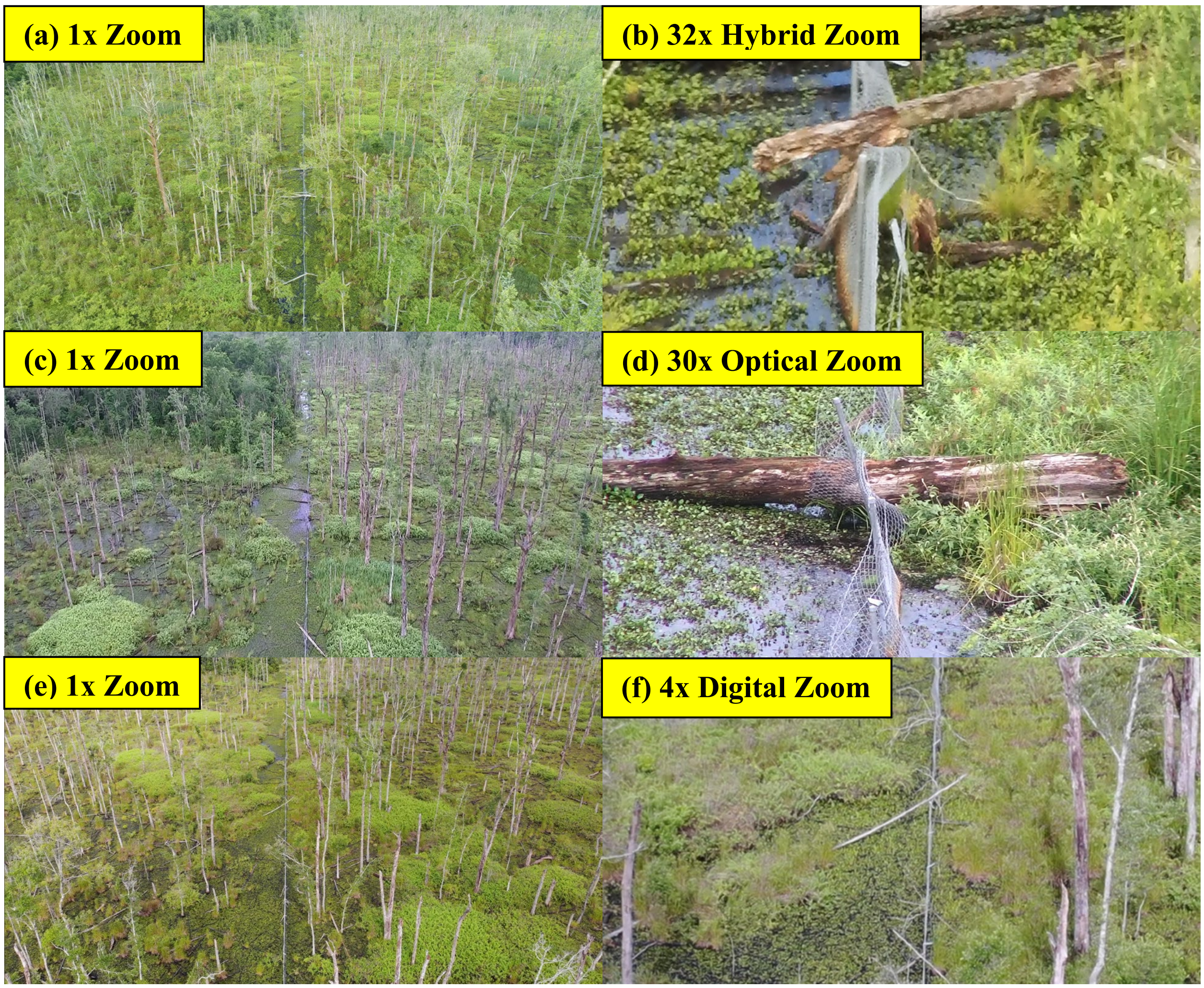

Figure 62. Payload Zoom Capabilities from 100 ft AGL: (a–b) ANAFI Triple, (c–d) Z30, and (e–f) M2ED

While the zoom capability would not help security personnel detect areas of minor damage during an inspection, it was concluded that it could help perform a more detailed assessment of damage once it has been spotted during a patrol. This feature would be particularly useful in areas where the UAS cannot fly at a low altitude, such as Test Area 1 at SAV.

It should be noted that each payload in Figure 62 employs a different method of zoom. The Z30 uses optical zoom, which allows for zero loss in resolution when zooming up to 30x. When available and practical, this is the best type of zoom available. The ANAFI USA provides 5x optical zoom blended with digital zoom to achieve 32x. This allows the image to remain at 1080p HD quality despite the digital zoom. This type of zoom was also found to be acceptable. The M2ED uses digital zoom, in which the level of zoom directly correlates with a loss in resolution. While this type of zoom can allow an operator to identify major elements, such as a downed tree on a fence, it cannot match the level of detail offered by the other payloads.

4.5 PHASE 2 TESTING: CINCINNATI/NORTHERN KENTUCKY INTERNATIONAL AIRPORT

The final Phase 2 test effort took place at CVG in Hebron, Kentucky. CVG is a towered public use airport located in Class B airspace extending from the surface to a ceiling of 10,000 ft MSL. Certificated under 14 CFR Part 139, CVG services an average of more than 370 aircraft operations per day, the majority of which is commercial air traffic.

CVG was selected for inclusion in this research effort due to its heavily trafficked urban environment. In addition, CVG was selected due to its expansive perimeter and the presence of public-use roadways that bisect, travel alongside, or travel underneath the AOA, creating a varied and complex perimeter. In addition, it allowed for the validation of previous findings in Class B airspace, which is the most congested airspace in the nation.

4.5.1 Test Areas

UAS testing was performed at CVG inside four test areas, as illustrated in Figure 63. These test areas were identified during a site survey conducted prior to testing. Each test area was selected to provide a unique environment to validate data collection technologies and methodologies developed in earlier test efforts.

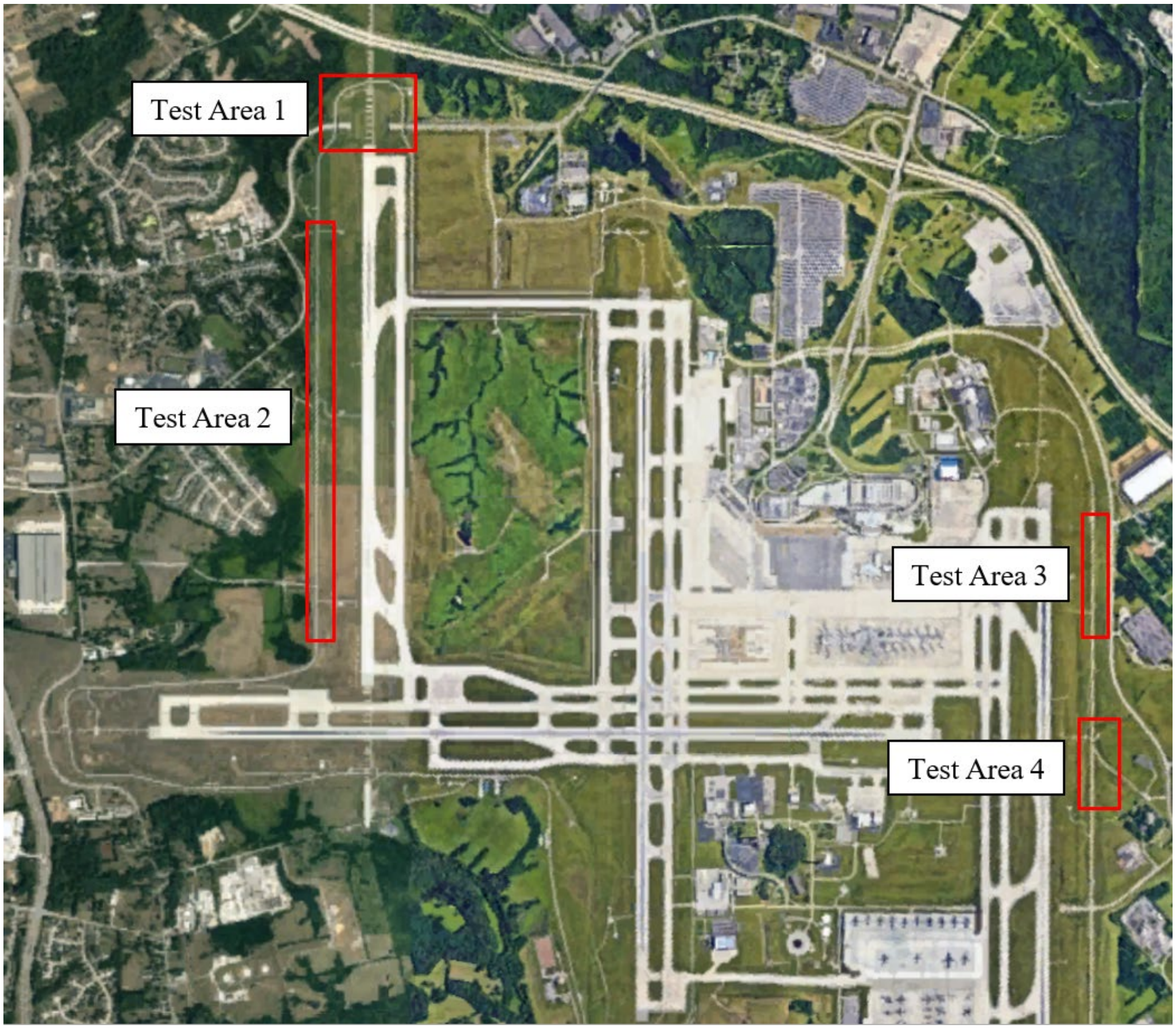

Figure 63. Cincinnati/Northern Kentucky International Airport Test Areas

Test Area 1 is a complex perimeter section directly off the north end of runway 18R/36L. Operations in this test area were only conducted during a period when Runway 18R/36L was closed for scheduled maintenance. In this area a public roadway passes underneath the AOA, resulting in two overpasses and a tunnel. Both the grass above the tunnel and the roadway overflying the public road are within the AOA. This area can be seen in a Google Earth™ rendering in Figure 64 and is pictured in FIGURE 65.

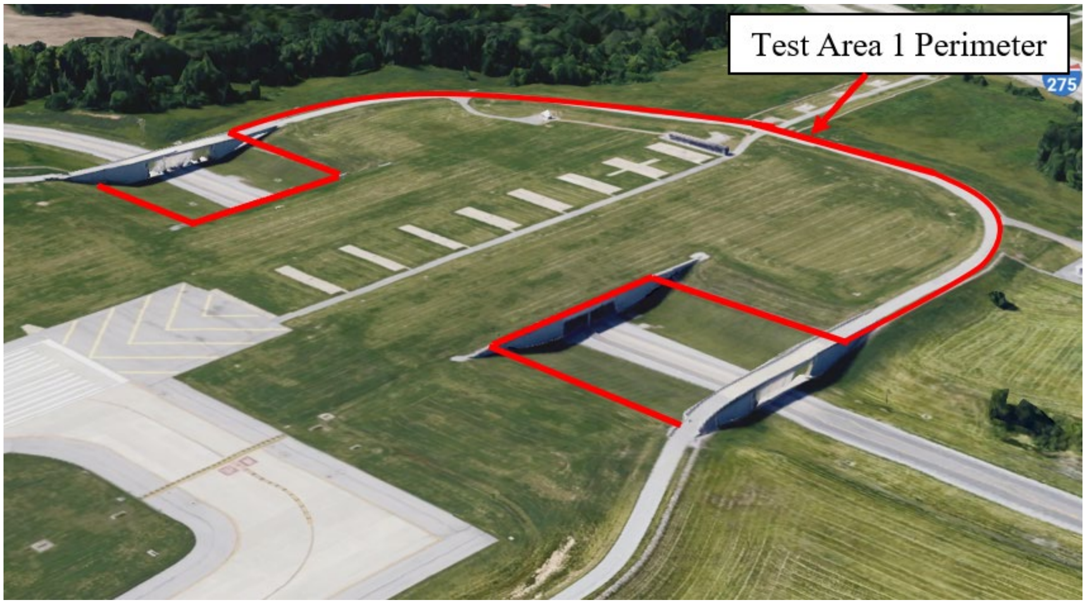

Figure 64. Google Earth™ Rendering of Test Area 1 Showing the Perimeter Section Inspected

Figure 65. Western Half of Test Area 1

Test Area 2, pictured in Figure 66, is a 1.25-mile-long, relatively straight fence line along the western side of the airfield. This fence is set on a series of rolling hills, allowing for additional evaluation of using UASs for perimeter sections with varying elevations.

Figure 66. Test Area 2

The perimeter fencing in Test Area 3, pictured in Figure 67, runs adjacent to a heavily trafficked public roadway.

Figure 67. Test Area 3

Test Area 4 lies directly under the approach of Runway 27 on the eastern border of the airfield. Testing in this area was only conducted when Runway 27 was closed for scheduled maintenance. This area is unique because it lies adjacent to an aircraft viewing area just outside of the perimeter fencing. According to CVG staff, this viewing area is frequently occupied by a local group of aviation enthusiasts and other civilians, making it a key spot of the perimeter that requires surveillance. Figure 68 shows a photograph of this viewing area.

Figure 68. Test Area 4 and Public Aircraft Viewing Area

4.5.2 Test Parameters

UAS testing at CVG used similar parameters as those used in earlier Phase 2 test efforts. The goal of this effort was to validate these parameters when conducting patrols at a large, urban commercial airport. Flight plans conducted included the following configurations:

- 0-ft offset flights with a 0-degree horizontal camera angle at 40 ft AGL
- 30-ft offset flights with a 30-degree horizontal camera angle at 20 ft AGL

All visual camera payloads were configured to record video at a resolution of 1080p. In previous test efforts, recordings in 4K were found to present minimal benefits with regard to enhanced detail, but significantly increased the data storage burden. Appendix D contains the full list of test flight parameters conducted at CVG.

4.5.3 Results and Discussion

Sections 4.5.3.1 through 4.5.3.5 present the results from UAS testing at CVG. The results address evaluations of recorded visual camera performance and questionnaire responses provided by SMEs. These questionnaires evaluated various aspects of the UAS platforms and GCSs used during testing, and the quality and usability of footage collected.

4.5.3.1 Onboard Recorded Visual Camera Analysis

Figure 69 compares screenshots taken from full resolution recorded camera footage captured using each payload tested at CVG. Each flight was conducted in Test Area 1 with a 30-ft offset and 30-degree horizontal camera angle at an altitude of 20 ft AGL. It should be noted that AGL flight altitudes are approximate due to varying terrain present in the test area. All footage was collected without zoom; therefore, any perceived difference in zoom level is a product of differences between each camera's lens and FOV.

Evaluators found that each of the videos pictured in Figure 69 provided enough detail to assess the general condition of the fence in Test Area 1, including the chain links and the barbed wire. Each video was found to be acceptable for conducting daylight perimeter inspections.

Figure 70 compares screenshots taken from full-resolution, recorded camera footage captured using each payload tested at CVG. Each flight was conducted in Test Area 3 with a 30-ft offset and 30-degree horizontal camera angle at an altitude of 20 ft AGL. It should be noted that AGL flight altitudes are approximate due to varying terrain present in the test area. All footage was collected without zoom; therefore, any perceived difference in zoom level is a product of differences between each camera's lens and FOV.

Similar to the comparison shown in Figure 69, evaluators found that each recorded visual camera video captured in Test Area 3 at CVG provided adequate detail to conduct a general inspection of the fence. Key aspects of the fence were visible, including the chain links and barbed wire, and each of these videos weas found to be acceptable for conducting a high-level fence inspection during daylight conditions.

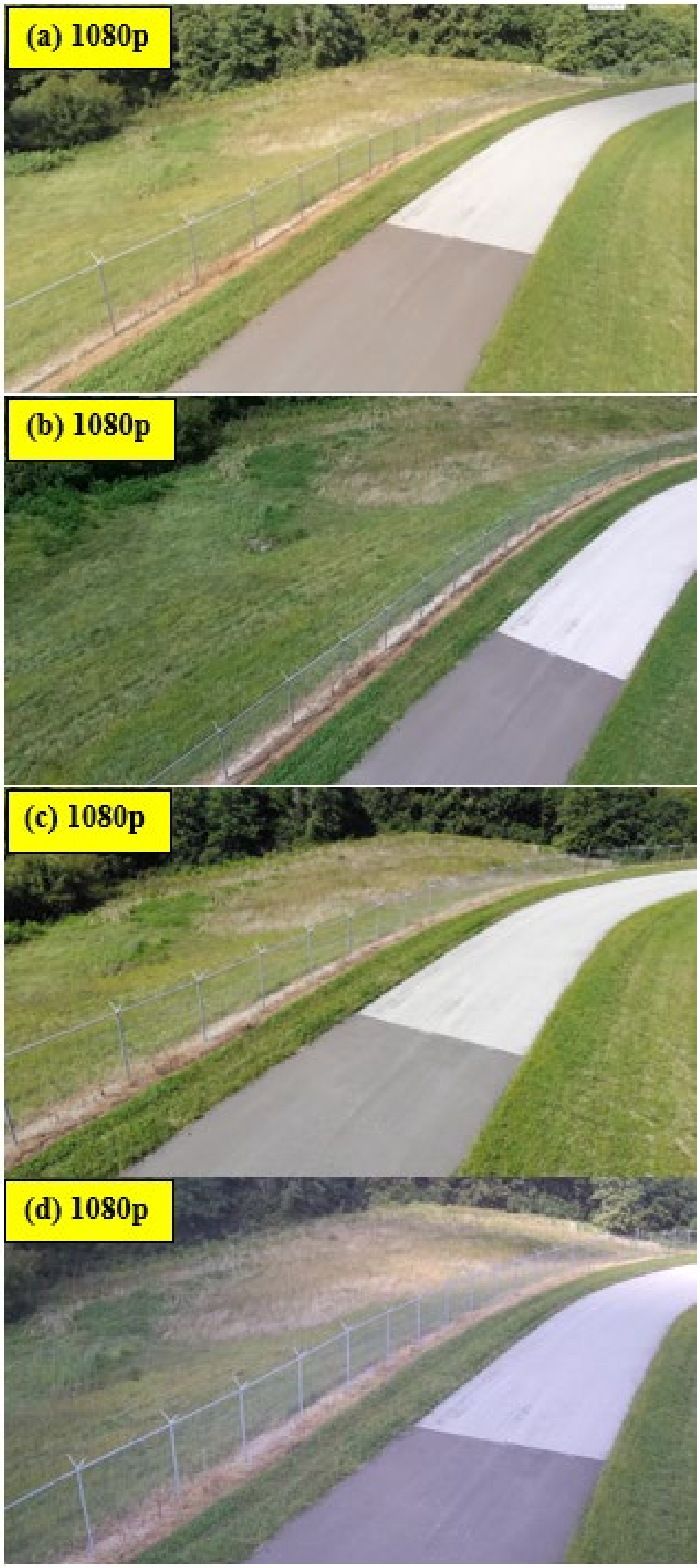

Figure 69. Recorded Visual Camera Footage of Test Area 1 from 20 ft AGL: (a) ANAFI Triple, (b) XT2 9mm, (c) M2ED, and (d) XT2 9mm

Figure 70. Recorded Visual Camera Footage of Test Area 3 from 20 ft AGL: (a) ANAFI Triple, (b) Z30, (c) M2ED, and (d) XT2 9mm

4.5.3.2 Unmanned Aircraft System Platform Evaluations

Sections 4.5.3.4.1 through 4.5.3.4.2 present the results from the UAS platform evaluation at CVG. These results address evaluations of each UAS platform's ease and speed of deployment, GCS screen size and brightness, and an overall rating for each platform with regard to conducting perimeter inspections at airports.

4.5.3.2.1 Ease of Deployment/Deployment Time

Overall, deployment ratings received from subjects at CVG validated previous findings from the other airports in Phase 2. Subjects preferred the ease of deployment of the two foldable UAS platforms (ANAFI USA and M2ED) compared to the M210, with all subjects giving an "excellent" rating to the ANAFI USA and "good" and "excellent" ratings to the M2ED. Subjects provided the following comment regarding the time and ease of deployment of the M2ED:

- "Very portable and appears to be easy to deploy."

Subjects provided the following comment regarding the time and ease of deployment of the ANAFI USA:

- "Very quick deployment and ease of use to set up the system."

The M210 ratings were more mixed, with an equal split between "marginal," "satisfactory," and "good" ratings. Subjects provided the following comment regarding the time and ease of deployment of the M210:

- "Takes longest to deploy with most parts."

4.5.3.2.2 Ground Control System Screen Size/Brightness

Ratings received from subjects regarding GCS screen size and brightness also validated previous ratings from other airports. Overall, the subjects preferred the CrystalSky screen used with the M210, with all subjects rating its size (7.85") as "excellent," and all subjects rating its screen brightness as "good" or "excellent." The M210 received the following comment regarding its GCS screen size and brightness:

- "Good screen size and brightest of all displays."

The iPad Mini used with the ANAFI USA received more mixed ratings regarding screen size, despite having the largest screen of the GCSs tested (7.9″). At CVG subjects rated the iPad mini screen size as either "satisfactory" or "good." This was in line with previous subject responses and is likely a result of its low brightness, which can cause its screen to be perceived as smaller. Regarding screen brightness, iPad Mini was rated the lowest of the GCSs used and received ratings of either "satisfactory" or "marginal." The ANAFI USA received the following comment regarding its GCS screen size and brightness:

- "Screen size is good but hard to see the screen in sunny situations."

The DJI Smart Controller, with its 5.5-in. screen, used with the M2ED, received the lowest ratings regarding its screen size, with all subjects rating it as “satisfactory.” With regard to brightness, it also received only “satisfactory” ratings, placing it in second place behind the M210. Both of these ratings were consistent with the Smart Controller’s specifications. The M2ED received the following comment regarding its GCS screen size and brightness:

- “Small screen on the controller and brightness was okay.”

4.5.3.2.3 Quality of Payload Feed

Subjects most preferred the payload video quality from the M210 (equipped with the Z30 and XT2 9mm payloads), rating it as either “excellent” or “good.” The M210 payload feed received the following comment from subjects:

- “Very good camera and zoom capabilities to be able to do just about anything you want. Good for this operation.”

The quality of the payload feed from the M2ED was ranked second place, with all subjects rating it as “good.” Subjects provided the following comment regarding the quality of the payload feed from the M2ED:

- “Good quality for performing the inspection.”

The payload video feed from the ANAFI USA received the lowest ratings of the systems tested, with subjects rating it as either “satisfactory” or “good.” This was also consistent with its specifications since the ANAFI streams video at the lowest resolution (720p) of the systems tested. Subjects provided the following comment regarding the quality of the payload feed from the ANAFI USA:

- “Good camera and combination for such a small platform.”

4.5.3.2.4 Overall Assessment of UASs for Perimeter Inspections

The M2ED received the highest rating for its overall use and practicality for conducting perimeter inspections. This is believed to be due to its ease of deployment combined with bright GCS screen. The M2ED received the following comment regarding its overall assessment for perimeter inspections:

- “Overall, this seems to be a well-balanced platform for this application.”

The M210 was ranked second of the systems testing, with subjects rating it as either “good” or “satisfactory.” Subjects found that it has the best GCS screen and payload capabilities but required the most training and was the slowest to deploy. The M210 received the following comments regarding its overall assessment for perimeter inspections:

- "Would require the most training and expertise, but perfect for this application and other use cases around the airport."
- "Good for long term deployments, excellent visual coverage."
- "Need dedicated operations personnel. Does it improve efficiency?"

Consistent with ratings received at previous airports in Phase 2, subjects at CVG gave the ANAFI USA the lowest overall rating of the UAS platforms tested. Most subjects rated it as "satisfactory," but it also received one "marginal" rating. While subjects like its speed and ease of deployment, they expressed concerns regarding its susceptibility to the wind. The ANAFI USA received the following comments regarding its overall assessment for perimeter inspections:

- "This is a super easy drone to operate, setup, and use."
- "Good for in a pinch deployment, however [this UAS] does not reduce manpower from operational perspective."
- "Lightweight. Very dependent on good weather."
- "This system would be great for a quick deployment and apprehend situation. The downfall would be its short flight time and unable to be in higher wind situations."

4.5.3.3 Post-Flight Questionnaire Results

The post-flight questionnaire consisted of two sections. The first section, titled CONOPs Assessment, had subjects rate the extent to which they agreed or disagreed with three statements regarding the practicality and usefulness of UAS for perimeter inspections. The second section was a Benefits and Limitations Assessment and featured open-ended questions regarding the benefits and limitations of UAS for this application. Sections 4.5.3.5.1 through 4.5.3.5.2 present the results from each of these sections.

4.5.3.3.1 Concept of Operations Assessment

The first statement in this section was: "Based on what you have seen, there is value in the use of UASs for performing perimeter fence inspections and surveillance." Eight percent of respondents agreed, or strongly agreed with the statement. Following are the comments from subjects regarding the value they see in the use of UAS for perimeter fence inspections and surveillance:

- "This is very helpful for both an efficiency standpoint and field of view provided. The ultimate goal would be autonomous flight that provides a feed and auto reporting of issues found."
- "Increase in technology drives additional use cases. Increase in perimeter safety. Do see that manpower is still there, would like to see increase in operational efficiency."
- "Not sure it replaces the human element, at least not completely."
- "Beneficial during night shifts when visibility is low."
- "Based on CVG's fence line that is easily accessible. The time and manpower involved for a UAS flight is overly cumbersome."

The second statement was: “Based on what you have seen, it is practical to use UASs to perform perimeter inspections and surveillance rather than accomplishing these tasks on foot or in ground vehicles.” The response to this statement was mixed, with 60% selecting “neither agree nor disagree,” 20% selecting “agree,” and 20% selecting “Disagree.”

Generally, subjects expressed that UAS would be less efficient than current means of completing perimeter inspections and surveillance for areas that are easily accessible. They did, however, mention that in certain circumstances, such as at night or in inaccessible areas, UAS would provide a benefit that outweighs any inefficiencies. Following are comments regarding the practicality of using UASs for perimeter inspections and surveillance:

- “In its current state, regular patrols on foot are most likely more efficient. There is a significant night benefit at this time. It is also helpful for non-planned responses day or night for wildlife or suspicious persons reports.”
- “Still need an increase in operational efficiency for perimeter fence inspection. However there are other use cases ops would be interested in, airfield sign/marking inspection, pavement.”
- “As discussed, we need to see washouts, locks in perimeter gates, animals/traps, dig holes, etc. Bad weather-What is practical and what are the limitations of the drone? How long can drone operate at a time? Issues with lens capability, washout in daylight, etc.”
- “Practical if unmanned. If must be manned, then not as beneficial.”
- “For CVG: As stated prior, the amount of time required (someone viewing a perimeter check) is not an efficient use of manpower. For a non-accessible area, I see a definite need.”

The final statement in this section was: “Live video streaming to an operations or security office provides a meaningful benefit for monitoring UAS perimeter inspection operations.” Responses to this statement were mixed but generally positive. Sixty percent of subjects selected “agree” or “strongly agree,” while 20% selected “neither agree nor disagree,” and 20% selected “strongly disagree.” Comments received regarding the perceived benefits of live-streaming video from UASs to an operations or security office included:

- “Strongly agree if autonomous. In current state I don't see a lot of value for perimeter security. A lot of value in streaming for unplanned event.”
- “Additional eyes never hurt. Use case for AI implementation.”
- “Just think this is an obvious application.”
- “If it is fed to airport ops, then yes.”
- “Not [an] efficient use of time.”

4.5.3.3.2 Benefits and Limitations Assessment

This section included five open-ended questions intended to assess SME opinions regarding how UASs could be used to benefit perimeter inspections and surveillance the most, as well as the limitations that must be overcome to maximize these benefits.

The first question in this section was: “What are the most significant benefits you see in this technology?” The most cited benefits were the ability to conduct surveillance at night with a thermal camera, and for the video to be streamed directly to an operations center. The comments received from subjects included:

- “Autonomous perimeter inspections. Good - view remotely. Best - reports issues and entire footage doesn't have to be viewed. Night flights provide significant benefit no matter what.”
- “Starting point for use in UAS applications at CVG.”
- “Definitely [for] nighttime operations. Ability to reach more remote areas.”
- “I see many benefits from a security aspect. Better visuals, different angles, etc.”
- “The night vision/FLIR capabilities would be helpful when searching for humans or animals.”
- “Live video streaming to an operations or security office provides a meaningful benefit for monitoring perimeter security UAS operations.”

The second question asked subjects, “What do you see as the biggest hurdles to implementing this technology?” The most common response to this question referenced the increased time UAS operations require versus traditional ground inspections, and operational limitations UASs are subject to, such as weather and line-of-sight regulations. The comments received from subjects included:

- “BVLOS hurdles. Incorporation of AI.”
- “Policy, user implementation.”
- “As mentioned earlier, weather, time used, lens capability, AI integration.”
- “Changing old school mindsets to accept new tech. Cost of operations vs. one officer driving perimeter.”
- “With no AI capabilities to generate a status report, it would take too much time.”

Following are responses to the question: “Do you see value in using UASs to perform perimeter surveillance at night?” Subjects unanimously agreed that UAS would provide value for conducting surveillance at night when equipped with a thermal camera payload. The comments received from subjects included:

- “Yes. A lot.”
- “Absolutely, increase in visibility using FLIR.”
- “Yes, but as mentioned earlier, the ability to see unlocked gates, holes in fencing, etc.”
- “Yes, the most value would be at night.”
- “Yes, if AI capabilities are incorporated.”

The final question in this section was: “Would you be interested in using UASs to respond to perimeter alarms or security breaches?” Subjects again unanimously agreed that a UAS would be a tool they would like to implement for responding to potentially dangerous ongoing security situations at the airport. The comments received from subjects included:

- "Yes. There is significant cost though to add detection systems for an airport of our size."
- "Yes."
- "Again, obviously yes. Need to ensure a quick start up and application. Time is of the essence in these cases. How does the human element impact actual operation and start-up?"
- "Yes, if police personnel were involved. SSI has to be maintained."
- "Yes, in conjunction with human response."

4.6 PHASE 2 FINDINGS SUMMARY

The findings from the results of the testing conducted during Phase 2 are presented below.

Overall Findings:

- For perimeter inspections, UASs provided the greatest benefit when used to inspect areas that are inaccessible from the ground and cannot be seen while on foot or in a ground vehicle.
- UASs provided the most benefit when conducting a patrol after dark using a thermal camera payload.
- Due to operational limitations of using UASs, including the time required to set up and pack up, the need for battery changes, and the requirement to remain within line-of-sight, UASs did not offer a time-saving benefit for inspections of perimeter sections that can be easily accessed or viewed from the ground.
- Testing confirmed that the level of detail visible in both recorded and live payload feeds is limited and does not meet the level of detail that is visible when conducting an in-person inspection on foot or in a vehicle.
- Evaluators felt that the most immediate benefit UASs can provide for perimeter inspections and surveillance is during night operations when equipped with a thermal camera, or for inspecting or surveilling areas that cannot be easily accessed on foot or in a vehicle.
- Evaluators agreed that UASs would provide benefit for responding to perimeter alarms or ongoing security situations.
- Evaluators generally agreed that live-streaming the UAS payload video to a security operations center would greatly enhance situational awareness during security incidents.

Flight Parameters:

- For daylight fence inspections, testing confirmed that flights with a 30-ft offset, and approximately 30-degree horizontal camera angle produced the most useful footage. These flights should take place at the lowest safe and practical altitude, preferably 40 ft AGL or lower.
- UAS flights directly over the fence looking forward provided the greatest overall situational awareness for general surveillance purposes (e.g., detecting open gates and

unauthorized persons or vehicles) and are best suited for areas where obstructions limit the ability of the UAS to fly at an offset to the fence line.

Unmanned Aircraft System Platforms:

- Evaluators preferred the larger (7.85″) GCS monitor of the M210.
- Evaluators preferred the brighter (1,000 nit or greater) displays of the M210 and M2ED.
- Evaluators preferred the portability and ease of deployment of smaller UAS platforms (M2ED and ANAFI USA) that are compact in size and require minimal assembly.

Payload Performance:

- For live-streamed video, 720p (1280x720) was found to be an acceptable minimum resolution.
- For recorded video, a resolution of 1080p (1920x1080) was confirmed to provide the best combination of image quality and manageable file size.
- 320x256 was confirmed to be the minimum acceptable resolution for thermal camera footage.
- Optical zoom and hybrid optical/digital zoom are highly effective for conducting more thorough inspections of areas of interest.

Additional Considerations:

- When operating in an area with varying elevation, UAS flight path altitudes should be designed to remain at a consistent altitude relative to the highest elevation in the flight area. Because the altitude indicated on the GCS is relative to the take-off point, operators should launch the UAS from the highest elevation possible to maximize the accuracy and usefulness of the altitude readout on the GCS.

5. SUMMARY

Sections 5.1 through 5.3 summarize the findings regarding the benefits and limitations of using UASs for airport perimeter inspections, recommended performance specifications, and additional technical and operational considerations.

5.1 BENEFITS AND LIMITATIONS

Sections 5.1.1 and 5.1.2 summarize benefits and limitations of using UASs for airport perimeter inspections.

5.1.1 Benefits

UASs were found to provide a significant benefit for supplementing airport perimeter inspections and surveillance, particularly for perimeter areas that cannot be easily accessed or viewed on foot or in a ground vehicle. In addition, UASs are beneficial for conducting surveillance for unauthorized persons or vehicles, particularly after dark while equipped with a thermal camera payload. Following are additional benefits of using UASs for perimeter inspections and surveillance:

- UASs can enhance the safety of airport operations personnel by allowing them to remotely inspect or surveil potentially dangerous areas around the airport perimeter.

- UASs greatly enhance the ability for operations or security personnel to patrol for unauthorized persons or vehicles near the perimeter. In some cases, a UAS might be able to see things that could never be spotted during a typical ground patrol.

- Specialized payloads further increase the ability of UASs to increase situational awareness. Cameras with enhanced zoom allow for identification of unauthorized individuals or detailed inspection of damage. Thermal camera payloads allow for the detection of unauthorized persons or vehicles after dark.

- In the instance of a triggered alarm or perimeter breach, UASs could enhance safety of responding personnel by providing situational awareness of the scene while maintaining a safe distance.

- By streaming the live payload feed directly to a security operations center or other relevant stakeholders, UASs can facilitate quick and efficient collaboration if an anomaly or situation is observed that requires immediate action.

5.1.2 Limitations

FAA researchers identified several limitations in conducting UAS perimeter inspections and surveillance. Due to these limitations, it is recommended that UASs be used to supplement, rather than replace, ground-based perimeter inspections and surveillance.

- The level of detail captured by UAS during inspections was not found to be sufficient to see fine details such as whether AOA gates are locked, if there is slight damage to the fencing, or if erosion is present under the fence.

- Operations could be limited by ATC and airspace restrictions. The ATC facility may disapprove, restrict, or delay UAS flight operations covered by an airspace authorization at any time. Additionally, UAS operations could be limited by temporary flight restrictions (TFR). RPICs are required to check the airspace they are operating in and comply with all restrictions that might be present in accordance with 14 CFR §107.45 and §107.49 (a)(2), such as a TFR. A TFR defines an area restricted to air travel due to a hazardous condition, a special event, or a general warning for the entire FAA airspace.

- In many cases, UASs did not increase the efficiency of conducting an inspection of a given area when compared to a traditional ground-based patrol. UAS operations on an airfield typically require at least two personnel (a RPIC and VO), compared to single individual conducting a traditional perimeter patrol. Additionally, a human is required to review the video footage captured by the UAS (either in real-time, or from recorded footage). UASs also require personnel to travel to the section of the perimeter to be inspected, set up the base of operations, conduct the flight, tear down the base, and return. This entire process can present a significant time constraint and could take longer than conducting the inspection on foot or in a ground vehicle.

- UAS operations can also be limited by weather conditions at the time of the operation. The RPIC must consider the operating limitations of the UAS and the weather, including the temperature, precipitation, and wind speed, to ensure operations can be safely conducted (refer to Section 5.3.5 for additional information regarding UAS environmental tolerances). Also, 14 CFR 107.51, *Operating Limitations for Small Unmanned Aircraft*, requires no less than 3 statute miles (SMs) of visibility and 500-ft vertical/2,000-ft horizontal separation from clouds, limiting the ability to legally conduct UAS operations in these conditions. However, it is possible to obtain an operational waiver of this requirement from the FAA.

5.2 RECOMMENDED PERFORMANCE SPECIFICATIONS

Based on the findings from testing and analysis of the capabilities of current technologies, FAA researchers created recommended UAS performance specifications for conducting airport perimeter inspections. These performance specifications address general UAS platform (features and capabilities) and payload, including visual and thermal cameras. Appendix E presents these performance specifications in table format.

5.2.1 Unmanned Aircraft System Platform

The following are the recommended minimum UAS platform requirements to enhance safety, ensure consistency, and minimize the task load on the operator:

- The UAS must be capable of stable and predictable flight behavior and must be able to maintain a stationary hover without input from the RPIC.
- The UAS must be capable of executing preprogrammed waypoint flight plans.
- The UAS must have the capability of restricting horizontal and vertical flight boundaries using a programmable geofence.
- The UAS must include a return-to-home failsafe feature in case of control link loss.
- For night and twilight operations, the UAS must be equipped with an anti-collision light visible from at least 3 SMs. This lighting requirement is based on Title 14 CFR § 107.29, Paragraph (b) (Operation at Night, 2022).
- When stored, all components of the UAS must be resistant to the typical shocks and forces a ground vehicle can be subjected to, including off-road driving.

5.2.2 Payload

Sections 5.2.2.1 through 5.2.2.3 contain the minimum payload requirements.

5.2.2.1 General

The following are the recommended requirements for the required payload sensors:

- If used solely for daylight inspections, the UASs must be equipped with a visual camera payload.
- If used after dark, the UASs must be equipped with a thermal camera payload.

5.2.2.2 Visual Camera

The following are the recommended minimum visual camera requirements:

- The visual camera must transmit live footage with a minimum resolution of 720p (1280x720).
- The visual camera must record footage with a minimum resolution of 1080p (1920x1080).
- The visual camera must record footage with a minimum frame rate of 30 FPS.
- The visual camera must be capable of automatically focusing to minimize the task load on the operator.
- The visual camera must be capable of automatically adjusting the exposure.

5.2.2.3 Thermal Camera

The following are the recommended minimum thermal camera requirements:

- The thermal camera must detect long-wave infrared (LWIR) energy (8 μm to 12 μm). This is the most effective wavelength for human, vehicle, and wildlife detection and is the predominant type of thermal camera available for UASs. Because LWIR sensors do not require internal cooling, they have a low size, weight, and power characteristics.
- The thermal camera must have a minimum resolution of 640x512. During testing, this resolution provided a superior level of performance compared to the lower resolution thermal camera payloads, allowing evaluators to identify individuals and vehicles in a variety of environments.
- The thermal camera must have a minimum refresh rate (frame rate) of 30 Hz. A 30-Hz refresh rate provides smoother video of objects and people in motion than a lower refresh rate, such as 9 Hz. A refresh rate of 30 Hz will also ensure that the thermal video is visually in sync with the visual camera video.
- The thermal camera must include automatic focus and gain control to ensure clarity and the ability to detect details,
  such as people and vehicles, as temperatures in the frame change.
- The thermal camera must have a high-contrast filter that will show low-contrast objects in a dynamic thermal scene.

5.2.2.4 Gimbal

The following are the recommended minimum payload gimbal requirements:

- The payload gimbal must have 3-axis stabilization (yaw, pitch, and roll) and a vibration dampening mount to ensure the video remains as steady as possible.
- The payload gimbal must have a controllable vertical range of motion of -90 to 0 degrees, and a horizontal range of motion of 360 degrees to allow viewing in all directions below the UAS.

5.3 TECHNICAL AND OPERATIONAL CONSIDERATIONS

In addition to performance specifications, FAA researchers made the following recommendations regarding technical and operations considerations for the use of UASs to conduct perimeter inspections and surveillance at airports. These include general UAS characteristics, UAS operation, payloads, GCS, user interface, and UAS environmental tolerances.

5.3.1 General Unmanned Aircraft System Characteristics

The following are general considerations for selecting an UAS:

- Rapid deployment and minimizing downtime are critical to maximizing UASs benefit for perimeter inspections. Operators should consider the size, portability, and ease of deployment of a UAS when selecting a platform. Compact UAS platforms with integrated payloads and fold-out airframes requiring minimal assembly (e.g., fold-out airframe, integrated payload, integrated GCS, and controller) were the easiest and fastest to deploy.
- A UAS in its case should be able to be stored in a compartment on an airport operations vehicle for maximum protection and ease of transport. Some airport operators might choose to deploy the UAS from other types of vehicles, such as pick-up trucks or SUVs.
- Operators should consider the flight endurance (i.e., the length of time a UA can remain airborne before needing to replace batteries), typically from 20 to 40 minutes, when selecting a UAS. The actual amount of flight time will be less than the specified flight time due to the presence of wind, use of external payloads, and the need to maintain enough reserve power for emergency purposes (typically 20%). To complete an inspection of an airport with a large perimeter, operators would most likely need to land and change batteries several times.

5.3.2 Unmanned Aircraft System Operation

The following are considerations for the operation of a UAS:

- Optimal UAS flight plan parameters, including offset, horizontal camera angle, and altitude, will vary based on the use case and operating environment.
- For daylight inspections of fence condition, flights with a 30-ft offset and 30- to 45-degree horizontal camera angle are most effective.

- For surveillance, flights conducted directly over the fence at a 0-ft offset and 0-degree horizontal camera angle are most effective for maximizing visibility on both sides of the perimeter fence. In addition, flights with these parameters should be employed when inspecting sections of the perimeter with obstructions near to the fence that prevent flying at an offset.
- Low altitudes provide footage with greater detail. Operators should seek to balance capturing detail with avoiding obstacles and maintaining safety.
- When flying at an offset to the fence, it is recommended that operators ensure the UAS always remains at least 20 ft above the ground. When conducting operations at a 0-ft offset, it is recommended that operators ensure the UAS remains 40 ft above the highest point on the ground.
- When areas with varying elevations are present, the operator should ensure that the UAS remains at a safe altitude. AGL altitudes reported by the UAS on the GCS are typically the altitude above the take of position. Operators should seek to launch the UAS from the highest elevation they can to maximize the usefulness of the altitude readout on the GCS. When flight planning, the altitude should be set relative to the highest elevation present in the flight area.
- Flying at a slower speed increases the level of detail captured in the footage. Operators should balance capturing detail with completing the inspection in a timely manner. It is recommended that operators conduct initial inspections at 10 to 15 mph and adjust the speed higher or lower to suit their specific use case and needs.
- Camera pitch angles should be adjusted to account for the altitude of flight and the operating environment. Camera pitch should ensure the fence being inspected is centered in the frame while keeping the camera pitch as shallow as possible to increase situational awareness and minimize the sense of motion.
- Operators should ensure that they have FAA and ATC authorization when operating in controlled airspace. This includes making the proper notifications to ATC and airport stakeholders prior to each UAS operation.
- Operators must ensure that they comply with all 14 CFR Part 107 regulations, including remaining within visual line-of-sight of the RPIC.

5.3.3 Payloads

The following are considerations regarding the payload and sensors:

- The capability to blend visual and thermal video helped enhance the clarity of lower resolution thermal cameras, but this benefit was significantly degraded in low-light conditions. Blending visual and thermal video does not provide a suitable replacement for higher resolution payloads.
- It is recommended that the visual camera payload should be capable of optical zoom with a minimum of 10x magnification. Visual camera payloads with optical zoom outperformed those without this feature. Optical zoom allows airport operations personnel to inspect small details from a distance, enhancing the ability of the UAS to perform a thorough inspection.
- Resolution significantly affects the file sizes of recorded video. The files sizes of 4K resolution video can be up to four times greater than 1080p.

5.3.4 Ground Control Stations and User Interface

The following are considerations for selecting a GCS:

- The minimum recommended resolution for the GCS monitor is 1280x720 (720p).
- The minimum recommended size for the GCS monitor is 7 in. (diagonally) to ensure ease of UAS operation and viewing payload footage.
- The minimum peak brightness of the screen should be 1,000 nits.
- The GCS should display a user interface that provides the following information on screen: current UA altitude (AGL), speed, global navigation satellite system (GNSS) signal strength, flight mode, current GNSS coordinates, distance and location (relative to the launch location), live video feeds, battery percentage, and estimated remaining flight time.
- The graphical user interface should be capable of providing simultaneous visual and thermal video feeds in a side-by-side or picture-in-picture format.
- The user interface should provide full pan-tilt-zoom controls of the visual and thermal payloads.
- The GCS should have the capability to display the live payload feed on an external monitor either wirelessly or through a direct connection.
- The GCS should include a function to capture a screenshot of the on-screen content.

5.3.5 Environmental Tolerances

The following are considerations regarding the environmental tolerance of the UAS:

- It is recommended that if UASs are used in mild inclement weather, the platform selected have a minimum ingress protection (IP) rating of IP-43. This IP rating would provide protection from the effects of dust and other solid particles, and protection from water spray up to 60 degrees from vertical.

  The International Electrotechnical Commission (IEC) has established a rating system to categorize a device’s ability to resist dust and water, known as an IP rating. An IP rating contains two digits, with higher numbers indicating a higher level of protection. As shown in Table 11, the first digit specifies the level of resistance to dust and solid objects, from 0 (no protection) to 6 (dust tight). The second digit specifies resistance to water, from 0 (no protection) to 9 (protected from high pressure and temperature water jets from all directions).

Table 11. The IP Rating Matrix (IEC, n.d.)

Dust (First Number)	Moisture (Second Number)
IP 0x—No Protection	IP x0—No protection
IP 1x—Objects ≥50mm	IP x1—Vertically falling water
IP 2x—Objects ≥12mm	IP x2—Vertically falling water when enclosure tilted up to 15 degrees
IP 3x—Objects ≥2.5mm	IP x3—Sprayed water (up to 60 degrees from vertical)
IP 4x—Objects ≥1mm	IP x4—Splashed water (from all directions)
IP 5x—Dust Protected (Vacuum)	IP x5—Low-pressure water jets (from all directions)
IP 6x—Dust Tight	IP x6—Powerful water jets (from all directions)
	IP x7—Temporary immersion
	IP x8—Indefinite immersion
	IP x9—High-pressure and temperature water jets (from all directions)

- The operator should select a UAS with an operating temperature range that encompasses all conditions a specific airport is likely to experience.
- The UAS should be able to operate in sustained winds as specified by the manufacturer and should provide an on-screen alert if wind conditions exceed operating limits.

6. CONCLUSION

The Federal Aviation Administration's (FAA) Airport Technology Research and Development Branch conducted a research effort to explore the use of small unmanned aircraft systems (UASs) for conducting perimeter inspections and surveillance in the airport environment. The objectives of this effort were to identify benefits and limitations and to develop minimum recommended performance specifications and technical/operational considerations for the use of UASs to conduct perimeter inspections and surveillance.

This research effort was conducted in two phases. Phase 1 tested various flight plan parameters, UASs, and payloads at Cape May County Airport (WWD) to develop preliminary performance specifications and best practices on how to use UASs to conduct perimeter inspections and surveillance. During Phase 1, 168 UAS flights were conducted during daylight and night conditions. Phase 2 consisted of validation testing at three airports with varying environments and size, McGhee Tyson Airport (TYS), Savannah/Hilton Head International Airport (SAV), and Cincinnati/Northern Kentucky International Airport (CVG), to further evaluate the benefits and limitations of UASs and validate the recommended performance specifications and technical/operational considerations of using UASs for airport perimeter inspections. During Phase 2, 50 UAS flights were conducted in daylight, twilight, and night conditions. Both during and following these flight operations, FAA researchers collected feedback from airport operations and perimeter security subject matter experts to determine the flight parameters and technologies that provided the most benefit.

FAA researchers found that UASs equipped with thermal and visual cameras provided a significant benefit for inspecting hard-to-reach or inaccessible areas and detecting unauthorized persons or vehicles. However, the detail visible during UAS inspections of fencing is limited by payload resolution and the elevated viewing angle, making it difficult to see certain types of security concerns, such as gate locks, erosion under the fence, and damage to chain links. Due to this inability to see fine detail, it is recommended that UASs be used to supplement, rather than replace, current methods of conducting visual inspections of airport perimeters. Additional limitations of using UASs for airport perimeter inspections included weather, the requirement to remain within line-of-sight, and the increased time required to deploy UASs versus performing a ground inspection.

Minimum recommended performance specifications were also identified to ensure the effectiveness of the payload video, including minimum recorded resolutions of 1080p (1920x1080) for recorded visual camera footage, 720p (1280x720) for live-streamed visual camera footage, and 640x512 for thermal camera footage.

FAA researchers also developed technical and operational guidance to maximize the benefits of UASs for airport perimeter inspections. This guidance addresses technical aspects such as the UAS, ground control stations, and payloads; and operational considerations regarding using UASs to perform perimeter inspections and surveillance.

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APPENDIX A—UNMANNED AIRCRAFT SYSTEM PLATFORM SPECIFICATIONS

A.1 INTRODUCTION

This appendix provides the specifications for the small unmanned aircraft system (UAS) platforms used during this research effort. Table A-1 shows the specifications for the Da-Jiang Innovations (DJI) Matrice 210 RTK v.2 (DJI M210); Table A-2 shows the specifications for the DJI Mavic Enterprise Dual System (M2ED); and Table A-3 shows the specifications for the Parrot ANAFI USA platform.

Table A-1. Specifications for the DJI M210 (DJI, 2020)

DJI Matrice 210 RTK v2	
Type	Rotary aircraft (4)
Wingspan	25.3-in. motor-to-motor cross measurement
Weight	10.83 lb with batteries only
Maximum flight time	±25 minutes
Average speed of flight during image capture	±15 mph
Operating temperature range	-4 °F–122 °F
Transmitter range	5 miles (unobstructed)
Communication with transmitter	Radio (2.4000–2.4835 GHz; 5.725– 5.850 GHz)
Maximum sustained wind speed limit for safe flight	Up to 27 mph
Lost link procedure (if > 3 seconds)	Autonomous return-to-home at predetermined AGL with manual override available once link has been reestablished.
Low-battery procedure	Autonomous return-to-home if no action taken by the pilot after 10 seconds. If battery critically low, the UAS will initiate autonomous landing.
Operational area procedure	On-board, preprogrammed flight area prohibits flying outside of predetermined geofence.
Obstacle avoidance	Forward, Down, Above, DJI AirSense (ADS-B Receiver)
Ingress protection rating	IP-43

ADS-B = Automatic Dependence Surveillance-Broadcast
AGL = Above ground level
IP = Ingress Protection

Table A-2. Specifications for the DJI M2ED (DJI, 2021)

Mavic 2 Enterprise Dual	
Type	Rotary aircraft (4)
Wingspan	13.9-in. motor-to-motor cross measurement
Weight	1.98 lb (without accessories)
Maximum Flight Time	31 minutes
Operating Temperature Range	-50 °F–104 °F
Transmitter Range	6.2 miles (unobstructed)
Communication with Transmitter	Radio (2.400–2.483 GHz; 5.725–5.850 GHz)
Maximum sustained wind speed limit for safe flight	Up to 23.6 mph
Lost link procedure (if >2 seconds)	Autonomous return-to-home at predetermined AGL with manual override available once link has been reestablished.
Low-battery procedure	Autonomous return-to-home if no action taken by the pilot after 10 seconds. If battery critically low, the UAS will initiate autonomous landing.
Operational area procedure	Preprogrammed flight area prohibits flying outside of predetermined geofence.
Obstacle avoidance	Omnidirectional – Forward, Backward, Upward, Downward, Sides, DJI AirSense (ADS-B Receiver)

ADS-B = Automatic Dependence Surveillance-Broadcast
AGL = Above ground level

Table A-3. Specifications for the Parrot ANAFI USA (Parrot, 2020)

Parrot Anafi USA	
Type	Rotary aircraft (4)
Wingspan	14.6-in. motor-to-motor cross measurement
Weight	1.0 lb
Maximum flight time	±32 minutes
Average speed of flight during image capture	±15 mph
Operating temperature range	-32 °F–110 °F
Transmitter Range	2.5 miles (unobstructed)
Communication with Transmitter	Radio (2.4000–2.4835 GHz; 5.725–5.850 GHz)
Maximum sustained wind speed limit for safe flight	Up to 33 mph
Lost Link Procedure (if >3 seconds)	Autonomous return-to-home at predetermined AGL with manual override available once link has been reestablished.
Low-battery procedure	Autonomous return-to-home if no action taken by the pilot when there is only enough battery for return-to-home. If battery critically low, the UAS will initiate autonomous landing at current position.
Operational area procedure	No built-in limitation for NFZ, On-board, preprogrammed flight area prohibits flying outside of predetermined geofence—radially limited.
Obstacle avoidance	Down
Ingress protection rating	IP-53

AGL = Above ground level
IP = Ingress Protection
NFZ = No-fly zone

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APPENDIX B—UNMANNED AIRCRAFT SYSTEM PAYLOAD SPECIFICATIONS

B.1 INTRODUCTION

This appendix provides the payload specifications for the small unmanned aircraft system (UAS) platforms used in the current research. Table B-1 shows the specifications for the Da-Jiang Innovations (DJI) Zenmuse XT2; Table B-2 shows the specifications for the DJI Zenmuse Z30; Table B-3 shows the specifications for the M2ED Visual and Thermal Cameras; and Table B-4 shows the specifications for the Parrot ANAFI Triple payload.

Table B-1. Specifications for the DJI Zenmuse XT2 (DJI, 2018)

DJI Zenmuse XT2	
Gimbal control (3D Stabilized)	Tilt: +45° to -130° Pan: ±330° Roll: -90° to +60°
Visual camera sensor	1/1.7-in. CMOS, 12 MP
Visual camera resolution	4K; 1080p
Visual camera frame rate	29.97 FPS
Visual camera FOV	57.12°x42.44°
Digital zoom	Thermal—1x, 2x, 4x, 8x Visual—1x, 2x, 4x, 8x (Live-view only)
Thermal camera sensor	FLIR Tau2 Uncooled VOx Microbolometer
Thermal camera resolution	9mm: 336x256 13mm/19mm/25mm: 640x512
Thermal camera frame rate	30 Hz
Thermal camera FOV	9mm: 35° x 27° 13mm: 45° x 37° 19mm: 32° x 26° 25mm: 25° x 20°
Thermal camera temperature range	High gain: 640x512: -13 °F to 275 °F 336x256: -13 °F to 212 °F Low gain: -40 °F to 1022 °F
Thermal camera spectral band	7.5–13.5 µm
Thermal camera sensitivity	<50 mK
Photo formats	Thermal - JPEG, TIFF, R-JPEG Visual - JPEG
Video format	Thermal—8 bit: MOV, MP4 14 bit: TIFF Sequence, SEQ** Visual—MOV, MP4

FLIR = Forward-looking infrared
FOV = Field of view
FPS = Frames per second

Table B-2. Specifications for the DJI Zenmuse Z30 (DJI, 2019)

DJI Zenmuse Z30	
Gimbal control (3D Stabilized)	Pitch: -120° to +30° Pan: ±320° Roll: +90° to -50°
Visual camera sensor	1/2.8-in. CMOS, 2.13 MP
Visual camera resolution	1080p
Visual camera frame rate	30 Hz
Visual camera FOV	63.7° (wide) to 2.3° (max zoom)
Digital zoom	6x
Optical zoom	30x
Photo format	JPEG
Video formats	MOV, MP4

FOV = Field of view

Table B-3. Specifications for the M2ED Integrated Payload (DJI, 2021)

M2ED Thermal/Visual Camera	
Gimbal control (3D Stabilized)	Tilt: -135 – +45° Pitch: -90- – +30 ° Pan: -100 – +100°
Visual camera sensor	1/2.3-in. CMOS, 12MP
Visual camera resolution	4K; 2688x1512; 1080p
Visual camera frame rate	30 FPS
Visual camera FOV	85°
Digital zoom	3x
Thermal camera sensor	FLIR Lepton Uncooled VOx Microbolometer
Thermal camera resolution	160x120
Thermal camera framerate	8.7 Hz
Thermal camera FOV	57° Horizontal
Thermal camera temperature range	High gain: 14 °F to 284 °F Low gain: 14 °F to 752 °F
Thermal camera spectral band	8–14 µm
Thermal camera sensitivity	<50 mK
Photo Formats	JPEG
Video Formats	Thermal/Visual:MP4, MOV (MPEG-4 AVC/H.264)

FLIR = Forward-looking infrared
FOV = Field of view
FPS = Frames per second

Table B-4. Specifications for the Parrot ANAFI Triple (Parrot, 2020)

Parrot ANAFI Triple	
Gimbal control (3D Stabilized)	Pitch: -140° – +110°
Visual camera sensors	(2) 1/2.4″ CMOS Wide: 21MP Rectilinear: 16MP
Visual camera resolution	4K; 1080p
Visual camera frame rate	24/25/30/48/50/60 FPS
Visual camera FOV	Wide: 84° Rectilinear: Up to 75.5°
Digital zoom	32x
Thermal camera sensor	FLIR Boson
Thermal camera resolution	320x256
Thermal camera frame rate	9 Hz
Thermal camera FOV	Not specified.
Thermal camera temperature range	-40 °F to 302 °F
Thermal camera spectral band	7.5–13 µm
Thermal camera sensitivity	<60 mK
Photo formats	JPEG, DNG
Video format	MP4

FLIR = Forward-looking infrared
FOV = Field of view
FPS = Frames per second

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APPENDIX C—PHASE 1 TEST PARAMETERS

This appendix provides the test parameters used during Phase 1A (Table C-1) and Phase 1B (Table C-2) UAS testing conducted at the Cape May County Airport (WWD).

Table C-1. Test Parameters: Phase 1A Testing

Test #	Payload	Horizontal Camera Angle	Offset	Altitude	Lighting
1	XT2 9mm	0°	0 ft	30 ft	Daylight
2	XT2 9mm	0°	0 ft	40 ft	Daylight
3	XT2 9mm	0°	0 ft	60 ft	Daylight
4	XT2 9mm	0°	0 ft	80 f.	Daylight
5	XT2 9mm	0°	0 ft	100 ft	Daylight
6	XT2 9mm	30°	30 ft	10 ft	Daylight
7	XT2 9mm	30°	30 ft	20 ft	Daylight
8	XT2 9mm	30°	30 ft	30 ft	Daylight
9	XT2 9mm	30°	30 ft	40 ft	Daylight
10	XT2 9mm	30°	30 ft	60 ft	Daylight
11	XT2 9mm	30°	30 ft	80 ft	Daylight
12	XT2 9mm	90°	30 ft	10 ft	Daylight
13	XT2 9mm	90°	30 ft	20 ft	Daylight
14	XT2 9mm	90°	30 ft	30 ft	Daylight
15	XT2 9mm	90°	30 ft	40 ft	Daylight
16	XT2 9mm	90°	30 ft	60 ft	Daylight
17	XT2 9mm	90°	30 ft	80 ft	Daylight
18	XT2 13mm	0°	0 ft	30 ft	Daylight
19	XT2 13mm	0°	0 ft	40 ft	Daylight
20	XT2 13mm	0°	0 ft	60 ft	Daylight
21	XT2 13mm	0°	0 ft	80 ft	Daylight
22	XT2 13mm	0°	0 ft	100 ft	Daylight
23	XT2 13mm	30°	30 ft	10 ft	Daylight
24	XT2 13mm	30°	30 ft	20 ft	Daylight
25	XT2 13mm	30°	30 ft	30 ft	Daylight
26	XT2 13mm	30°	30 ft	40 ft	Daylight
27	XT2 13mm	30°	30 ft	60 ft	Daylight
28	XT2 13mm	30°	30 ft	80 ft	Daylight
29	XT2 13mm	90°	30 ft	10 ft	Daylight
30	XT2 13mm	90°	30 ft	20 ft	Daylight
31	XT2 13mm	90°	30 ft	30 ft	Daylight
32	XT2 13mm	90°	30 ft	40 ft	Daylight
33	XT2 13mm	90°	30 ft	60 ft	Daylight

Test #	Payload	Horizontal Camera Angle	Offset	Altitude	Lighting
34	XT2 13mm	90°	30 ft	80 ft	Daylight
35	Zenmuse X5S	0°	0 ft	30 ft	Daylight
36	Zenmuse X5S	0°	0 ft	40 ft	Daylight
37	Zenmuse X5S	0°	0 ft	60 ft	Daylight
38	Zenmuse X5S	0°	0 ft	80 ft	Daylight
39	Zenmuse X5S	0°	0 ft	100 ft	Daylight
40	Zenmuse X5S	30°	30 ft	10 ft	Daylight
41	Zenmuse X5S	30°	30 ft	20 ft	Daylight
42	Zenmuse X5S	30°	30 ft	30 ft	Daylight
43	Zenmuse X5S	30°	30 ft	40 ft	Daylight
44	Zenmuse X5S	30°	30 ft	60 ft	Daylight
45	Zenmuse X5S	30°	30 ft	80 ft	Daylight
46	Zenmuse X5S	90°	30 ft	10 ft	Daylight
47	Zenmuse X5S	90°	30 ft	20 ft	Daylight
48	Zenmuse X5S	90°	30 ft	30 ft	Daylight
49	Zenmuse X5S	90°	30 ft	40 ft	Daylight
50	Zenmuse X5S	90°	30 ft	60 ft	Daylight
51	Zenmuse X5S	90°	30 ft	80 ft	Daylight
52	XT2 9mm	0°	0 ft	30 ft	Night
53	XT2 9mm	0°	0 ft	40 ft	Night
54	XT2 9mm	0°	0 ft	60 ft	Night
55	XT2 9mm	0°	0 ft	80 ft	Night
56	XT2 9mm	0°	0 ft	100 ft	Night
57	XT2 9mm	30°	30 ft	10 ft	Night
58	XT2 9mm	30°	30 ft	20 ft	Night
59	XT2 9mm	30°	30 ft	30 ft	Night
60	XT2 9mm	30°	30 ft	40 ft	Night
61	XT2 9mm	30°	30 ft	60 ft	Night
62	XT2 9mm	30°	30 ft	80 ft	Night
63	XT2 13mm+Z15 Spotlight	0°	0 ft	30 ft	Night
64	XT2 13mm+Z15 Spotlight	0°	0 ft	40 ft	Night
65	XT2 13mm+Z15 Spotlight	0°	0 ft	60 ft	Night
66	XT2 13mm+Z15 Spotlight	0°	0 ft	80 ft	Night
67	XT2 13mm+Z15 Spotlight	0°	0 ft	100 ft	Night
68	XT2 13mm+Z15 Spotlight	30°	30 ft	10 ft	Night
69	XT2 13mm+Z15 Spotlight	30°	30 ft	20 ft	Night
70	XT2 13mm+Z15 Spotlight	30°	30 ft	30 ft	Night
71	XT2 13mm+Z15 Spotlight	30°	30 ft	40 ft	Night
72	XT2 13mm+Z15 Spotlight	30°	30 ft	60 ft	Night
73	XT2 13mm+Z15 Spotlight	30°	30 ft	80 ft	Night

Table C-2. Test Parameters: Phase 1B Testing

Test #	Test Area	UAS	Payload	Horizontal Camera Angle	Offset	Altitude
1	1	DJI M210	XT2 9mm	0°	0 ft	40 ft
2	1	DJI M210	XT2 13mm	0°	0 ft	40 ft
3	1	DJI M210	XT2 19mm	0°	0 ft	40 ft
4	1	DJI M210	XT2 25mm	0°	0 ft	40 ft
5	1	DJI M210	XT2 9mm	0°	0 ft	100 ft
6	1	DJI M210	XT2 13mm	0°	0 ft	100 ft
7	1	DJI M210	XT2 19mm	0°	0 ft	100 ft
8	1	DJI M210	XT2 25mm	0°	0 ft	100 ft
9	1	DJI M210	XT2 9mm	30°	30 ft	20 ft
10	1	DJI M210	XT2 13mm	30°	30 ft	20 ft
11	1	DJI M210	XT2 19mm	30°	30 ft	20 ft
12	1	DJI M210	XT2 25mm	30°	30 ft	20 ft
13	1	DJI M210	X5S	0°	0 ft	40 ft
14	1	DJI M210	X5S	0°	0 ft	100 ft
15	1	DJI M210	X5S	30°	30 ft	20 ft
16	1	DJI M210	Z30	0°	0 ft	40 ft
17	1	DJI M210	Z30	0°	0 ft	100 ft
18	1	DJI M210	Z30	30°	30 ft	20 ft
19	1	DJI M2ED	M2ED	0°	0 ft	40 ft
20	1	DJI M2ED	M2ED	0°	0 ft	100 ft
21	1	DJI M2ED	M2ED	30°	30 ft	20 ft
22	1 Reverse	DJI M210	XT2 9mm	0°	0 ft	40 ft
23	1 Reverse	DJI M210	XT2 13mm	0°	0 ft	40 ft
24	1 Reverse	DJI M210	XT2 19mm	0°	0 ft	40 ft
25	1 Reverse	DJI M210	XT2 25mm	0°	0 ft	40 ft
26	1 Reverse	DJI M210	XT2 9mm	0°	0 ft	100 ft
27	1 Reverse	DJI M210	XT2 13mm	0°	0 ft	100 ft
28	1 Reverse	DJI M210	XT2 19mm	0°	0 ft	100 ft
29	1 Reverse	DJI M210	XT2 25mm	0°	0 ft	100 ft
30	1 Reverse	DJI M210	XT2 9mm	30°	30 ft	20 ft
31	1 Reverse	DJI M210	XT2 13mm	30°	30 ft	20 ft
32	1 Reverse	DJI M210	XT2 19mm	30°	30 ft	20 ft
33	1 Reverse	DJI M210	XT2 25mm	30°	30 ft	20 ft
34	1 Reverse	DJI M210	X5S	0°	0 ft	40 ft
35	1 Reverse	DJI M210	X5S	0°	0 ft	100 ft
36	1 Reverse	DJI M210	X5S	30°	30 ft	20 ft
37	1 Reverse	DJI M210	Z30	0°	0 ft	40 ft

Test #	Test Area	UAS	Payload	Horizontal Camera Angle	Offset	Altitude
38	1 Reverse	DJI M210	Z30	0°	0 ft	100 ft
39	1 Reverse	DJI M210	Z30	30°	30 ft	20 ft
40	1 Reverse	DJI M2ED	M2ED	0°	0 ft	40 ft
41	1 Reverse	DJI M2ED	M2ED	0°	0 ft	100 ft
42	1 Reverse	DJI M2ED	M2ED	30°	30 ft	20 ft
43	2	DJI M210	XT2 9mm	0°	0 ft	100 ft
44	2	DJI M210	XT2 13mm	0°	0 ft	100 ft
45	2	DJI M210	XT2 19mm	0°	0 ft	100 ft
46	2	DJI M210	XT2 25mm	0°	0 ft	100 ft
47	2	DJI M210	XT2 9mm	30°	30 ft	20 ft
48	2	DJI M210	XT2 13mm	30°	30 ft	20 ft
49	2	DJI M210	XT2 19mm	30°	30 ft	20 ft
50	2	DJI M210	XT2 25mm	30°	30 ft	20 ft
51	2	DJI M210	X5S	0°	0 ft	100 ft
52	2	DJI M210	X5S	30°	30 ft	20 ft
53	2	DJI M210	Z30	0°	0 ft	100 ft
54	2	DJI M210	Z30	30°	30 ft	20 ft
55	2	DJI M2ED	M2ED	0°	0 ft	100 ft
56	2	DJI M2ED	M2ED	30°	30 ft	20 ft
57	2 Reverse	DJI M210	XT2 9mm	0°	0 ft	100 ft
58	2 Reverse	DJI M210	XT2 13mm	0°	0 ft	100 ft
59	2 Reverse	DJI M210	XT2 19mm	0°	0 ft	100 ft
60	2 Reverse	DJI M210	XT2 25mm	0°	0 ft	100 ft
61	2 Reverse	DJI M210	XT2 9mm	30°	30 ft	20 ft
62	2 Reverse	DJI M210	XT2 13mm	30°	30 ft	20 ft
63	2 Reverse	DJI M210	XT2 19mm	30°	30 ft	20 ft
64	2 Reverse	DJI M210	XT2 25mm	30°	30 ft	20 ft
65	2 Reverse	DJI M210	X5S	0°	0 ft	100 ft
66	2 Reverse	DJI M210	X5S	30°	30 ft	20 ft
67	2 Reverse	DJI M210	Z30	0°	0 ft	100 ft
68	2 Reverse	DJI M210	Z30	30°	30 ft	20 ft
69	2 Reverse	DJI M2ED	M2ED	0°	0 ft	100 ft
70	2 Reverse	DJI M2ED	M2ED	30°	30 ft	20 ft
71	3	DJI M210	XT2 9mm	0°	0 ft	100 ft
72	3	DJI M210	XT2 13mm	0°	0 ft	100 ft
73	3	DJI M210	XT2 19mm	0°	0 ft	100 ft
74	3	DJI M210	XT2 25mm	0°	0 ft	100 ft
75	3	DJI M210	X5S	0°	0 ft	100 ft
76	3	DJI M210	Z30	0°	0 ft	100 ft
77	3	DJI M2ED	M2ED	0°	0 ft	100 ft

Test #	Test Area	UAS	Payload	Horizontal Camera Angle	Offset	Altitude
78	3 Reverse	DJI M210	XT2 9mm	0°	0 ft	100 ft
79	3 Reverse	DJI M210	XT2 13mm	0°	0 ft	100 ft
80	3 Reverse	DJI M210	XT2 19mm	0°	0 ft	100 ft
81	3 Reverse	DJI M210	XT2 25mm	0°	0 ft	100 ft
82	3 Reverse	DJI M210	X5S	0°	0 ft	100 ft
83	3 Reverse	DJI M210	Z30	0°	0 ft	100 ft
84	3 Reverse	DJI M2ED	M2ED	0°	0 ft	100 ft

APPENDIX D—PHASE 2 TEST PARAMETERS

This appendix provides the test parameters used during Phase 2 validation testing at McGhee Tyson Airport (TYS) (Table D-1), Savannah/Hilton Head International Airport (SAV) (Table D-2), and Cincinnati Northern Kentucky International Airport (CVG) (Table D-3).

Table D-1. McGhee Tyson Airport Test Parameters

Test #	UAS	Sensor	Horizontal Camera Angle	Offset	Altitude	Lighting
1	DJI M210	XT2 9mm	0°	0 ft	40 ft	Daylight
2	DJI M210	XT2 9mm	30°	30 ft	20 ft	Daylight
3	DJI M2ED	M2ED	0°	0 ft	40 ft	Daylight
4	DJI M2ED	M2ED	30°	30 ft	20 ft	Daylight
5	Parrot ANAFI USA	ANAFI Triple	0°	0 ft	40 ft	Daylight
6	Parrot ANAFI USA	ANAFI Triple	30°	30 ft	20 ft	Daylight
7	DJI M210	XT2 9mm	0°	0 ft	40 ft	Twilight
8	DJI M210	XT2 9mm	30°	30 ft	20 ft	Twilight
9	DJI M2ED	M2ED	0°	0 ft	40 ft	Twilight
10	DJI M2ED	M2ED	30°	30 ft	20 ft	Twilight
11	Parrot ANAFI USA	ANAFI Triple	0°	0 ft	40 ft	Twilight
12	Parrot ANAFI USA	ANAFI Triple	30°	30 ft	20 ft	Twilight
13	DJI M210	XT2 9mm	0°	0 ft	40 ft	Night
14	DJI M210	XT2 13mm	0°	0 ft	40 ft	Night
15	DJI M210	XT2 19mm	0°	0 ft	40 ft	Night
16	DJI M210	XT2 25mm	0°	0 ft	40 ft	Night
17	Parrot ANAFI USA	ANAFI Triple	0°	0 ft	40 ft	Night
18	DJI M2ED	M2ED	0°	0 ft	40 ft	Night

DJI = Da-Jiang Innovations
M210 = Matric 20 RTK v2
M2ED = Mavic 2 Enterprise Dual

Table D-2. Savannah/Hilton Head International Airport Test Parameters

Test #	Test Area	UAS	Sensor	Horizontal Camera Angle	Offset	Altitude
1	1	DJI M210	XT2 9mm+Z30	0°	0 ft	40 ft
2	1	DJI M2ED	M2ED	0°	0 ft	40 ft
3	1	Parrot ANAFI USA	ANAFI Triple	0°	0 ft	40 ft
4	2	DJI M210	Z30	30°	30 ft	20 ft
5	2	DJI M2ED	M2ED	30°	30 ft	20 ft
6	2	Parrot ANAFI USA	ANAFI Triple	30°	30 ft	20 ft
7	3	DJI M210	XT2 9mm+Z30	0°	0 ft	40 ft
8	3	DJI M2ED	M2ED	0°	0 ft	40 ft
9	3	Parrot ANAFI USA	ANAFI Triple	0°	0 ft	40 ft
10	3	DJI M210	XT2 9mm+Z30	30°	30 ft	20 ft
11	3	DJI M2ED	M2ED	30°	30 ft	20 ft
12	3	Parrot ANAFI USA	ANAFI Triple	30°	30 ft	20 ft

DJI = Da-Jiang Innovations
M210 = Matrice 210 RTK v2
M2ED = Mavic 2 Enterprise Dual

Table D-3. Cincinnati/Northern Kentucky International Airport Test Parameters.

Test #	Test Area	UAS	Sensor	Horizontal Camera Angle	Offset	Altitude
1	1	Parrot ANAFI USA	ANAFI Triple	0°	0 ft	40 ft
2	1	DJI M210	Z30	30°	30 ft	20 ft
3	1	DJI M210	XT2 9mm	0°	0 ft	40 ft
4	1	DJI M2ED	M2ED	30°	30 ft	20 ft
5	1	Parrot ANAFI USA	ANAFI Triple	30°	30 ft	20 ft
6	2	Parrot ANAFI USA	ANAFI Triple	0°	0 ft	40 ft
7	2	DJI M210	Z30	30°	30 ft	20 ft
8	2	DJI M210	XT2 9mm	0°	0 ft	40 ft
9	2	DJI M2ED	M2ED	30°	30 ft	20 ft
10	2	Parrot ANAFI USA	Anafi Triple	30°	30 ft	20 ft
11	3	Parrot ANAFI USA	ANAFI Triple	0°	0 ft	40 ft
12	3	DJI M210	Z30	30°	30 ft	20 ft
13	3	DJI M210	XT2 9mm	0°	0 ft	40 ft
14	3	DJI M2ED	M2ED	30°	30 ft	20 ft
15	3	Parrot ANAFI USA	ANAFI Triple	30°	30 ft	20 ft
16	4	DJI M210	ANAFI Triple	0°	0 ft	40 ft
17	4	DJI M210	Z30	30°	30 ft	20 ft
18	4	DJI M210	XT2 9mm	0°	0 ft	40 ft
19	4	DJI M2ED	M2ED	30°	30 ft	20 ft
20	4	Parrot ANAFI USA	ANAFI Triple	30°	30 ft	20 ft

DJI = Da-Jiang Innovations
M210 = Matric 20 RTK v2
M2ED = Mavic 2 Enterprise Dual

APPENDIX E—RECOMMENDED MINIMUM PERFORMANCE SPECIFICATIONS

This appendix presents the recommended minimum performance specifications for unmanned aircraft systems (UASs) for conducting airport perimeter inspections and surveillance. Minimum performance specifications are presented for general UAS performance (Table E-1), live-streaming performance (Table E-2), visual camera payload (Table E-3), thermal camera payload (Table E-4), and payload gimbal (Table E-5).

Table E-1. General UAS Performance Specifications

Item	Specification
Flight Performance	The UAS should be capable of stable and predictable flight behavior, including the capability to hover in a fixed position at a commanded altitude with no control input.
Payload	If used solely for daylight inspections, the UAS must be equipped with a visual camera payload. If used after dark the UAS must be equipped with a thermal camera payload.
Flight Planning	The UAS must be capable of operating with preprogrammed waypoint flight plans.
Geofence	The UAS must have the capability of restricting horizontal and vertical flight boundaries using a programmable geofence.
Return-to-home failsafe	The UAS must include a programmable return-to-home failsafe mode.
Anti-collision beacon	For night and twilight operations, the UAS must be equipped with an anti-collision light visible from at least 3 SMs.
Durability	When stored, all components of the UAS must be resistant to the typical shocks and forces a ground vehicle could be subjected to, including off-road driving.

Table E-2. Live-Streaming Performance Specifications

Item	Criteria
Resolution	The UAS must live stream payload footage at a minimum resolution of 1280x720 (720p).
Frame rate	The UAS must live stream payload footage at a minimum refresh rate of 30Hz.

Table E-3. Visual Camera Payload Performance Specifications

Item	Criteria
Resolution	The visual camera payload must have a minimum resolution of 1920x1080 (1080p).
Frame rate	The visual camera payload must have a minimum refresh rate of 30Hz.
Autofocus	The visual camera payload must include auto focus.
Auto Exposure	The visual camera payload must include auto exposure.

Table E-4. Thermal Camera Payload Performance Specifications

Item	Criteria
Spectral Range	The thermal camera payload must detect long-wave infrared (8 μm–12 μm) energy.
Resolution	The thermal camera payload must have a minimum resolution of 640x512.
Frame rate	The thermal camera payload must have a minimum refresh rate of 30Hz.
Focus/Gain Control	The thermal camera payload must include automatic focus and gain control.

Table E-5. Payload Gimbal Performance Specifications

Item	Criteria
Gimbal	The payload gimbal must have 3-axis stabilization (yaw, pitch, and roll) and a vibration dampening mount to ensure the video remains as steady as possible.
Range of Motion	The gimbal must have a controllable vertical range of motion of -90 to 0 degrees, and a horizontal range of motion of 360 degrees to allow viewing in all directions below the UAS.