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16. Abstract

The Federal Aviation Administration (FAA) Airport Technology Research and Development Branch conducted a research effort to explore the use of unmanned aircraft systems (UASs) for documenting aircraft accident and incident scenes at airports. The objectives of this research effort were to assess the benefits and limitations of UAS for this application, and to develop minimum performance specifications and technical and operational considerations for using UAS to document aircraft accidents and incidents.

This research effort consisted of UAS flight testing at Atlantic City International Airport (ACY) and Cape May County Airport (WWD), and outreach to the National Transportation Safety Board (NTSB), which currently uses UASs to document aircraft accidents and incidents. During testing, mapping missions were conducted using a variety of UAS platforms and sensors over simulated emergency scenarios at each airport. These missions involved collecting image data with a variety of flight parameters, including varying forward and side overlaps and ground sample distances (GSDs). Data were processed with several software packages to generate two-dimensional (2D) orthomosaic maps of the scenes, which were evaluated to determine which hardware, software, and flight parameters resulted in the most efficient flight operations and the highest quality outputs.

This report provides a comprehensive summary of the testing conducted and recommended UAS platform and payload specifications. FAA researchers found that UASs equipped with camera payloads were effective tools for generating orthomosaics of aircraft accident and incident scenes for documentation purposes. Based on the testing results, FAA researchers set minimum performance specifications, including a minimum camera image resolution of 12 megapixels. FAA researchers recommend collecting mapping data with the camera in a nadir orientation (straight downward), with a minimum GSD of 1 in. and forward- and side-overlap values of 80% and 70%, respectively.

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LIST OF ACRONYMS

2D	Two-dimensional
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AC	Advisory circular
ACY	Atlantic City International Airport
AGL	Above ground level
ARFF	Aircraft rescue and firefighting
ATC	Air traffic control
C172	Cessna 172
C.F.R.	Code of Federal Regulations
CMOS	Complementary metal-oxide semiconductor
CONOPs	Concept of operations
CPU	Central Processing Unit
DJI	Da-Jiang Innovations
DRBA	Delaware River and Bay Authority
FAA	Federal Aviation Administration
FLIR	Forward-looking infrared
FOV	Field of view
GA	General aviation
GCS	Ground control station
GeoTIFF	Geographic tagged image file format
GPS	Global positioning system
GSD	Ground sample distance
IC	Incident commander
IEC	International Electrotechnical Commission
IP	Ingress protection
M210	Matrice 210 RTK v2
M2ED	Mavic 2 Enterprise Dual
MP	Megapixel
NRCAN	National Resources Canada
NTSB	National Transportation Safety Board
PDF	Portable document format
RAM	Random access memory
RPIC	Remote pilot-in-command
SM	Statute mile
SME	Subject matter expert
TFR	Temporary flight restriction
UAS	Unmanned aircraft system
UA	Unmanned aircraft
VTOL	Vertical takeoff and landing
WJHTC	William J. Hughes Technical Center
WWD	Cape May County Airport

EXECUTIVE SUMMARY

Aircraft accidents and incidents can create numerous challenges for aircraft rescue and firefighting (ARFF) personnel to document in the initial stages of the response. The preservation of life is paramount during an ARFF response, and, often, significant time has passed before the scene is documented. As time passes, the wreckage and debris field can change due to weather and foot and vehicle traffic. Documentation in the early stages after the event will preserve images of the site before much of this disruption, providing investigators with a clearer picture of what occurred prior to their arrival on site.

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 documenting aircraft accident and incident scenes at airports. The objectives of this research were to assess the benefits and limitations of UAS for this application, and to develop minimum performance specifications and technical and operational considerations for using UAS to document aircraft accidents and incidents.

This research effort consisted of outreach to the National Transportation Safety Board (NTSB) and three phases of UAS flight testing. Phase 1 consisted of the testing of various UASs, payloads, and processing software packages by conducting aerial mapping over a simulated commercial air carrier accident scene staged at the FAA's William J. Hughes Technical Center, which is collocated with the Atlantic City International Airport (ACY). The goal of this phase was to develop initial performance specifications and best practices on how to use UASs to generate two-dimensional (2D) orthomosaic maps of aircraft accident scenes in daylight conditions. Eight data sets were collected during Phase 1 in daylight conditions. Phase 2 testing followed a similar approach, consisting of 12 mapping flights over a simulated general aviation accident staged at the FAA's Research Taxiway (Taxiway C) at Cape May County Airport (WWD) during daylight conditions. The goal of this phase was to further refine the initial findings and evaluate their applicability for a smaller scale accident. Phase 3 testing was conducted at the same location as Phase 1, and consisted of 32 tests conducted during daylight, twilight, and nighttime conditions. In addition to validating previous findings, daylight testing during Phase 3 focused on evaluating various overlap settings with each platform and evaluating the effect dense vegetation and varying terrain elevations had on the orthomosaics. Tests conducted during twilight and nighttime conditions served as an initial proof of concept to evaluate the efficacy of conducting data collection in less-than-optimal lighting.

Following each phase of testing, FAA researchers evaluated the times required to acquire and process each data set, and the quality and level of detail present in each orthomosaic to determine which UAS hardware, processing software, and flight parameters resulted in the most efficient flight operations and the highest quality outputs.

FAA researchers found that UASs equipped with camera payloads were effective tools for generating orthomosaics of aircraft accident and incident scenes for documentation purposes. These orthomosaics can benefit accident investigators by providing them with an overview of the scene prior to their arrival on site, by which time key details could be lost due to the dynamic and changing environment. In addition, when provided to ARFF incident commanders during the

response, these maps could enhance their situational awareness and logistical management of the response. These benefits were limited, however, by the availability of staff required to operate the UAS, inclement weather conditions, and current federal restrictions on UAS operations in controlled airspace.

Based on the testing results, FAA researchers set minimum performance specifications, including a minimum camera image resolution of 12 megapixels (MP). FAA researchers recommend collecting mapping data with the camera in a nadir orientation with a minimum ground sample distance of 1-inch, and forward/side overlap values of 80%/70%. FAA researchers also developed technical and operational considerations to maximize the benefits of UASs for aircraft accident documentation. These considerations address technical aspects such as the UAS platform, payloads, data acquisition, and data processing.

This report provides a summary of the research conducted and provides benefits and limitations, minimum performance specifications, and technical and operational considerations for using UASs for aircraft accident and incident documentation at airports.

1. INTRODUCTION

Aircraft accident and incident scenes create numerous challenges for aircraft rescue and firefighting (ARFF) personnel to document the scene in the initial stages of the response. The preservation of life is paramount during an ARFF response, and, often, significant time has passed before the scene is documented. As time passes, the wreckage and debris field can change due to weather and foot and vehicle traffic. Documentation in the early stages after the event can preserve images of the site before much of the disruption, providing investigators with a clearer picture of what occurred prior to their arrival on site. Furthermore, because ARFF first responders often have limited visibility and situational awareness when responding to an ongoing accident or incident, early documentation of the event could help them manage the scene and evaluate the response actions. This could also enhance training for future accidents and incidents.

To address these challenges, the Federal Aviation Administration's (FAA) Airport Technology Research and Development Branch conducted research to explore the use of unmanned aircraft systems (UASs) to document aircraft accident and incident scenes. This research focused solely on small UASs, which are defined in Title 14 Code of Federal Regulations (C.F.R.) 107.3 as unmanned aircraft weighing less than 55 pounds on takeoff, including everything that is on board or otherwise attached to the aircraft. (Definitions, 2016). This report provides a summary of the research and testing, and provides benefits and limitations, minimum performance specifications, and technical and operational considerations for the use of UASs for aircraft accident and incident scene documentation.

1.1 BACKGROUND

FAA Advisory Circular (AC) 150/5200-12C, *First Responders' Responsibility for Protecting Evidence at the Scene of an Aircraft/Incident* (FAA, 2009) provides guidance for members of the airport community with responsibilities at the scene of an aircraft accident regarding the proper preservation of evidence. AC 150/5200-12C explains the need for the preservation of evidence and details operational actions which may be permitted if performed in the interest of preserving life. The AC goes on to state the following (FAA, 2009):

> *Airport fire and security departments should establish procedures whereby:*
> 1) *Photographic coverage of the accident scene must be accomplished. This may require a camera be made available by the airport operator.*
> 2) *Security of the accident scene is the responsibility of the airport operator until it is released to appropriate agency custody.*

Figure 1 shows photographs taken by the National Transportation Safety Board (NTSB) of the Asiana 214 accident scene at San Francisco International Airport in 2013, in which debris was dispersed over a large area. When viewed from ground level, as shown in Figure 1(a), it can be difficult for personnel to assess the full extent of the accident scene and debris field. When viewed from an aerial perspective, as shown in Figure 1(b), it becomes easier to assess the entire scene, thus providing potential benefits for the investigation and response.

Figure 1. View of Asiana 214 Accident Scene (a) from the Ground and (b) from the Air (NTSB, 2014)

Recent advances in UAS hardware and image-processing software make it possible for trained personnel to efficiently generate high-resolution, overhead maps to help document accident scenes. These maps can be used to supplement the photographic coverage of the accident or incident scene required under AC 150/5200-12 and to provide situational awareness to accident investigators and other personnel while they are enroute to the site. The incident commander (IC) and other public safety personnel can use these maps to coordinate the response and allocate resources effectively. By increasing the efficiency of documenting the accident site, UASs could allow ARFF and airport personnel to recover the site more quickly.

1.2 PURPOSE

The purpose of this research effort is to evaluate the capability of UASs for documenting aircraft accident scenes at airports, and to develop recommendations for minimum performance specifications and technical and operational considerations for this application.

1.3 OBJECTIVES

The objectives of this testing effort consisted of the following:

1. Evaluate the benefits and limitations of using UASs for aircraft accident site documentation.
2. Develop and validate recommendations for UASs, payloads, flight parameters, and processing software.
3. Provide technical and operational considerations for the use of UASs for aircraft accident site documentation.

1.4 RELATED DOCUMENTS

- FAA AC 150/5200-31, *Airport Emergency Plan*
- FAA AC 150/5200-12, *First Responders' Responsibility for Protecting Evidence at the Scene of an Aircraft Accident/Incident*
- National Fire Protection Association 2400 Standard for Small Unmanned Aircraft Systems Used for Public Safety Operations
- 14 C.F.R. Part 107, Small Unmanned Aircraft Systems

1.5 RESEARCH APPROACH

This research effort included initial outreach to the NTSB's UAS team, as well as three phases of UAS flight testing conducted at two airports with a variety of UAS platforms, camera payloads, and data collection parameters. These airports are:

1. Atlantic City International Airport (ACY), NJ
2. Cape May County Airport (WWD), NJ

These airports were chosen due to their unique test environments. The test area at ACY simulated an accident involving large commercial aircraft, and areas with vertical terrain variation and dense vegetation. The test area at WWD simulated a smaller accident involving a ground vehicle and general aviation (GA) aircraft, while the test area was flat and free from any varying terrain.

The research focused on collecting aerial imagery with different types of commercially available UAS platforms to generate orthomosaics of simulated accident scenes at each airport. Orthomosaics are two-dimensional (2D) composite images generated using specialized software that have a uniform scale and appearance throughout, similar to those available from services such as Google Earth™.

All UAS flights were conducted by contracted personnel. Following each aerial survey, data sets were processed utilizing various software packages to generate orthomosaics of the accident scenes. FAA researchers analyzed the data collected during these mapping missions to assess how the UAS platforms, payloads, flight parameters, and processing software packages affected the speed and efficiency of data collection and processing, and the quality of the resulting maps.

Phase 1 consisted of data collection of a simulated air carrier accident scene at ACY to develop initial recommendations regarding flight parameters, processing software, and minimum performance specifications. Phase 2 consisted of data collection of a simulated GA accident scene at WWD to further evaluate for smaller-scale incidents. Phase 3 returned to the initial location of testing at ACY, but significantly expanded the survey area to validate previous findings. In addition to daylight testing, Phase 3 included testing during twilight to evaluate mapping performance in lowlight conditions, and a single data set was also collected after dark with a thermal camera payload that served as a proof on concept.

2. AIRCRAFT ACCIDENT AND INCIDENT DOCUMENTATION CONCEPT OF OPERATIONS

In the initial stage of this research effort, FAA researchers developed an overall concept of operation (CONOP) for the use of UASs to conduct aerial mapping following an aircraft accident or incident to document the site and debris field. Sections 2.1–2.3 provide details regarding the CONOP.

2.1 CORE REQUIREMENTS

FAA researchers developed a set of basic requirements for UASs used for aircraft accident documentation, which consisted of the following:

- Conduct flight operations using preprogrammed flight plans to capture overhead imagery of the accident or incident scene with a visual camera payload.
- Process the image data to create a 2D map and export the map files in formats that can be easily shared with stakeholders.

The requirement for the UAS to operate using a preprogrammed flight plan (typically in a back-and-forth grid pattern) is to ensure consistency and repeatability when collecting data. It is not feasible for a UAS remote pilot-in-command (RPIC) to manually fly the aircraft while taking photographs with a consistent overlap. Preprogrammed flight plans allow users to specify forward and side overlap parameters, altitude, and ground sample distance (GSD), minimizing the cognitive load on the RPIC and maximizing the likelihood of capturing quality data.

The overhead imagery captured by the visual camera payload is the foundation of this application, as these data provide the input to the image-processing software that develops the 2D map, which will be provided to ARFF personnel during the ongoing response and accident investigators during the subsequent accident investigations. The quality of this imagery determines the usefulness of the data provided to these entities.

The image-processing software develops the overhead imagery into a 2D map to maximize the benefits of the aerial imagery for ARFF responders and investigators. Rather than having to individually view hundreds or potentially thousands of photos, the orthomosaic allows individuals to view a scaled overview of the entire scene at once. Processing the images into a 2D map rather than a three-dimensional (3D) map reduces the processing time and the resulting file size, ensuring that the data can be sent to ARFF responders and investigators as soon as possible.

The purpose of exporting the map in easily shared formats is to allow for the timely sharing of the map with ARFF responders and investigators. The sooner these parties can receive the map, the sooner they can leverage the enhanced situational awareness it provides. This is especially true for ARFF responders, who can use the map to better coordinate the response and potentially save lives. The NTSB recommends exporting map files in portable document format (PDF), which can easily be emailed to the NTSB and other stakeholders. The NTSB also acknowledged that files exported in the geographic tagged image file format (GeoTIFF) are helpful for their team, since these files can be opened using commonly available geographic information system software such as Google Earth, ArcGIS, Global Mapper, and QGIS.

2.2 SYSTEM OVERVIEW

The aircraft accident and incident documentation UAS mapping concept includes two primary systems: the UAS and the data processing system. The purpose of the UAS is to capture aerial images of the accident or incident scene using an onboard camera payload. The purpose of the data processing system, which includes the image-processing software, the computer running the software, and potentially an internet connection and printer, is to generate an orthomosaic using the images captured by the UAS. Figure 2 shows an overview of each of these systems. The specific devices shown in Figure 2 are for illustrative purposes and not intended as endorsements of specific products.

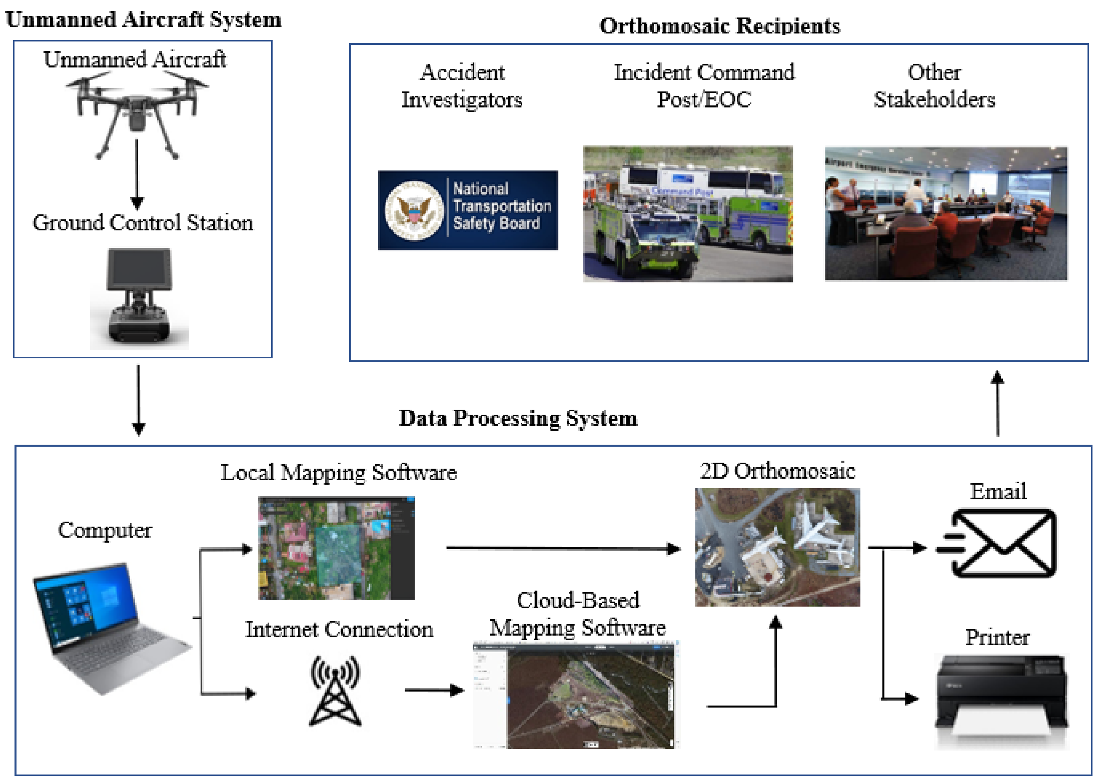


Figure 2. UAS Aircraft Accident and Incident Documentation CONOPs Diagram

As defined in 14 C.F.R. Part 107.3, 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).

For aerial mapping in support of aircraft accident and incident documentation, the UAS would be equipped with a high-definition visual camera sensor. Depending on the UAS model, this camera payload can 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 data processing system will include the data processing software, a computer, and potentially a wireless internet connection and a printer. The computer will either have the software installed on it directly or will host the software if it is a web-based service. If the software is web-based, a wireless internet connection will be required to access the service. The images captured by the UAS will be input into data processing software, which will generate an orthomosaic that can be provided to the NTSB, ARFF IC, or other relevant stakeholders. If this map is intended for use during the response, a printer will be required to provide a hard copy of the map to the IC.

2.3 OPERATIONAL DESCRIPTION

Aerial mapping is the process of capturing images of an area from an aircraft and using specialized software to convert those images into a map. Aerial mapping involves two general steps: (1) data acquisition, and (2) data processing. Sections 2.3.1 and 2.3.2 provide overviews of each of these steps. Figure 3 presents an overview of the aerial mapping operational workflow for ARFF accident and incident documentation.

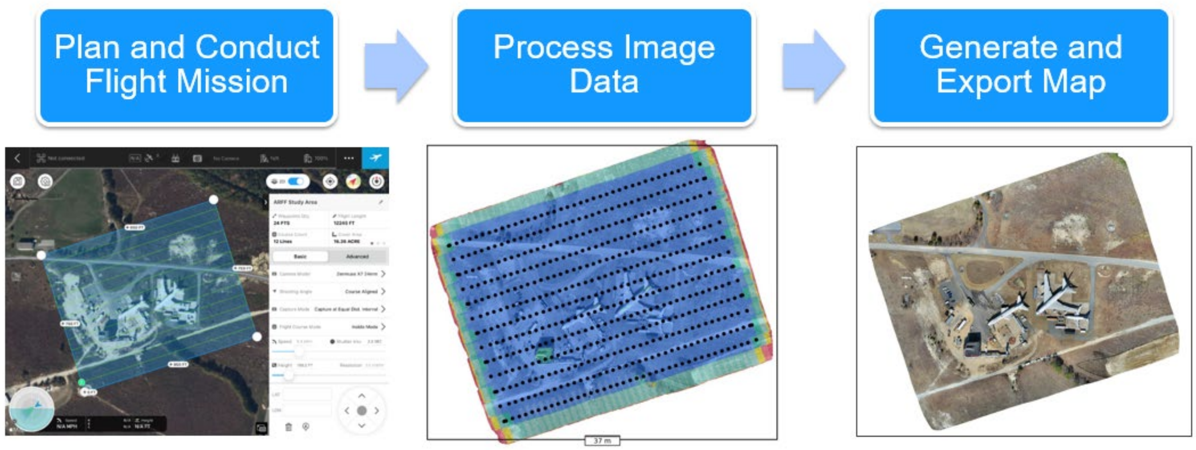


Figure 3. ARFF Accident and Incident Documentation Operational Workflow

2.3.1 Data Acquisition

Depending on the airport's organizational structure, the personnel deploying the UAS might be part of the ARFF department, airport operations department, or another department or entity. It is expected that each airport will develop and adopt standard operating procedures for UAS 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 visual line of sight of the RPIC and any visual observers. 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. In most cases, the UAS would be operated from a closed runway or taxiway. However, the RPIC is still responsible for giving way to manned aircraft that might be present.

Due to the time-sensitive nature of ARFF response and the need to preserve evidence as required in AC 150/5200-12C, the UAS should be deployed as soon as practical upon initial response to the incident or accident site. Before launching the UA, the RPIC performs a brief preflight checklist and verifies 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.

The RPIC will typically use software provided by the UAS manufacturer or a third-party company to create and execute a preprogrammed waypoint flight plan. The flight plan will include specific data acquisition parameters, including the image resolution, overlap, altitude, and the boundaries of the area that will be mapped. Flight parameters should be selected to allow for timely data collection and processing while ensuring the imagery is of high enough quality to support the development of the orthomosaic.

Once the mission is completed, the RPIC lands the UA and transfers the imagery collected from the UAS to a device to either process the images locally or upload them to a cloud-based processing software package.

2.3.2 Data Processing

Following the completion of data acquisition, the images are then processed locally on a computer or uploaded to a cloud-based processing service. The processing software or service will use global positioning system (GPS) coordinates embedded in each image and automatically identify common features in overlapping images to properly orient images during the processing. For example, Figure 4 shows an example data set made up of 520 images. The black points in the image represent the GPS locations where each individual image was captured.

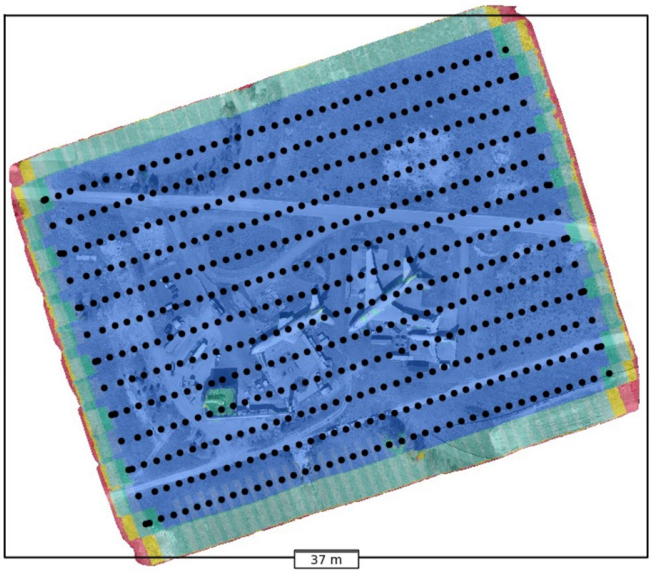


Figure 4. Example of Image Orientation During Processing

Several types of mapping outputs can be generated depending on the software used. These can include orthomosaics and digital elevation models (shown in Figure 5), as well as 3D models and point clouds.

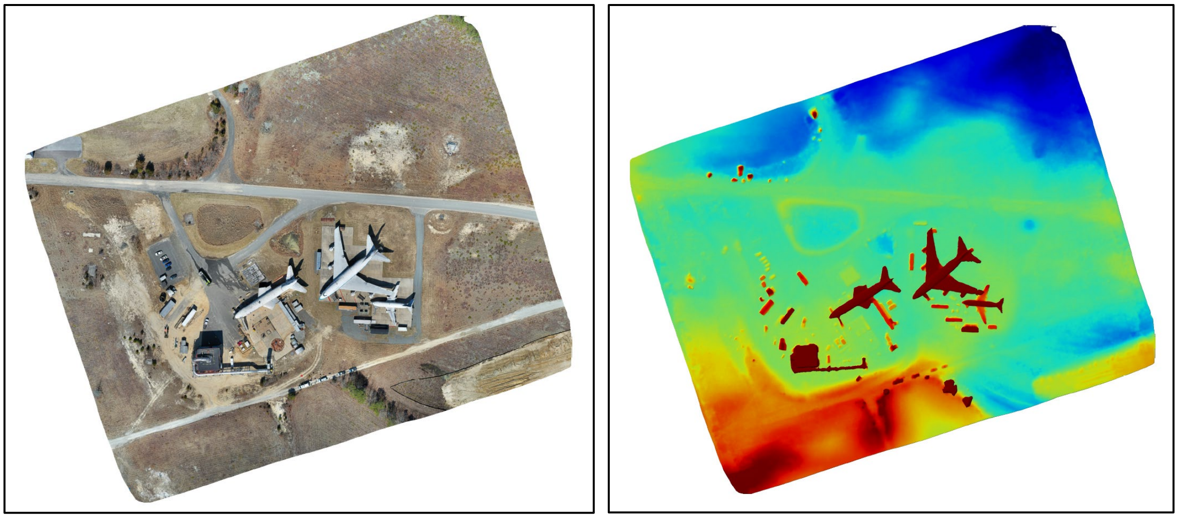


Figure 5. Example of Orthomosaic (Left) and Digital Elevation Model (Right)

3. METHODOLOGY

Sections 3.1 through 3.3 describe the specific methodologies for this research effort, including outreach with the NTSB, UAS data collection, and data processing and analysis.

3.1 NTSB OUTREACH

Prior to testing, FAA researchers conducted outreach to the NTSB UAS team to leverage their insights and perspectives and to discuss the application of UASs for aircraft accident documentation at airports. This outreach included email correspondence and a phone interview. During this outreach, the NTSB UAS team stated that having access to an overview map of an accident or incident site generated from UAS imagery would be of great value to aid the NTSB's planning prior to arriving at an accident or incident scene. These overview maps would be used by NTSB investigators for situational awareness, inventory, site access planning, and gathering various other information to assist the recovery team.

The NTSB UAS team conducts their own comprehensive UAS forensic mapping and data collection when they arrive on scene and do not expect local UAS RPICs to capture the same level of detail as the NTSB's trained investigators. Therefore, it is not necessary for airport operators to use ground control points, which are survey markers used to georeference aerial images, aligning the images with known locations on the earth.

During the outreach, the NTSB representatives indicated that they have successfully used UASs to perform aerial mapping of aircraft accident sites and shared the flight plan parameters they have found to consistently generate useful orthomosaics. These parameters include 80% forward overlap, 70% side overlap, and a GSD of 1 inch or better.

3.2 UAS DATA COLLECTION

UAS aerial surveys were conducted by a contracted UAS flight service provider at each airport using various UAS platforms and camera payloads. These aerial surveys collected nadir imagery (imagery captured with the camera facing straight down at the ground) over predefined study areas using system-specific, preprogrammed flight planning software.

3.2.1 UAS Platforms and Camera Payloads

Sections 3.2.1.1 through 3.2.1.3 describe the UAS platforms and payloads used to conduct testing.

3.2.1.1 UAS Selection Criteria

Prior to testing, researchers developed basic UAS selection criteria to identify UAS platforms that could adequately perform aircraft accident and incident documentation in an airport environment, including safety, cybersecurity, ease-of-use, environmental tolerance, and cost. These criteria were used to select the UAS platforms and payloads included in this testing effort.

- Safety

  Safety is the top priority for all activity in the airport environment. Therefore, the UAS platforms 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.

- 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 UAS platforms selected for this research program featured secure, encrypted connections between the aircraft, GCS, and any other devices that receive data.

- Ease-of-Use

  An aircraft accident scene and the ongoing response could be overwhelming to a UAS RPIC. UAS platforms were selected that would be as simple as possible to operate, reducing the chance of user error.

- Environmental Tolerance

  The UAS should have the ability to operate in inclement weather and other environmental conditions that might exist during an accident or incident. These include excessive cold or heat, wind, precipitation, dust, and smoke. UAS platforms were selected with various levels of ingress protection (IP) against water and particulates, and features such as self-heating batteries for operations in cold conditions.

- Cost

  Airports vary significantly in the resources that they have available to purchase equipment. Therefore, UAS platforms ranging in price from $1,800 to $24,000 were included in testing to find solutions that could be effective for different organizational budgets.

3.2.1.2 UAS Platforms

FAA researchers selected the following commercial-off-the-shelf UAS platforms that met the selection criteria in Section 3.2.1.1 for inclusion in this research effort. The selected UAS platforms represent a variety of sizes, capabilities, and price points:

- Da-Jiang Innovations® (DJI) Mavic 2 Pro™
- DJI Mavic 2 Enterprise Dual™ (M2ED)
- DJI Matrice 210 RTK v2™ (M210)
- Parrot ANAFI USA™
- SenseFly® eBee X RTK™
- Wingtra® WingtraOne PPK™

The UAS platforms selected included multi rotors (M210, M2ED, Mavic 2 Pro, and ANAFI USA), a fixed-wing platform (eBee X), and a hybrid fixed-wing platform (WingtraOne) capable of vertical takeoff and landing (VTOL). Hybrid VTOL UASs have the capability to take off and land vertically, but transition to fixed-wing flight during data collection. These UASs are pictured in Figure 6. Table 1 provides an overview comparison of key specifications for each UAS. Additional specifications for each platform are presented in Appendix A.

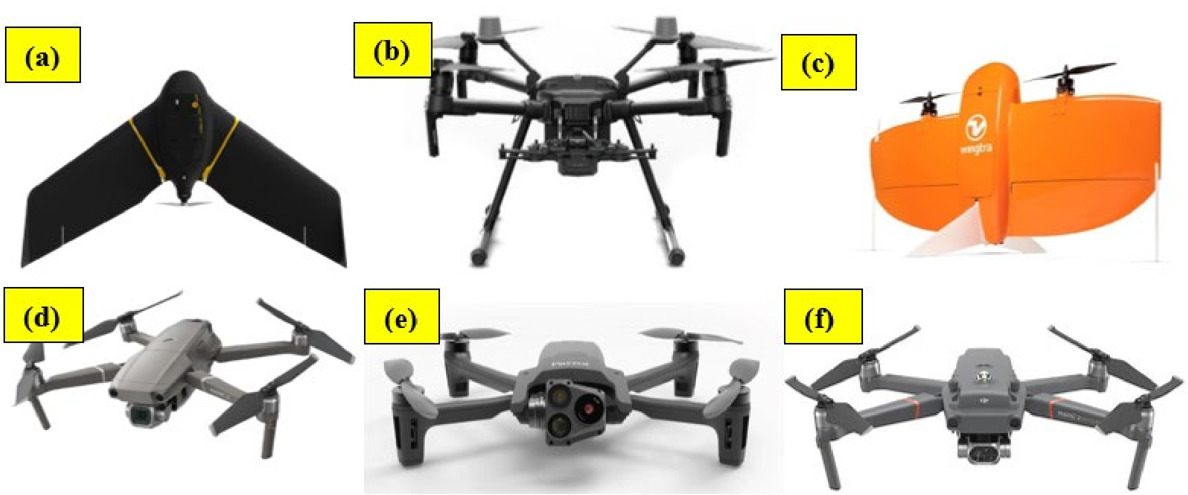


Figure 6. UAS Platforms: (a) eBee X, (b) M210, (c) WingtraOne, (d) Mavic 2 Pro, (e) Parrot ANAFI USA, and (f) M2ED

Table 1. Comparison of UAS Platform Specifications (SenseFly, 2019; DJI, 20120a DJI 2020b; DJI 2021; Parrot, 2020; Wingtra, 2022)

	SenseFly eBee X	DJI M210	DJI Mavic 2 Pro	DJI M2ED	Parrot ANAFI USA	Wingtra WingtraOne
UAS Type	Fixed-wing	Rotorcraft	Rotorcraft	Rotorcraft	Rotorcraft	Hybrid VTOL
Maximum Take Off Weight	3.1 lb	10.8 lb	2 lb	1.98 lb	1 lb	9.9 lb
Endurance	90 min	25 min	31 min	31 min	32 min	55 min
Maximum RF Range	5 miles	5 miles	6.2 miles	6.2 miles	2.5 miles	5 miles
Maximum Wind Tolerance (Sustained)	29 mph	27 mph	23.6 mph	23.6 mph	33 mph	28 mph (cruise) 18 mph (landing)
Operating Temperature Range	5 °F–95 °F	-4 °F–122 °F	14 °F–104 °F	14 °F–104 °F	14 °F–104 °F	-4 °F–122 °F
Approximate Cost	$20,000	$15,000	$1,800	$3,300	$7,500	$24,000

3.2.1.3 Payloads

FAA researchers tested the following payloads to determine minimum performance requirements for the implementation of aircraft accident and incident documentation. While several of these payloads include a thermal camera, only visual cameras were used to collect data during Phases 1 and 2. A single thermal camera data set was collected with the DJI Zenmuse XT2 during Phase 3.

- SenseFly S.O.D.A. 3D (visual camera)
- Sony RX1R-II (visual camera)
- DJI Zenmuse X5S (visual camera)
- DJI Zenmuse X7—16 mm (visual camera)
- DJI Zenmuse XT2 (dual visual and thermal camera)
- DJI Mavic 2 Pro Hasselblad Integrated Camera (visual camera)
- DJI M2ED Integrated Camera (dual visual and thermal camera)
- Parrot ANAFI USA Triple (dual visual cameras and one thermal camera)

Figure 7 shows photos of these payloads. Table 2 compares key specifications of each payload. Detailed specifications for each payload are presented in Appendix B.

Figure 7. UAS Camera Payloads: (a) SenseFly S.O.D.A. 3D, (b) Sony RX1R-II, (c) DJI Zenmuse X5S, (d) DJI Zenmuse X7, (e) DJI Zenmuse XT2, (f) DJI Mavic 2 Pro Hasselblad Integrated Camera, (g) DJI M2ED Integrated Camera, and (h) Parrot ANAFI USA Triple

The DJI Mavic 2 Pro, DJI M2ED, and Parrot ANAFI USA payloads are integrated with the UAS, while the SenseFly S.O.D.A. 3D, DJI X7, XT2, and Sony RX1R-II are interchangeable with other payloads. The resolutions of the payloads range from 12 MP for the DJI XT2 and M2ED, to 42 MP for the Sony RX1R-II. The SenseFly S.O.D.A. 3D and Sony RX1R-II use global shutters, which capture all pixels of the image at once mechanically. All other payloads use rolling shutters, which digitally capture images one pixel row at a time, which can result in images with less clarity while in motion.

Table 2. Comparison of Payload Specifications (SenseFly, 2020; DJI, 2018a; DJI, 2018b; DJI 2018c; DJI, 2020b; DJI, 2021; Parrot, 2020; Sony, 2015)

Payload	Visual Camera Sensor	Effective Pixels	Shutter Type	Approximate Cost[1]
SenseFly S.O.D.A. 3D	1 in. CMOS	20 MP	Global	$4,000
DJI Zenmuse X5S	4/3 in. CMOS	20.8 MP	Rolling	$2,000
DJI Zenmuse X7 16mm	23.5 x 15.7 mm CMOS	24 MP	Rolling	$4,400
DJI XT2	1/1.7 in. CMOS	12 MP	Rolling	$7,500–13,000 (Depending on thermal sensor)
DJI Mavic 2 Pro	1 in. CMOS	20 MP	Rolling	N/A (Integrated)
DJI M2ED	1/2.3 in. CMOS	12 MP	Rolling	N/A (Integrated)
Parrot ANAFI USA (Wide-Angle)	1/2.4 in. CMOS	21 MP	Rolling	N/A (Integrated)
Sony RX1R-II	35.9 x 24 mm CMOS	42 MP	Global	$3,000

CMOS = Complementary metal-oxide semiconductor

3.2.2 Data Collection Parameters

The primary data collection parameters tested in this research effort were image resolution and image overlap. These are further discussed in Section 3.2.2.1 through 3.2.2.3.

3.2.2.1 Image Resolution

The resolution of UAS imagery is commonly expressed in GSD. GSD represents the area each pixel of an image equates to on the ground. For example, in an image with a 1-inch GSD, each pixel would represent 1 square inch of area on the ground. All other factors being equal, an image with a lower GSD value will have more detail than an image with a higher GSD. The GSD is based

[1] As of February 2022

on the specifications of the camera (i.e., focal plane, focal length, and lens), and the distance of the camera above ground level (AGL) or surface being mapped. Figure 8 provides a diagram that illustrates the concept of GSD.

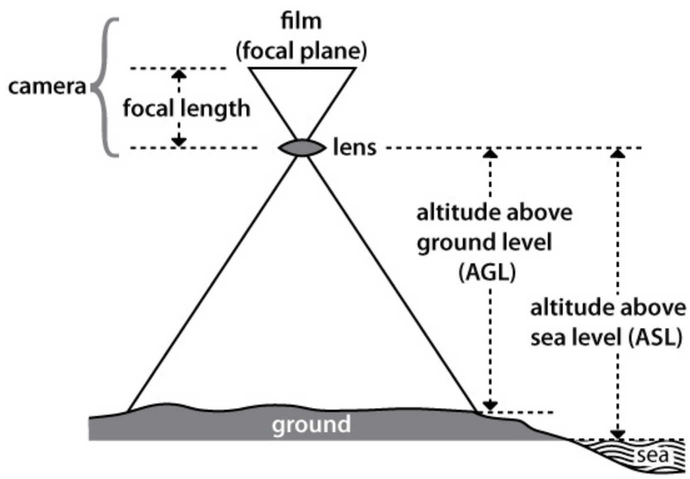


Figure 8. GSD Illustration (National Resources Canada [NRCAN], 2016)

The GSD is calculated by taking the distance between the camera and the ground and dividing by the focal length of the camera. The focal length is the distance between the camera lens and the image sensor.

GSDh = flight height x sensor height/focal length x image height
GSDw = flight height x sensor width/focal length x image width

The relevant GSD number will be whichever value is the lowest, to allow for the worst-case scenario.

This means that for any given altitude, different cameras can have different GSD values at the same altitude. This also means that images captured with the same camera at a higher or lower altitude will result in a higher or lower GSD value. Figure 9 shows the relationship between altitude and GSD for the SenseFly S.O.D.A. 3D payload. It should be noted that actual GSD values can fluctuate from the planned GSD value due to changing terrain elevations and minor fluctuations in UAS altitude.

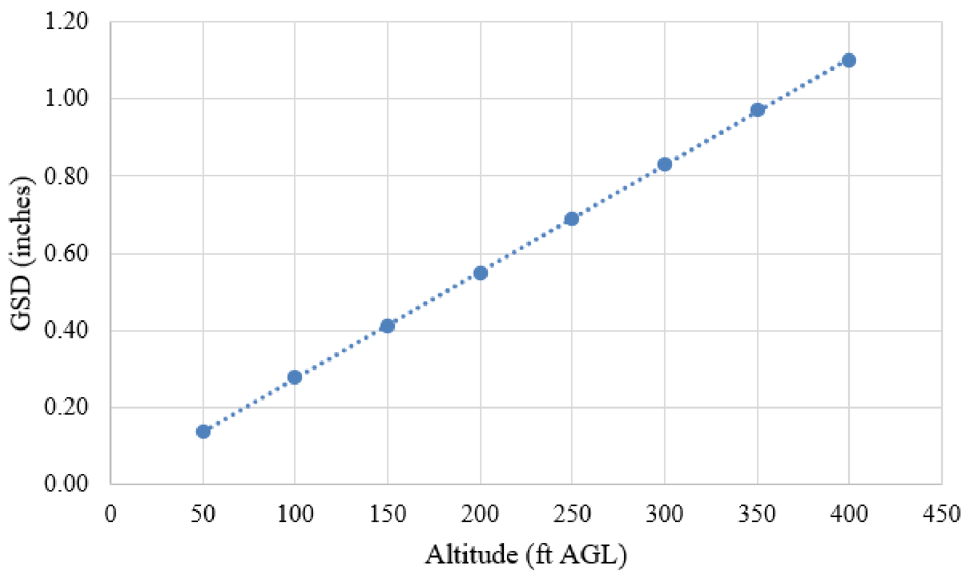


Figure 9. Altitude vs GSD Comparison: SenseFly S.O.D.A. 3D

3.2.2.2 Image Overlap

The overlap value describes the proportion of area covered by adjacent photos. Overlap values are expressed in percentages of forward and side overlap. Forward overlap is the overlap between images on the same flight line, while side overlap is the portion of images overlapping laterally across flight lines. Figure 10 shows examples of each of these types of overlap. All other factors being equal, higher overlap values will increase the likelihood of successfully generating a 2D map but will result in longer flight and processing times due to the greater number of images captured and additional flight lines.

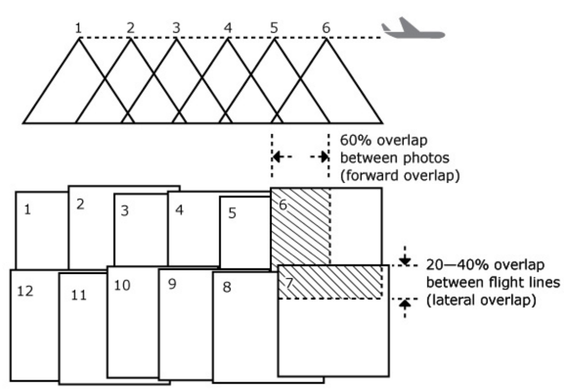


Figure 10. Image Overlap Illustration (NRCAN, 2016)

3.2.2.3 Flight Path

Once the data collection parameters have been set, the UAS flight planning software automatically generated a flight plan based on these parameters. Figures 11 and 12 show examples of multirotor and fixed-wing flight plans, respectively. As shown in Figure 12, fixed-wing flights will typically cover a larger flight area due to their increased turning radius. Once the flight plan has been finalized, the RPIC will conduct any necessary safety checks and execute the flight. The UAS will operate autonomously during the mission, with the RPIC monitoring the safety of the flight.

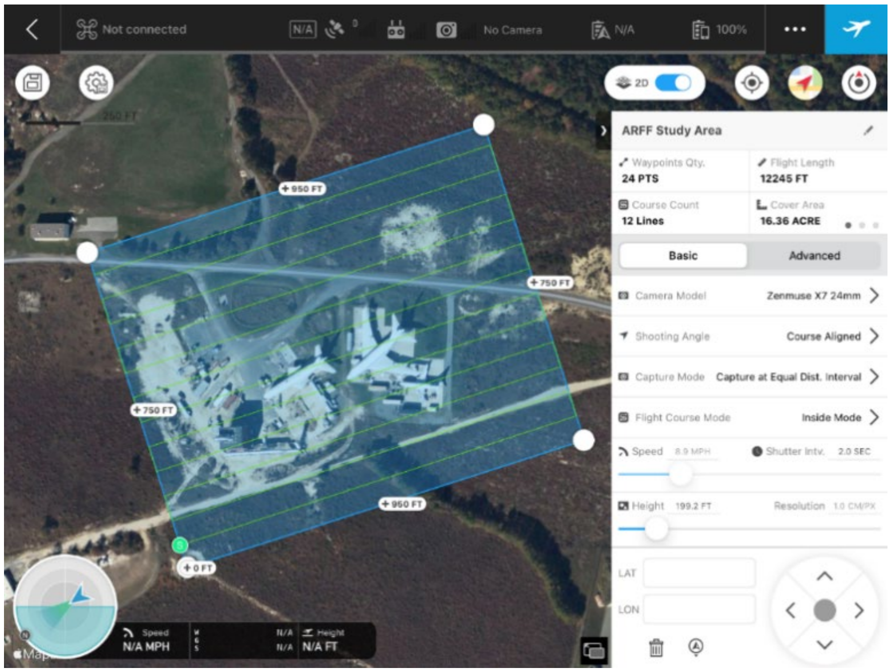


Figure 11. Example of a Multirotor Flight Plan

Figure 12. Example of a Fixed-Wing Flight Plan

3.3 UAS DATA PROCESSING AND ANALYSIS

Imagery data acquired during testing was processed with the following four commercially available software applications/services:

- DroneDeploy
- DroneDeploy Live Map
- Maps Made Easy
- Pix4DReact

DroneDeploy and Maps Made Easy are both cloud-based processing services requiring the user to upload image data prior to processing. Pix4DReact is a software application designed to run locally on a computer, does not require an internet connection, and can begin processing as soon as images are transferred to the computer from the UAS. Pix4DReact uses an algorithm optimized for rapidly producing orthomosaics. DroneDeploy Live Map also runs locally and uses the live video stream from the UAS to begin building the orthomosaic while the flight is still in progress. Table 3 compares characteristics of each processing software package used during Phase 1.

Table 3. Data Processing Services Tested

	DroneDeploy	**DroneDeploy LiveMap**	**Maps Made Easy**	**Pix4DReact**
Type	Cloud-based Processing	Local Processing	Cloud-based Processing	Local Processing
Functions	Data Capture and Processing	Data Capture and Processing	Data Processing only	Data Processing only
Data Input	Still Imagery	Live Video	Still Imagery	Still Imagery
Map Output Types	2D and 3D	2D only	2D and 3D	2D only
Export Formats	JPG, GeoTIFF, and OBJ	JPG, PDF	JPG, GeoTIFF, and OBJ	GeoTIFF, PDF Report, JPG
Ground Control Point Support	Yes	No	Yes	No
Cost	$329+ per month (billed annually)	$329+ per month (billed annually)	Pay-as-you-go or annual subscription tiers ranging from $50 to $450 per year	$32.50 per month (billed annually) or $990 one-time fee

4. PHASE 1 TESTING: ACY

Phase 1 testing took place at the FAA's William J. Hughes Technical Center (WJHTC), collocated with ACY. ACY is a towered airport certificated under Title 14 C.F.R. Part 139 and located in Class C airspace. In this phase, aerial mapping flights were conducted using various flight parameters with multiple UAS platforms and visual camera payloads over a simulated accident scene created using retired commercial aircraft, props simulating a debris field, ARFF trucks, and water. Following data acquisition, each data set was processed with three different processing software packages that were used to generate orthomosaics. The orthomosaics were reviewed and evaluated regarding their respective quality and usefulness for aircraft accident documentation. This analysis was used to identify initial findings regarding minimum performance specifications for UAS platforms, payloads, and processing software, and recommended flight parameters for balancing map quality with efficiency.

4.1 UAS PLATFORMS AND PAYLOADS

Sections 4.1.1 through 4.1.2 describe the UAS platforms and payloads used to conduct Phase 1 testing.

4.1.1 UAS Platforms

FAA researchers tested the following UAS platforms during Phase 1 testing:

- DJI Mavic 2 Pro
- DJI M2ED
- DJI M210
- Parrot ANAFI USA
- SenseFly eBee X RTK
- Wingtra WingtraOne PPK

These UAS platforms are pictured in Figure 6. Table 1 provides an overview comparison of key specifications for each UAS. Additional specifications for each platform are presented in Appendix A.

4.1.2 Payloads

The following payloads were used to collect imagery during Phase 1 UAS testing at ACY:

- SenseFly S.O.D.A. 3D (visual camera)
- Sony RX1R-II (visual camera)
- DJI Zenmuse X7—16 mm (visual camera)
- DJI Zenmuse XT2 (dual visual and thermal camera)
- DJI Mavic 2 Pro Hasselblad Camera (visual camera)
- DJI M2ED Integrated Camera (dual visual and thermal camera)
- Parrot ANAFI Triple (dual visual cameras and one thermal camera)

These payloads are pictured in Figure 7. While several of these payloads include a thermal camera, only visual cameras were used to collect imagery during Phase 1. Table 2 compares key specifications of each payload. Detailed specifications for each payload are presented in Appendix B.

4.2 TEST METHODS AND PROCEDURES

Sections 4.2.1 through 4.2.5 describe the test setup and procedures employed during Phase 1 UAS testing at ACY.

4.2.1 Mapping Area

Testing at ACY was performed inside a designated operations area to the northeast of the airfield's movement areas. The mapping area, shown in Figure 13, was approximately 16 acres in size and included the ARFF and aircraft fire testing research area/facilities. The test area contained three retired aircraft that serve as test articles for FAA research purposes, including a Boeing 747, Boeing 737, and a Lockheed L-1011. These aircraft were used during Phase 1 to stage the simulated accident scene. The ARFF and aircraft fire testing research area/facilities are pictured in Figure 14.

Figure 13. ACY UAS Mapping Area

Figure 14. ARFF and Aircraft Safety Test Areas (Left) and ARFF Research Facility (Right)

4.2.2 Site Setup

Prior to testing, a variety of objects were placed around the L-1011 at the ARFF Test Facility. These objects were used to simulate an accident site and debris field and provided a means to assess the quality of the resulting maps. These items included an ARFF vehicle, two full-size manikins, an aircraft wheel, a suitcase, and aircraft seat cushions. Figure 15 shows the layout of these objects, while Figure 16 shows a view of the scene from the ground. In addition to these items, water was dispersed from the FAA ARFF vehicle to assess the ability of a UAS to document a simulated contaminant spill, shown in Figure 17.

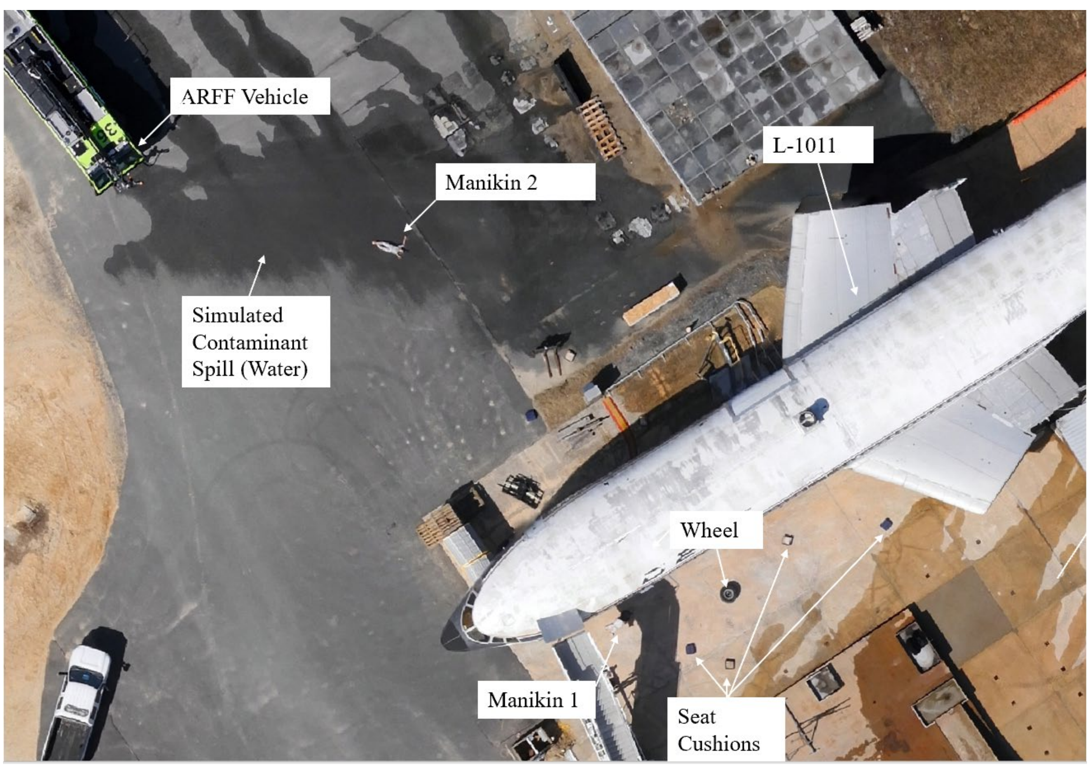


Figure 15. Aerial View of ACY Debris Layout

Figure 16. Ground View of ACY Debris

Figure 17. Water Dispersal by ARFF Vehicle

4.2.3 Flight Parameters

Data collection was conducted using preprogrammed waypoint flight plans. These parameters were selected based on recommendations from the NTSB UAS team. Per the NTSB's recommendation, a 1-in. GSD and 80%/70% forward/side overlap settings were used for flights with each payload except for the XT2. To explore the potential benefit of higher resolution GSDs, an additional test was conducted with the DJI Mavic 2 Pro with a 0.39-in. GSD. The WingtraOne's Sony RXIR-II sensor was not able to conduct a 1-in. GSD at or below 400 ft AGL due to its high-resolution sensor, so data were collected with a 0.5-in. GSD. Table 4 shows the parameters for each mapping data set collected at ACY.

Table 4. ACY Test Parameters

Test #	UAS	Payload	Overlap % (Forward/Side)	Altitude (AGL)	GSD (in.)
1	Mavic 2 Pro	Mavic 2 Pro	80/70	145 ft	0.39 (1 cm)
2	WingtraOne PPK	Sony RX1R-II	80/70	310 ft	0.50
3	M210	XT2 13mm	80/70	191 ft	0.54
4	M2ED	M2ED	80/70	236 ft	1.00
5	Anafi USA	Anafi Triple	80/70	249 ft	1.00
6	M210	X7 16mm	80/70	340 ft	1.00
7	eBee X	S.O.D.A. 3D	80/70	369 ft	1.00
8	Mavic 2 Pro	Mavic 2 Pro	80/70	373 ft	1.00

4.2.4 Data Processing

Sections 4.2.4.1 through 4.2.4.3 describe the software, hardware, and settings used to process data collected during Phase 1.

4.2.4.1 Processing Software

Imagery acquired during Phase 1 testing was processed with the following software applications:

- DroneDeploy
- Maps Made Easy
- Pix4DReact

4.2.4.2 Processing Hardware

The primary device used for processing and/or uploading data was a Dell laptop. Following are the specifications for the Dell laptop:

- Processor: Intel i9-8950HK central processing unit (CPU) @ 2.90Ghz
- Random-Access Memory (RAM): 16GB
- Video card: NVIDIA Quadro P2000
- Operating System: Windows 10 Enterprise 64bit
- Power source: Alternating current power supply

In the interest of time, most of the data sets requiring data to be uploaded to a cloud server used a home internet connection with an upload speed of approximately 5–6 Mbps. Two of the data sets were uploaded using a Verizon Jet Pack mobile hotspot to determine how well this solution would work in a remote location.

4.2.4.3 Processing Settings

Following are the processing settings used for each processing application/service:

- Pix4DReact:

  Imagery was post-processed via the Pix4DReact downloadable suite with no changes to the default processing options. If a data set exceeds a certain threshold in size or resolution, Pix4dReact asks the user if they would like to process the data set at a lower resolution. For these tests, this option was declined, and the data sets were all processed at the "full" resolution offered by Pix4DReact.

- Maps Made Easy:

  Imagery was post-processed via the MapsMadeEasy cloud-based software suite with the "Classic" format selected. The urgency was set to "ASAP," for an additional fee.

- DroneDeploy:

  Imagery was post-processed via the online "MapEngine." The "Turbo Upload" option was turned off due to its compression of imagery. The "Processing Options" slider was moved to quickest speed setting. The information listed by the MapEngine states the "Processing Options" slider reduces 3D model quality while also reducing processing time.

4.2.5 Safety and Coordination

All UAS operations were conducted in accordance with the regulations of Title 14 C.F.R. Part 107 and an FAA-approved airspace authorization, which permitted the operation of UASs in the operating area at ACY, specified in Figure 13 in Section 4.2.1. 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-certified RPICs experienced in the operation of UASs at airports.

In preparation for working at ACY, evaluations were completed to check for potential flight restrictions enforced by DJI. ACY 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 with the M210 and M2ED UAS platforms.

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 and maintained a sterile cockpit while operating the UAS.

4.3 RESULTS AND DISCUSSION

Sections 4.3.1 through 4.3.4 provide results and additional discussion from Phase 1 testing at ACY. These sections address data acquisition and processing times, orthomosaic quality, and additional software features.

4.3.1 Data Acquisition Times

As shown in Figure 18, data acquisition times ranged from 5 minutes to 21 minutes to collect image data for the 16-acre test area at ACY. The most significant factors affecting data acquisition time were the selected GSD and altitude. Mapping missions conducted at higher altitudes were generally able to be completed in significantly less time than missions conducted at lower altitudes. For example, the Mavic 2 Pro was able to map the test area more than four times faster (5 minutes versus 21 minutes) when flying at 372 ft AGL (1-in. GSD) compared to 145 ft AGL (0.39-in. GSD).

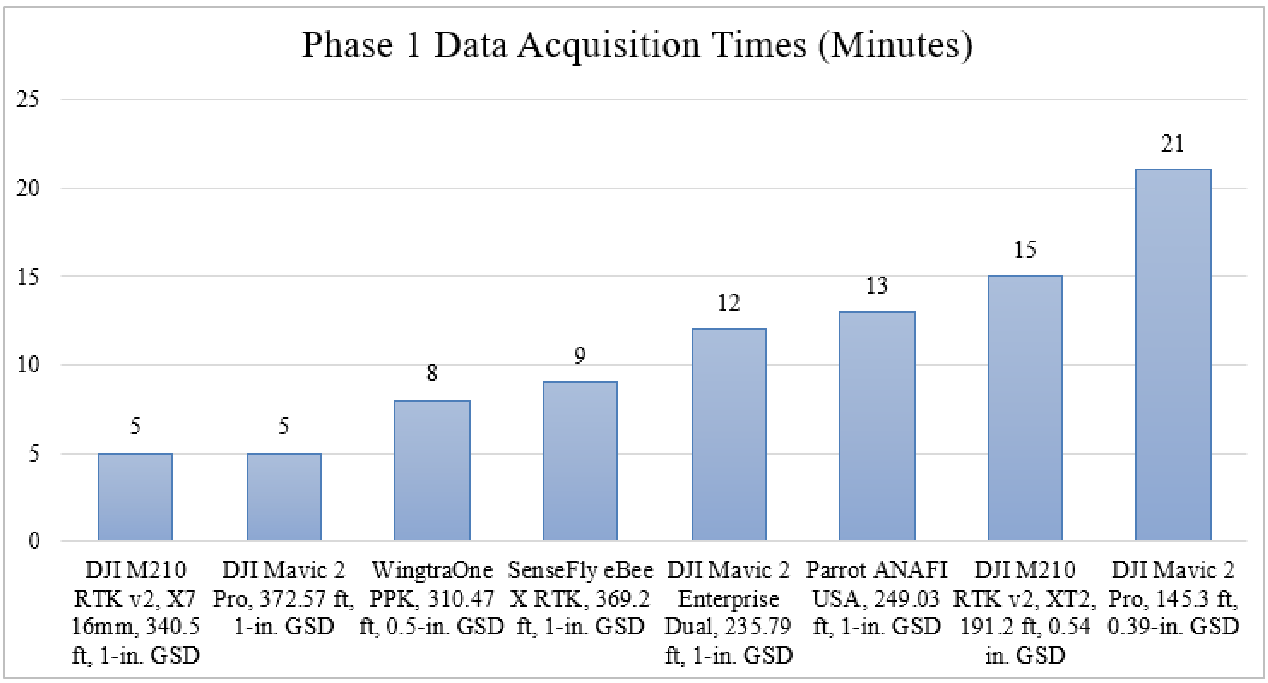


Figure 18. Phase 1 Data Acquisition Times

Payload specifications were also a factor in data acquisition efficiency. Certain UAS payloads were able to capture data at higher altitudes while maintaining a 1-in. or better GSD value, thereby increasing the area covered in each photo and reducing the amount of time it took to map the test area. For example, the DJI Mavic 2 Pro was able to capture 1-in. GSD imagery at an altitude of 372 ft AGL, whereas the Mavic 2 Enterprise Dual and Parrot ANAFI USA captured 1-in. GSD imagery at 236 and 249 ft AGL, respectively. Another notable example is the WingtraOne equipped with the 42 MP Sony RX1R-II sensor, which was able to capture 0.5-in. imagery in less time than the SenseFly eBee was able to capture 1-in. GSD imagery.

4.3.2 Data Processing Times

Figure 19 shows the processing times for each data set. DroneDeploy did not provide processing times in the reports generated; therefore, only upload times are shown. Also, two data sets (marked with asterisks in Figure 19) were uploaded using a portable Wi-Fi hotspot to simulate conditions at a remote site, while the rest used an office internet connection. It should also be noted that the X7 payload is not compatible with Pix4DReact and that the eBee data set was not able to be successfully processed using Maps Made Easy due to an unknown technical issue; therefore, these data sets were excluded from the analysis.

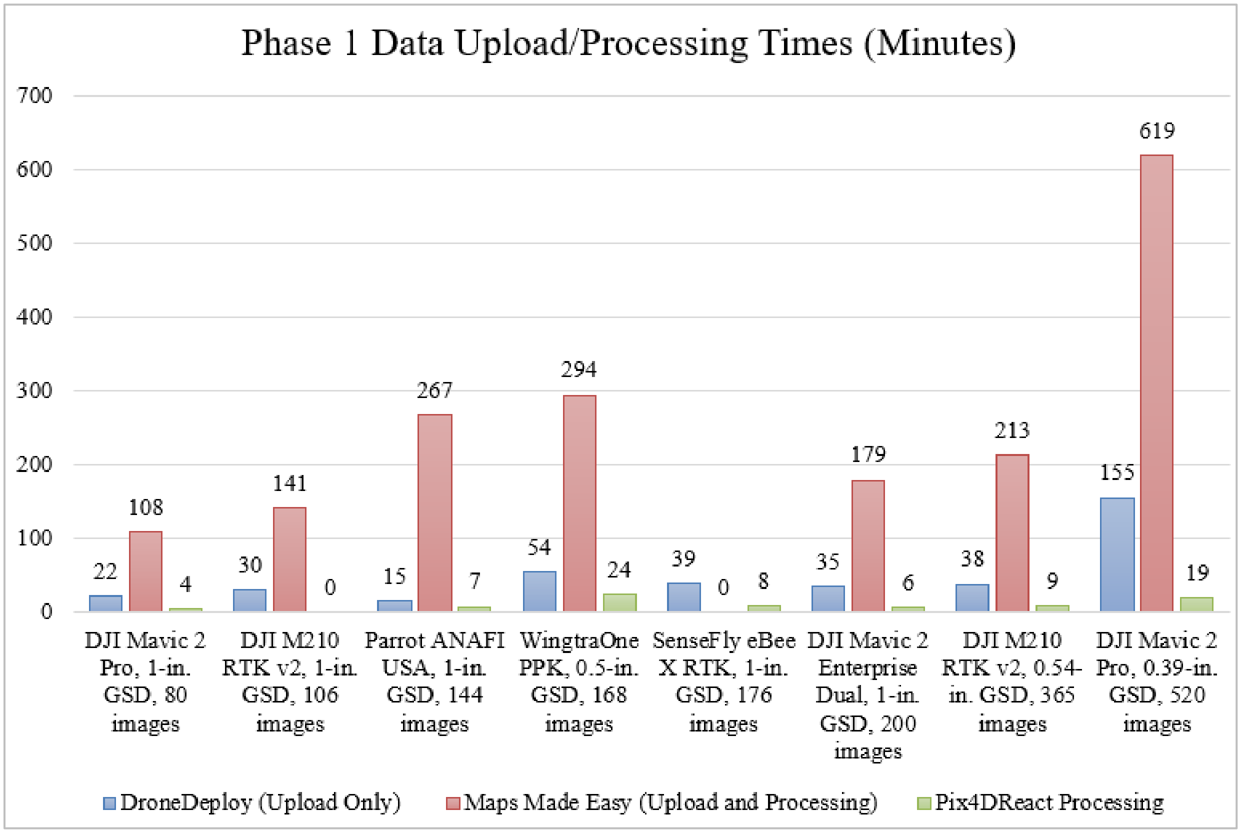


Figure 19. Phase 1 Data Processing Times (in minutes)

As indicated by the orange bars in Figure 19, Pix4DReact processed each data set significantly faster than the other cloud-based software packages, generating maps from 4 and 24 minutes. This was because it processes the photos locally and is not dependent on an internet connection or the speed of the host servers.

Processing and upload times generally correlated to the size of the data set, with data sets with more images requiring more time for processing. Data upload to Maps Made Easy took between 20 and 151 minutes, and processing took between 88 and 468 minutes. DroneDeploy data upload times ranged from 15 to 155 minutes. Although DroneDeploy did not report processing times, most data sets appeared to process in 30 to 120 minutes depending on the number of images. Uploading data sets using a mobile Wi-Fi hotspot took approximately twice as long as a wired internet connection. This accounted for the longer upload time for the Parrot ANAFI USA processed with Maps Made Easy and WingtraOne processed with DroneDeploy. Also, the WingtraOne/RX1R-II data set had higher processing times in Maps Made Easy and Pix4DReact relative to the number of images processed. This was because these images were much larger in size (42 MP), whereas other images were 24 MP or less.

4.3.3 Orthomosaic Analysis

After processing was completed, each orthomosaic was assessed to identify any distortion or processing errors, and to assess the overall level of detail. These results are presented in Sections 4.3.3.1 and 4.3.3.2.

4.3.3.1 Processing Errors/Distortion

Each orthomosaic was analyzed to look for signs of distortion or other processing errors. All maps had some degree of distortion or visible processing errors. However, in most cases the distortion was relatively minor and did not impact the usability of the map for situational awareness purposes, as evaluated by an ARFF subject matter expert (SME). Most of this distortion occurred on and around vertical structures, such as aircraft fuselages and the ARFF fire test building. All data sets that were able to be processed did not have any gaps or uncorrelated images. Table 5 presents a screenshot of each orthomosaic processed during Phase 1.

Table 5. Phase 1 Processing Outputs

	DroneDeploy	Maps Made Easy	Pix4DReact
Flight 1: Mavic 2 Pro 80%/70% 0.39-in. GSD 145 ft AGL			
Flight 2: WingtraOne/ RX1R-II 80%/70% 0.5-in. GSD 310 ft AGL			
Flight 3: M210/XT2 80%/70% 0.54-in. GSD 191 f. AGL			Sensor not compatible with processing software.

Table 5. Phase 1 Processing Outputs (Continued)

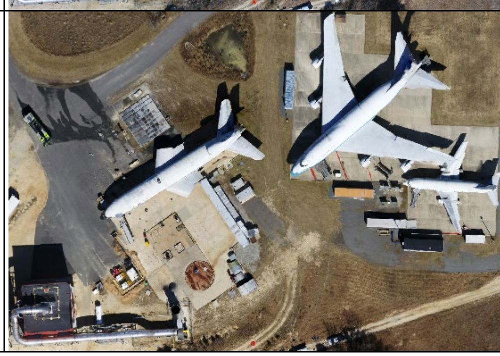
	DroneDeploy	Maps Made Easy	Pix4DReact
Flight 4: M2ED 80%/70% 1-in. GSD 235 ft AGL			
Flight 5: ANAFI USA 80%/70% 1-in. GSD 249 ft AGL			
Flight 6: M210/X7 80%/70% 1-in. GSD 340 ft AGL			Sensor not compatible with processing software.

Table 5. Phase 1 Processing Outputs (Continued)

	DroneDeploy	Maps Made Easy	Pix4DReact
Flight 7: eBee X/ S.O.D.A. 3D 80%/70% 1-in. GSD 369 ft AGL		Sensor not compatible with processing software.	
Flight 8: Mavic 2 Pro 80%/70% 1-in. GSD 372 ft AGL			

DroneDeploy produced the least amount of distortion among the three processing applications tested at ACY. The distortion in these maps was generally limited to portions of the aircraft horizontal and vertical stabilizers. Two data sets, the DJI M210/X7 16mm and ANAFI USA, had minor distortion on the airstairs adjacent to the L-1011, shown in Figure 20. DroneDeploy did have some minor distortion on the ARFF fire test building structure and roof vents, but this distortion was minimal compared to the other two processing applications.

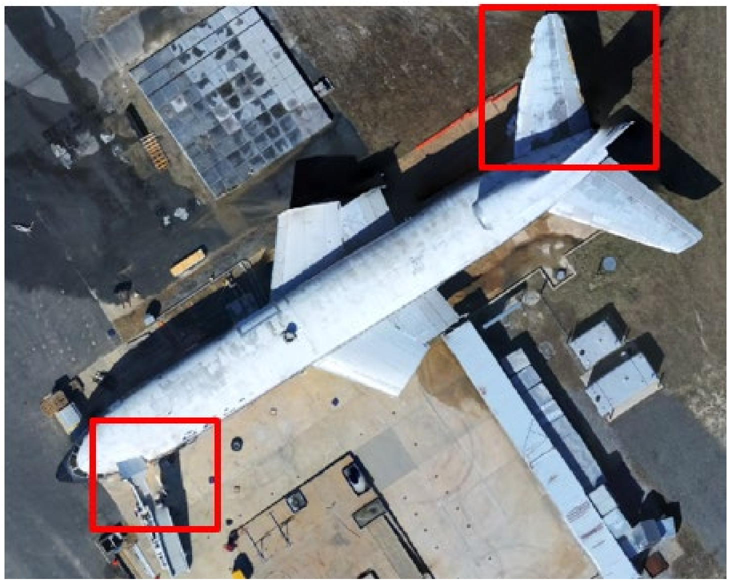


Figure 20. Flight 5 Processed with DroneDeploy

Orthomosaics generated using Maps Made Easy also had distortion on and around vertical structures. For example, Maps Made Easy produced a “clipping” effect with white borders around aircraft and buildings, as shown in Figure 21. This effect was most significant in the M210/X7 16mm, Parrot ANAFI USA, and Mavic 2 Enterprise Dual data sets. As shown in Figure 22, one result of this clipping effect was that it partially obscured the manikin placed beside the aircraft in data sets captured at 1-in. GSD. This effect was not present in the data set collected by the Mavic 2 Pro at 0.39-in. GSD, shown in Figure 23. Another example of distortion was in the WingtraOne/RX1R-II data set, in which the same manikin was warped and disfigured. Maps Made Easy also produced distortion on the ARFF Test Laboratory roof in all data sets, with this distortion most significant in the data set collected with the DJI M210/X7 16mm (shown in Figure 24).

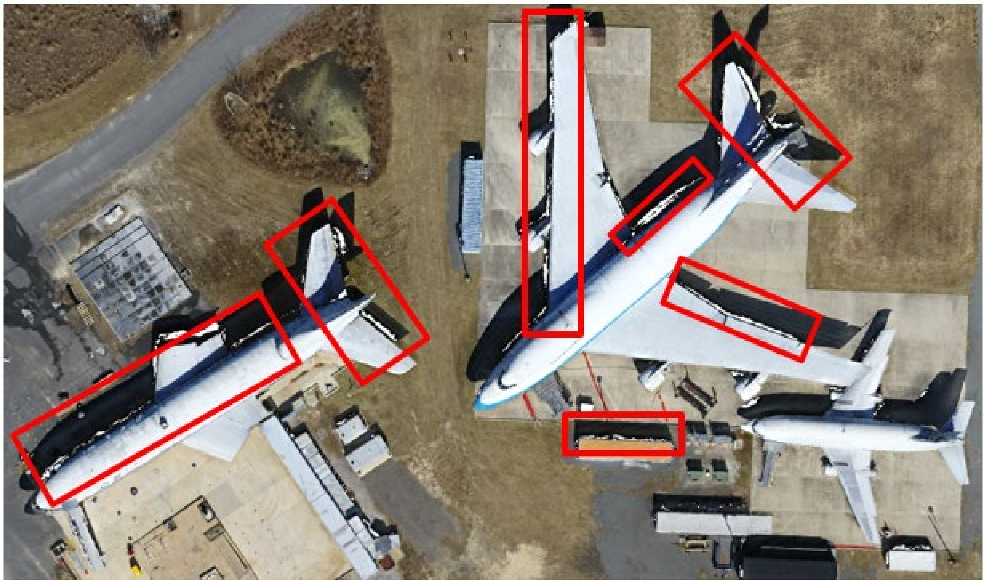


Figure 21. White Clipping Distortion Along Aircraft Edges in 1-in. GSD M210/X7 Data Set Processed with Maps Made Easy

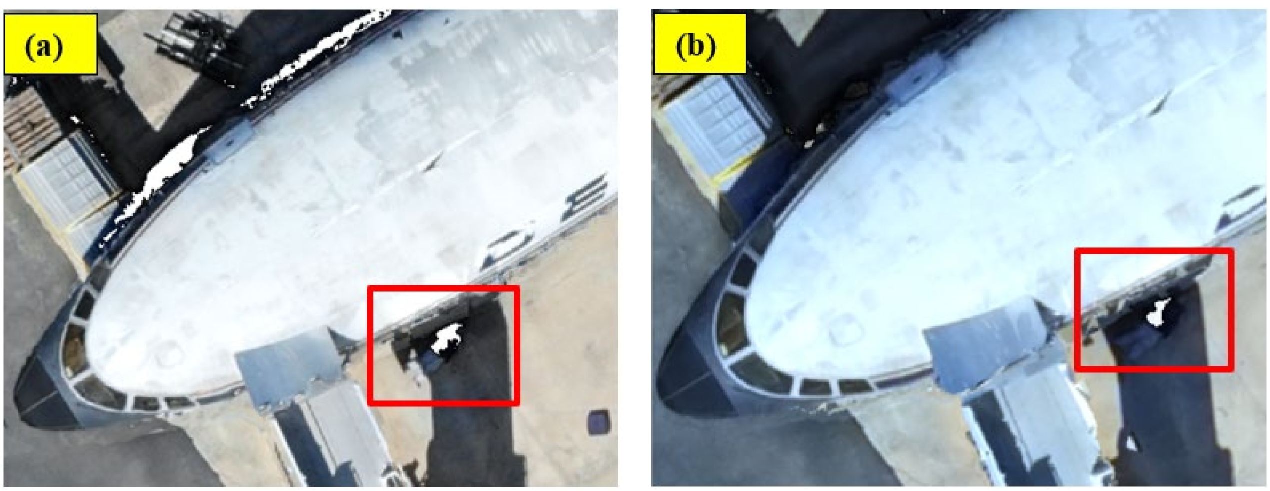


Figure 22. White Clipping Obscuring Manikin in 1-in. GSD Data Sets Processed with Maps Made Easy and Collected with the (a) M2ED and (b) Parrot ANAFI USA

Figure 23. Distorted Manikin in 0.39-in. GSD M2ED Data Set Processed with Maps Made Easy

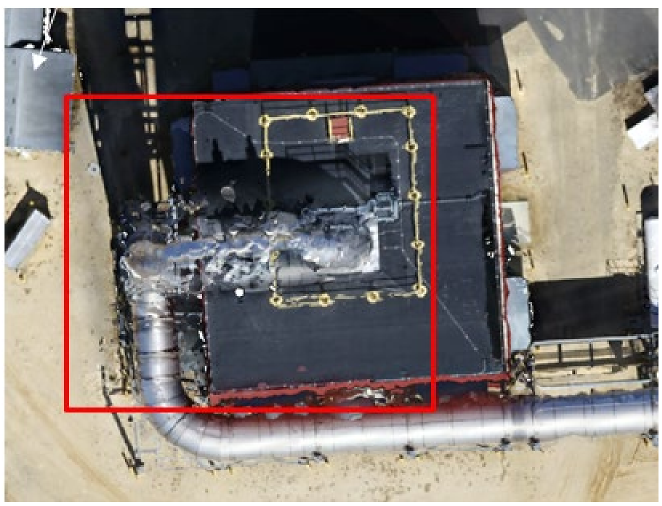


Figure 24. Significant Distortion of ARFF Research Facility 1-in. GSD M210/X7 Data Set Processed with Maps Made Easy

Pix4DReact also produced distortion for certain vertical structures. This distortion consisted mainly of portions of the aircraft becoming transparent or misaligned features, such as the exhaust vent for the ARFF Research Facility. An example of this distortion can be seen in Figure 25.

Figure 25. Errors in 0.5-in. GSD WingtraOne Data Set Processed with Pix4DReact

Data sets captured at higher altitudes tended to have fewer processing errors than data sets collected at lower altitudes. For instance, Figure 26 compares the distortion present in maps produced with the Mavic 2 Pro at 0.39-in. GSD (flown at 145 ft AGL) and 1-in. GSD (flown at 372 ft AGL), respectively. In the 0.39-in. GSD map, the nose of the L-1011 is partially missing, and the ARFF Test Laboratory exhaust vent is misaligned and partially missing. In the 1-in. GSD map, the nose of the L-1011 is properly reconstructed, and the ARFF Test Laboratory exhaust vent, while not perfectly reconstructed, is shown with significantly less distortion.

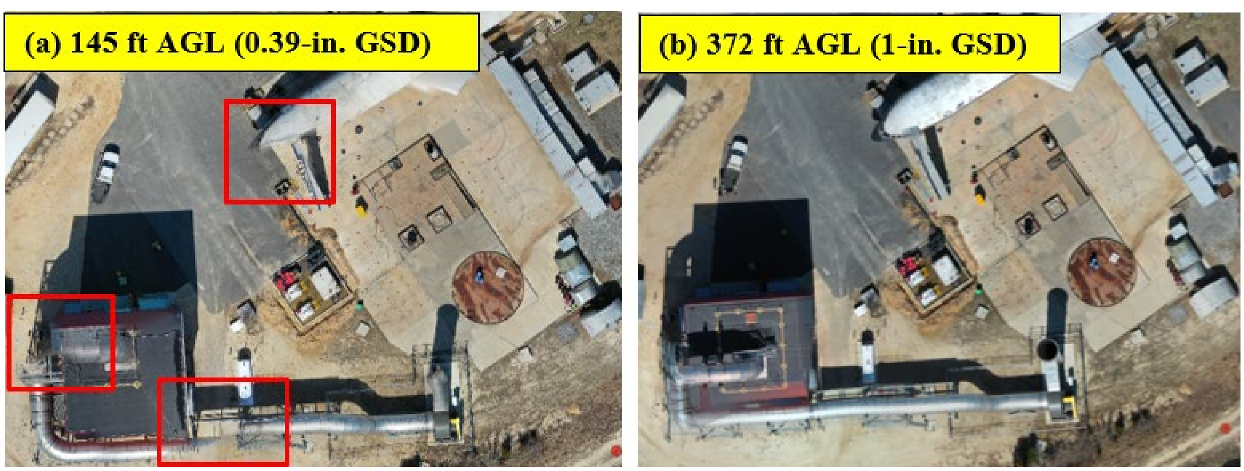


Figure 26. Comparison of Distortion in Mavic 2 Pro Data Sets Processed with Pix4DReact and Captured at (a) 145 ft AGL and (b) 372 ft AGL

4.3.3.2 Orthomosaic Quality/Level of Detail

FAA researchers next assessed the image quality and level of detail of each map. Table 6 shows a comparison of objects placed on the south side of the aircraft, while Table 7 shows an additional close-up comparison of the manikin on the north side of the aircraft. In all the generated maps, each of the test items were visible, including manikins, aircraft wheel, suitcases, and seat cushions. Although not pictured in these tables, the ARFF vehicle and simulated contaminant spill were also visible in all maps.

Forward/side overlap settings of 80%/70% were used for each data set collected. These settings were sufficient to produce orthomosaics that were free from distortion that impacted the usability of the maps for aircraft accident and incident documentation.

As expected, imagery captured at lower GSDs (i.e., higher resolutions) was noticeably clearer and provided a greater amount of detail than imagery with higher GSDs. For example, the thumb on the hand of the manikin can be differentiated from the rest of the hand in the 0.39-in., 0.50-in., and 0.54-in. imagery, but not in the 1-in. imagery. However, the manikin itself was still recognizable in the 1-in. imagery. Differences between maps captured at the same GSD were relatively small excluding the distortion of the manikin adjacent to the aircraft shown in Figure 22 in Section 4.3.3.1. This suggested that orthomosaic resolution is determined primarily by the GSD and not the processing software.

Table 6. Phase 1 Image Detail Comparison

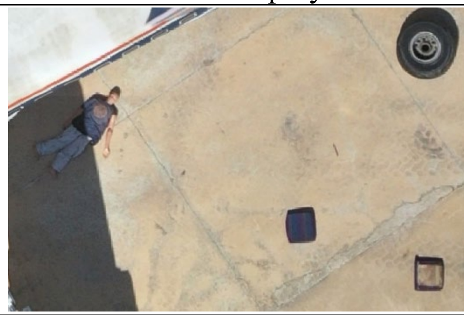
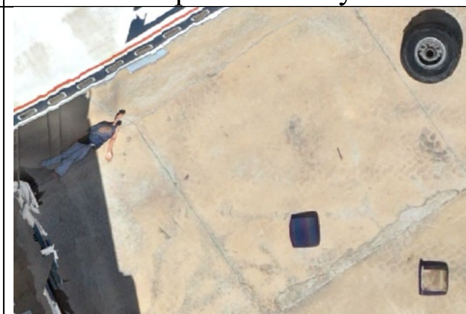
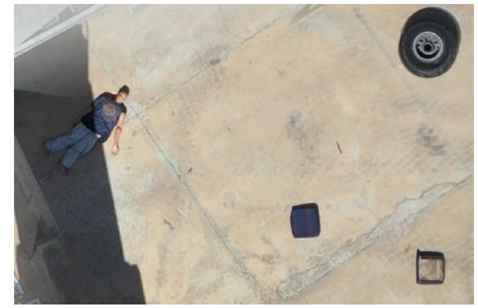
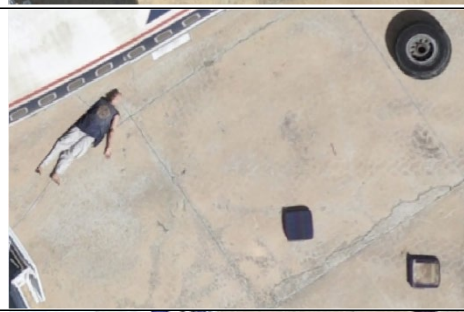
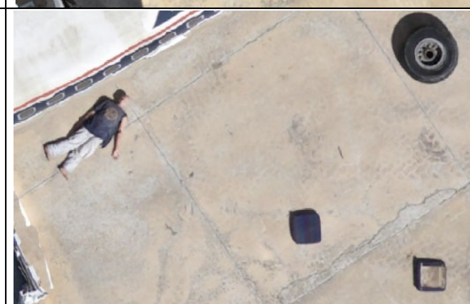
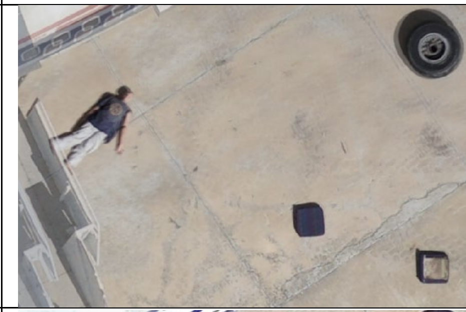
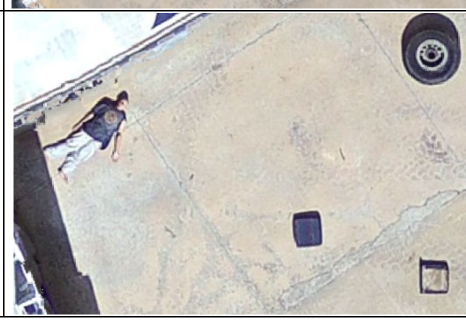
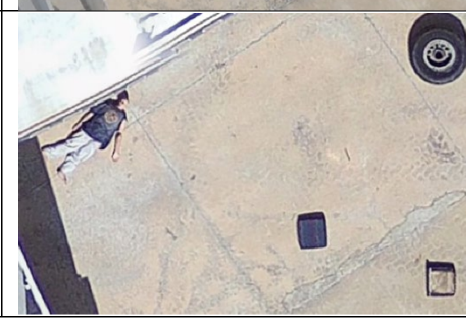
	DroneDeploy	Maps Made Easy	Pix4DReact
Flight 1: Mavic 2 Pro 80%/70% 0.39-in. GSD 145 ft AGL			
Flight 2: WingtraOne/ RX1R-II 80%/70% 0.5-in. GSD 310 ft AGL			
Flight 3: M210/XT2 80%/50% 0.54-in. GSD 191 ft AGL			

Table 6. Phase 1 Image Detail Comparison (Continued)

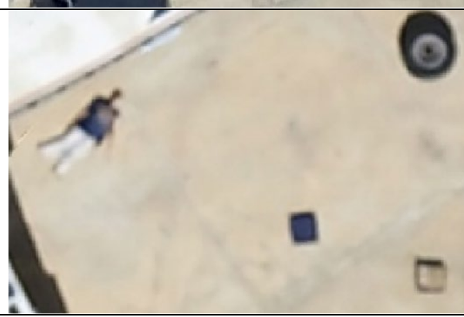
	DroneDeploy	Maps Made Easy	Pix4DReact
Flight 4: M2ED 80%/70% 1-in. GSD 235 ft AGL			
Flight 5: ANAFI USA 80%/70% 1-in. GSD 249 ft AGL			
Flight 6: M210/X7 80%/70% 1-in. GSD 340 ft AGL			Sensor not compatible with processing software.

Table 6. Phase 1 Image Detail Comparison (Continued)

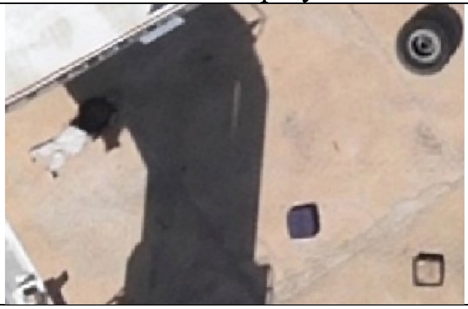
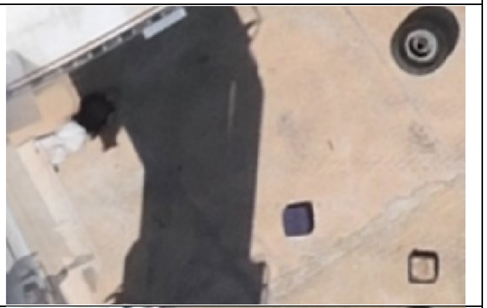
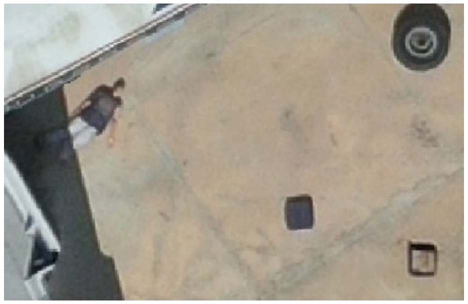
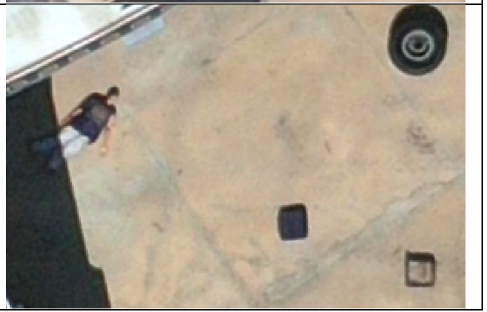
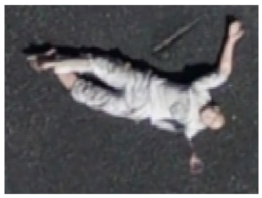
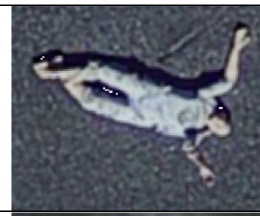
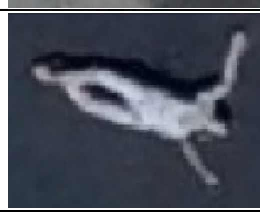
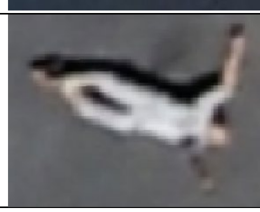
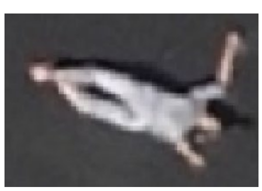
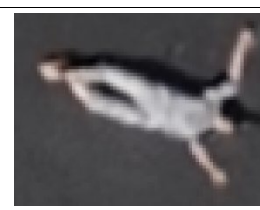
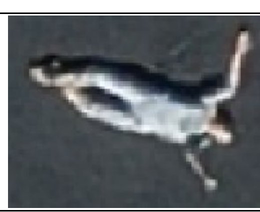
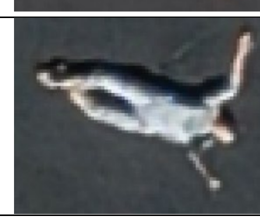
	DroneDeploy	Maps Made Easy	Pix4DReact
Flight 7: eBee X/ S.O.D.A. 3D 80%/70% 1-in. GSD 369 ft AGL		Sensor not compatible with processing software.	
Flight 8: Mavic 2 Pro 80%/70% 1-in. GSD 372 ft AGL			

Table 7. Phase 1 Image Detail Comparison: Manikin

	DroneDeploy	Maps Made Easy	Pix4DReact
Flight 1: Mavic 2 Pro 80%/70% 0.39-in. GSD 145 ft AGL			
Flight 2: WingtraOne/ RX1R-II 80%/70% 0.5-in. GSD 310 ft AGL			
Flight 3: M210/XT2 80%/50% 0.54-in. GSD 191 ft AGL			
Flight 4: M2ED 80%/70% 1-in. GSD 235 ft AGL			
Flight 5: ANAFI USA 80%/70% 1-in. GSD 249 ft AGL			
Flight 6: M210/X7 80%/70% 1-in. GSD 340 ft AGL			Sensor not compatible with processing software.
Flight 7: eBee X/ S.O.D.A. 3D 80%/70% 1-in. GSD 369 ft AGL		Sensor not compatible with processing software.	
Flight 8: Mavic 2 Pro 80%/70% 1-in. GSD 372 ft AGL			

4.3.4 Additional Features/Capabilities

Pix4DReact provided a marking and annotation feature that allowed certain objects of interest to be marked and provided as zoomed views in the PDF overview map. Examples of this marking feature can be seen in Figures 27 and 28. These annotations were created by the FAA research team in Pix4DReact as a proof-of-concept to demonstrate this feature.

Figure 27. Pix4DReact PDF Marker Feature

Figure 28. Pix4DReact Annotation Feature Example

4.4 FINDINGS

Following are the primary findings from Phase 1 UAS testing at ACY.

- An 80% forward overlap and a 70% side overlap were sufficient to produce acceptable orthomosaics of an accident scene involving large aircraft.
- A 1-in. GSD resolution provided the best combination of image detail and time efficiency. This resolution provided sufficient detail to see aircraft and ground vehicle positions and orientations, and additional features of a scene including manikins, liquid spills, and debris of various sizes. Tests conducted at higher resolutions/lower altitudes were able to provide increased detail but took significantly longer to collect and process and, in some cases, resulted in an increased number of processing errors and distortion.
- All UAS payloads used during Phase 1 were able to capture imagery that was of sufficient resolution and quality to generate orthomosaics that were acceptable for aircraft accident documentation.
- UAS airframe type affected data acquisition time, with the fixed-wing and hybrid systems collecting data faster than multirotor platforms using the same overlap and GSD parameters.
- The hybrid UAS platform (WingtraOne) provided the benefits of fixed-wing data collection (faster data collection) while requiring the same ground footprint as a multirotor platform.
- Higher-resolution cameras allowed the UAS to fly higher while maintaining an equivalent or better GSD than lower-resolution sensors. This allowed UASs equipped with higher-resolution payloads to complete the mapping missions faster than those equipped with lower resolution payloads.
- Higher-resolution sensors can result in longer processing times due to the larger file size of each individual photo.
- All processing software packages were able to consistently generate orthomosaics that were found to be acceptable for aircraft accident documentation.
- The Pix4DReact processing software was able to generate orthomosaics significantly faster than cloud-based processing solutions that required images to be uploaded to a server.
- The cloud-based processing solutions generated orthomosaics that generally exhibited less distortion than the locally installed processing software.

5. PHASE 2 TESTING: WWD

Phase 2 aircraft accident and incident documentation testing followed a similar approach to Phase 1: FAA researchers conducted a series of aerial mapping flights with various UAS platforms and visual camera payloads over a simulated aircraft accident scene. Phase 2 focused on the mapping of a simulated GA accident site involving a small aircraft and a ground vehicle. Following data collection, the data sets were processed into orthomosaics using two software packages. The goal of this phase was to further develop and refine the minimum technology performance specifications and operational recommendations for UAS flight parameters, payloads, and processing software packages when supporting aircraft accident documentation.

Phase 2 testing took place at WWD in Rio Grande, NJ. WWD is a dual runway (Runways 1/19 and 10/28), non-towered airport located in uncontrolled (Class G) airspace from the surface to 700 ft AGL. WWD was selected for Phase 2 because it is the location of the FAA Research Taxiway (Taxiway C); and because of its proximity to the FAA WJHTC and an existing memorandum of agreement between the Delaware River and Bay Authority (DRBA), who owns and manages WWD, and the FAA. Due to weather and scheduling limitations, testing was conducted across two nonconsecutive days.

5.1 UAS PLATFORMS AND PAYLOADS

Sections 5.1.1 through 5.1.2 describe the UAS platforms and payloads used to conduct Phase 2 testing.

5.1.1 UAS Platforms

Phase 2 used many of the same UAS platforms as in Phase 1. These included the following:

- DJI Mavic 2 Pro
- DJI M2ED
- Parrot ANAFI USA
- SenseFly eBee X

These UAS platforms are pictured in Figure 6 in Section 3.2.1.2. Table 1 in Section 3.2.1.2 presents a comparison of key specifications for these UASs, and detailed specifications for each platform are presented in Appendix A.

The WingtraOne was excluded from further testing following Phase 1 because its payload, the Sony RX1R-II, has significantly higher performance specifications than the rest of the payloads included in this research effort and therefore would not provide further insight in the development of minimum performance specifications.

The M210 and its X7 payload were excluded from this phase of the research because the X7 is not compatible with Pix4DReact, which was the only post-processing software used (DroneDeploy Live Map processes during the flight).

5.1.2 Payloads

The following camera payloads were used to collect imagery during Phase 2 UAS testing at WWD:

- DJI M2ED Integrated Camera (visual and thermal camera)

- DJI Mavic 2 Pro Hasselblad Camera (visual camera)
- Parrot ANAFI Triple (dual visual cameras and one thermal camera)
- SenseFly S.O.D.A. 3D (visual camera)

Figure 7 in Section 3.2.1.3 depicts the camera payloads included in this testing. Table 2 in Section 3.2.1.3 compares key specifications of each payload. Detailed specifications for each payload are presented in Appendix B.

5.2 TEST METHODS AND PROCEDURES

Sections 5.2.1 through 5.2.5 describe the test setup and procedures employed during Phase 2 UAS testing at WWD.

5.2.1 Mapping Area

The mapping area at WWD was located directly over the FAA Research Taxiway (Taxiway C) to the north of Runway 10/28 and to the west of Runway 1/19. This mapping area is pictured in Figure 29. Taxiway C was closed during the operations, and Runway 10/28 was closed due to ongoing construction.

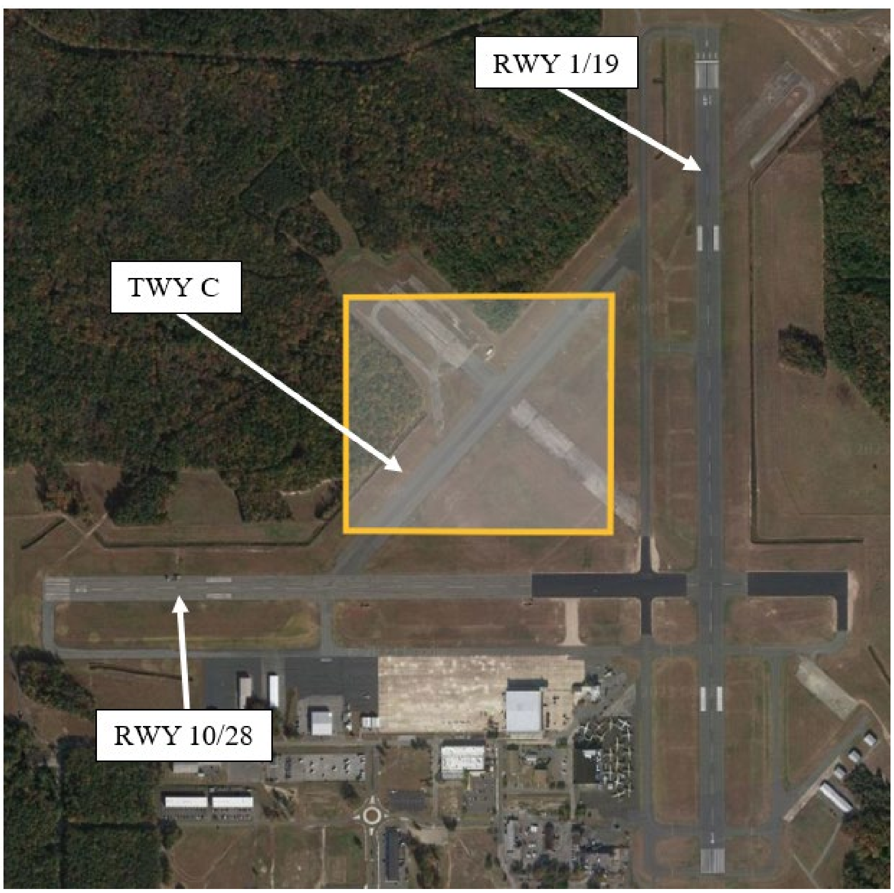


Figure 29. WWD UAS Operations Area

5.2.2 Site Setup

This scenario consisted of a simulated collision between a Cessna 172 (C172) and a Ford Expedition ground vehicle. Figure 30 provides an overview of the scene as it appeared during data collection. FAA researchers placed tire tracks on a disused portion of pavement to determine if these could be seen in the UAS maps, and released water under the aircraft, trailing away from the tail, to simulate a fuel spill.

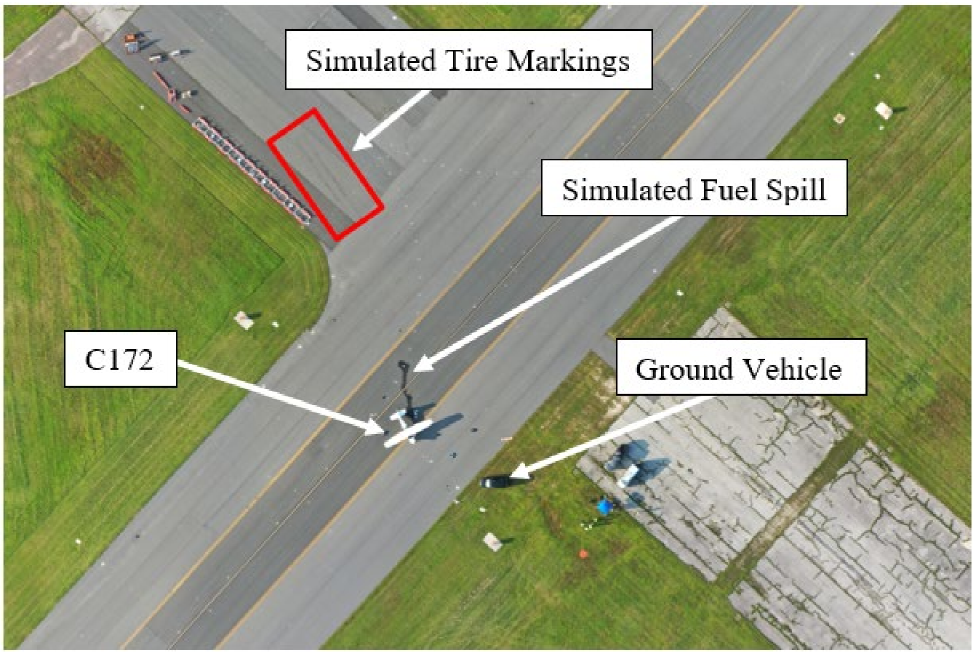


Figure 30. WWD Accident Site Overview

A variety of objects of various sizes were placed in a simulated debris field to assess the image detail of the UAS maps. Figure 31 shows an aerial view of the scene, and Figure 32 shows a view of the scene from ground level. FAA researchers attempted to recreate the exact same layout of test items on both test dates; however, there were small differences in the placement and orientation of certain objects.

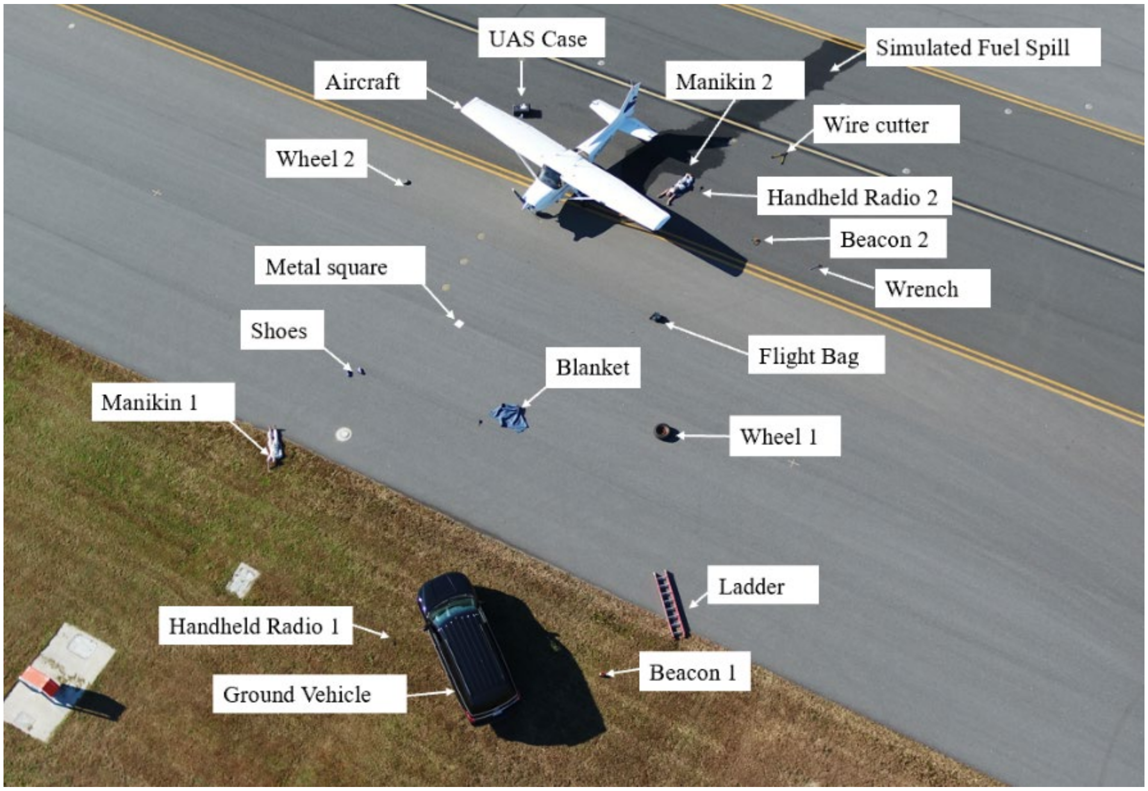


Figure 31. Aerial View of WWD Accident Site

Figure 32. Ground View of WWD Simulated Accident Site

5.2.3 Flight Parameters

Table 8 summarizes the parameters for each data set collected at WWD during Phase 2. Based on the results of the ACY testing, FAA researchers lowered the overlap values to determine if data could be acquired in less time without impacting the quality of the resulting orthomosaic. The baseline forward- and side-overlap values were lowered from 80%/70% to 70%/60% for each UAS platform/payload combination. For the Mavic 2 Pro, additional tests were also conducted with overlap values of 80%/70%, 60%/60%, 50%/50%, and 40%/40% to determine if a minimum overlap value could be identified.

Based on findings from Phase 1, the majority of testing was conducted with a GSD of 1 in., but, similar to the ACY testing, a 0.39-in. (1-cm) GSD data set was included for comparison. Due to the differing nature of the software packages used, the same set of parameters was repeated for each test that was processed with both Pix4DReact and the DroneDeploy Live Map software.

Table 8. Phase 2 Test Parameters

Test #	UAS	Payload	Overlap % (Forward/Side)	Altitude (AGL)	GSD (in.)	Processing Software
1A	Mavic 2 Pro	Hasselblad	70/60	147 ft	0.39	P4D React
1B	Mavic 2 Pro	Hasselblad	70/60	147 ft	0.39	DroneDeploy Live Map
2	M2ED	M2ED	70/60	236 ft	1.00	P4D React
3	Parrot ANAFI USA	ANAFI Triple	70/60	249 ft	1.00	P4D React
4	eBee X	S.O.D.A. 3D	70/60	368 ft	1.00	P4D React
5	Mavic 2 Pro	Hasselblad	80/70	373 ft	1.00	P4D React
6A	Mavic 2 Pro	Hasselblad	60/60	373 ft	1.00	P4D React
6B	Mavic 2 Pro	Hasselblad	60/60	373 ft	1.00	DroneDeploy Live Map
7A	Mavic 2 Pro	Hasselblad	50/50	373 ft	1.00	P4D React
7B	Mavic 2 Pro	Hasselblad	50/50	373 ft	1.00	DroneDeploy Live Map
8A	Mavic 2 Pro	Hasselblad	40/40	373 ft	1.00	P4D React
8B	Mavic 2 Pro	Hasselblad	40/40	373 ft	1.00	DroneDeploy Live Map

5.2.4 Data Processing

Sections 5.2.4.1 through 5.2.4.3 describe the specific software, hardware, and settings used to process the data collected during Phase 2.

5.2.4.1 Processing Software

Based on the findings from Phase 1 regarding cloud-based processing, FAA researchers decided to focus on software solutions that could process data locally. Two software packages were used to process the images captured at WWD:

- Pix4DReact
- DroneDeploy Live Map

DroneDeploy Live Map is unique among the software packages used in this project, in that it is an all-in-one program that supports flight plan development, execution, and data processing. DroneDeploy Live Map develops the orthomosaic on the GCS display using the video feed transmitted from the UAS while the flight is being executed, providing the completed map at the conclusion of the flight. At the time the test was conducted, this application did not have the capability of capturing photos while mapping using DroneDeploy Live Map; however, this feature has since been added by the company.

5.2.4.2 Processing Hardware

Each Pix4DReact data set was processed using a Dell Precision 7540 laptop computer with the following specifications:

- Processor: Intel i9-9980HK (2.4GHz)
- RAM: 32GB (2 x 16GB) DDR4 @ 2667MHz
- Video Card: NVIDIA Quadro T2000
- Operating System: Windows 10 Enterprise 64-bit
- Power Source: Alternating current power supply

The hardware used to process the DroneDeploy Live Map data was an Apple® iPad mini® (5th generation) with a 64-bit A12 Bionic central processing unit.

5.2.4.3 Processing Settings

Following are the processing settings used for each processing application/service:

- Pix4DReact:

  Imagery was post-processed via the Pix4DReact downloadable suite with no changes to the default processing options. If a data set exceeds a certain threshold in size or resolution, Pix4DReact asks the user if they would like to process the data set at a lower resolution. For these tests, this option was declined, and the data sets were all processed at the "full" resolution offered by Pix4DReact.

- DroneDeploy Live Map:

  Data sets were collected and processed using the default settings on DroneDeploy Live Map.

5.2.5 Regulatory and Safety Considerations

Prior to conducting UAS operations, FAA researchers submitted a Notice of Proposed UAS Operation form, as required by the DRBA, which provided details of the UAS operations. In addition, FAA researchers coordinated the closure of the FAA's Research Taxiway (Taxiway C). During the operations, members of the flight crew monitored the WWD common traffic advisory frequency to ensure deconfliction with local air traffic and the WWD automated weather observation system frequency to ensure they were operating within approved weather minimums. The flight team ensured the UAS operations did not cross the runway safety area of Runway 1/19.

5.3 RESULTS AND DISCUSSION

Sections 5.3.1 through 5.3.4 provide results and additional discussion from Phase 2 testing at WWD. These sections address data acquisition and processing times, orthomosaic quality, and additional software features.

5.3.1 Data Acquisition Times

As shown in Figure 33, data acquisition times at WWD ranged from 4 minutes to 16 minutes to cover the approximately 50-acre test area. (Note: Due to time limitations, the Mavic 2 Pro 0.39-in. GSD flight area was abbreviated and did not cover the full test area.) These results confirmed the finding from Phase 1 that altitude/GSD has a significant effect on data acquisition time. Flights conducted at higher altitudes/GSDs were generally able to be completed in less time than missions with lower altitudes/GSDs. In addition, the use of varying overlap parameters demonstrated how increasing overlap contributes to longer data acquisition times. Data sets collected with lower forward and side overlap also had lower data acquisition times. For example, lowering the forward/side overlap parameters for the Mavic 2 Pro from 80%/70% to 50%/50% at a 1-in. GSD led to a 40% reduction in acquisition time (from 10 minutes to 6 minutes) without any missing data.

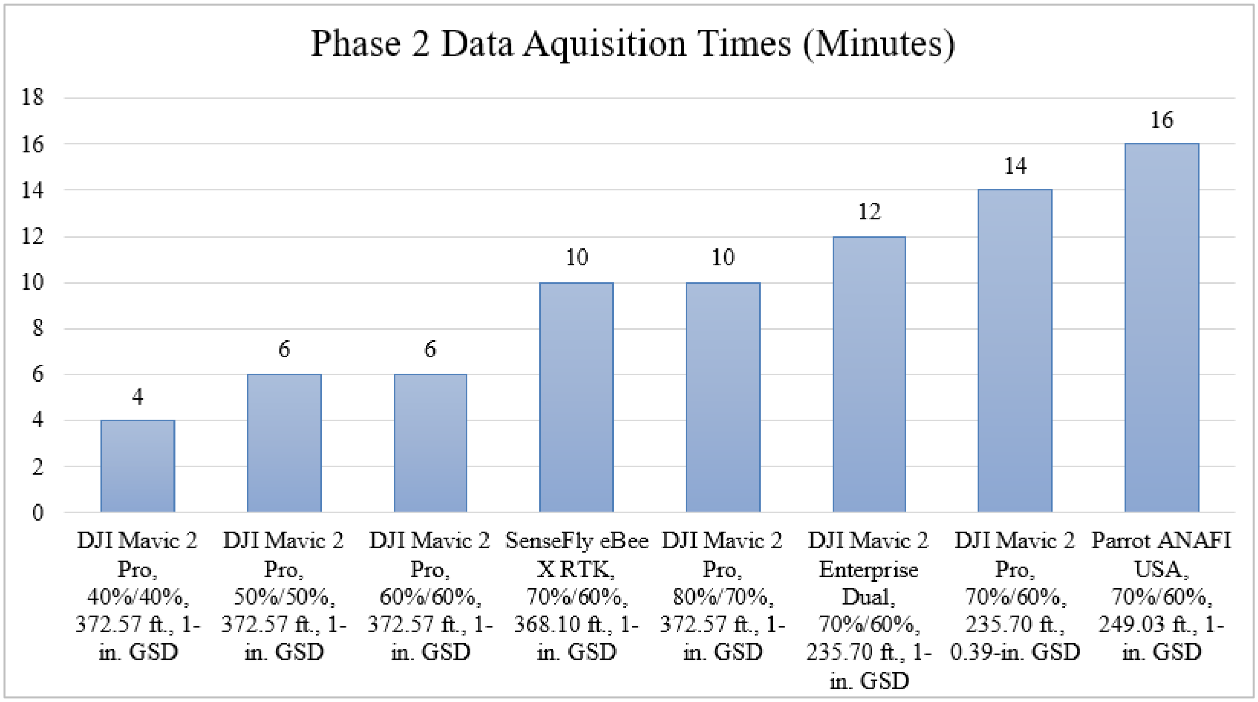


Figure 33. Phase 2 Data Acquisition Times

These results also confirmed the finding from Phase 1 that payload specifications are a critical component of data acquisition efficiency, since the payload resolution determines the altitude at which a UAS can achieve a given GSD. This was evident in the flight time of the Parrot ANAFI USA, which mapped the scene in 16 minutes with a 1-in. GSD and 70%/60% overlap settings. This was 60% longer than it took the eBee X to map the same area with the same parameters. Due to the ANAFI Triple's lower resolution sensor versus the S.O.D.A. 3D, the ANAFI USA had to be flown at 249.03 ft AGL to achieve a 1-in. GSD, while the eBee X was flown at 368.1 ft AGL.

5.3.2 Data Processing Times

Figure 34 shows the processing times for each data set using Pix4DReact in Phase 2. DroneDeploy Live Map processed all data sets in real time and, therefore, did not require post-flight processing. The Pix4DReact processing times ranged from 34 seconds to 126 seconds. Similar to Phase 1, processing times were generally correlated with the number of images in each data set, with larger data sets requiring more time to process.

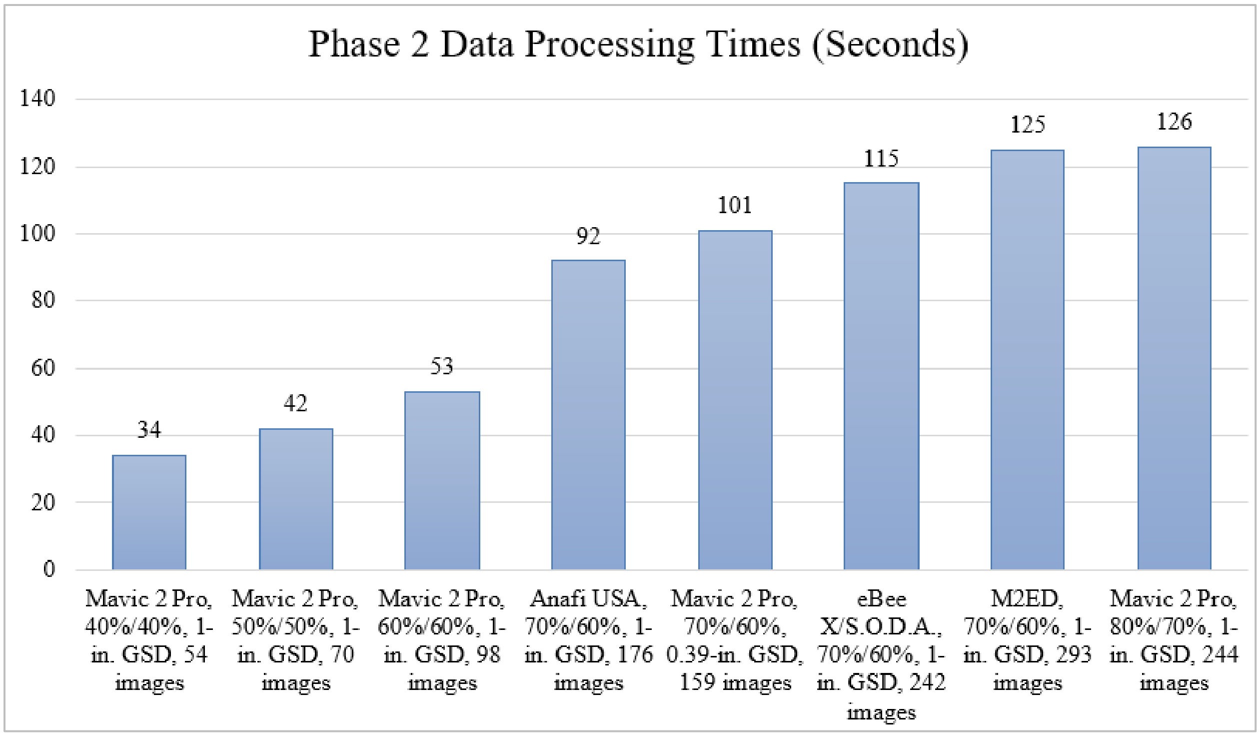


Figure 34. Phase 2 Data Processing Times (Pix4DReact)

5.3.3 Orthomosaic Analysis

After processing was complete, each orthomosaic was assessed to identify any distortion or processing errors and to assess the overall level of detail. These results are presented in Sections 5.3.3.1 and 5.3.3.2.

5.3.3.1 Processing Errors/Distortion

Orthomosaics were first examined for completeness, noting any gaps or uncorrelated images. The only map that did not fully process was the Mavic 2 Pro 1-in. GSD data set collected with 40%/40% forward/side overlap. This map had two gaps in heavily wooded/vegetated areas at the edges of the mapping area, as shown in Figure 35. Although these gaps did not affect viewing of the main accident scene, they did indicate the need for higher overlap values to map areas with dense vegetation.

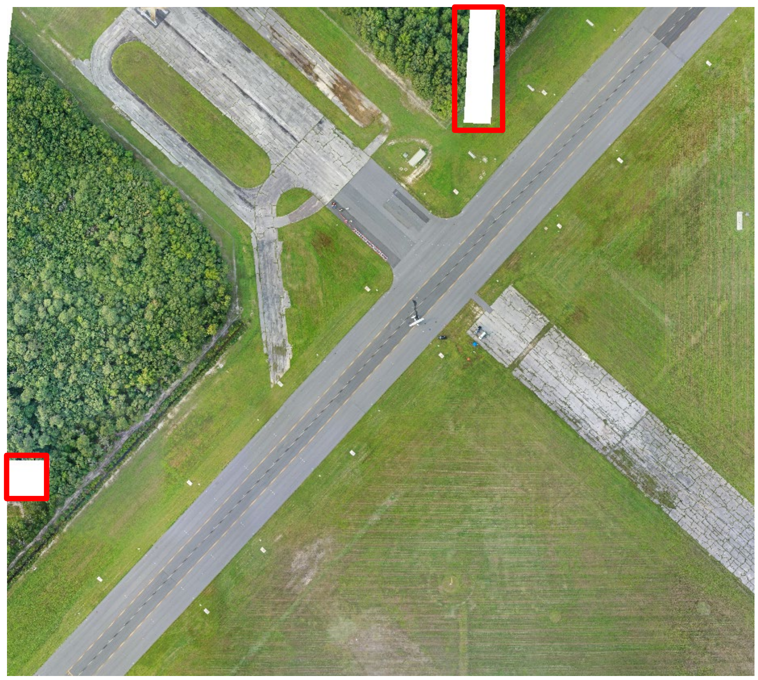


Figure 35. Flight 8A Processed with Pix4DReact

Next, FAA researchers visually inspected each map for other processing errors or distortion. The amount of distortion overall was relatively minimal and did not impact the usability of the maps for situational awareness purposes. Most of the distortion observed occurred on the wings of the C172 or the taxiway markings. Table 9 presents screenshots for each orthomosaic processed during Phase 2.

Table 9. Phase 2 Processing Errors/Distortion Comparison

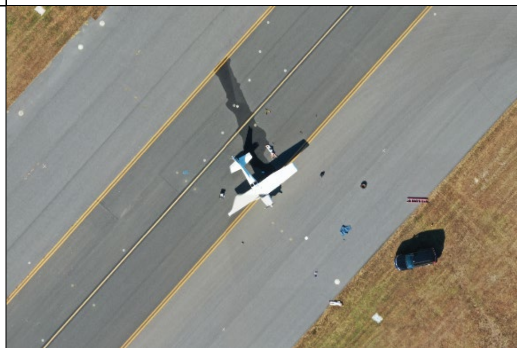
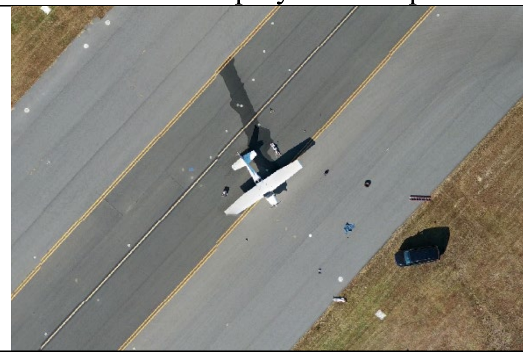
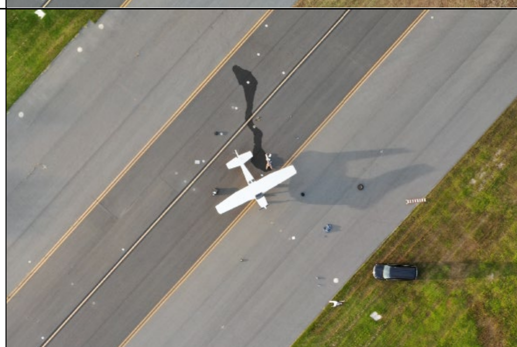
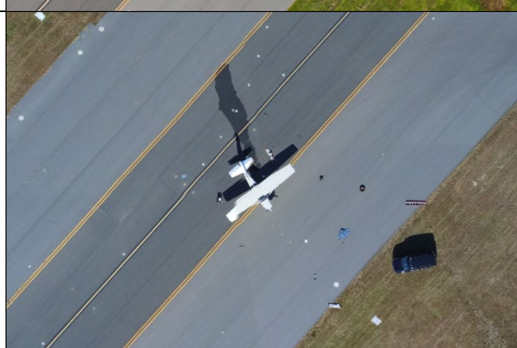
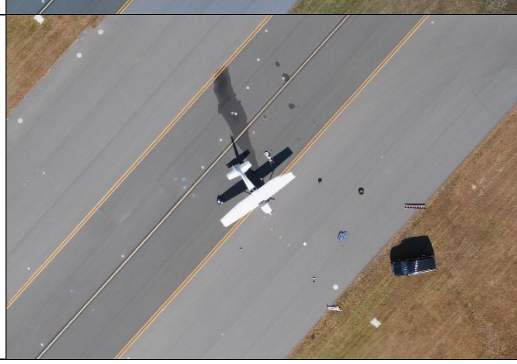
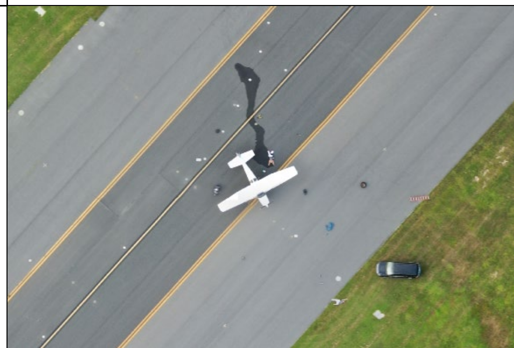
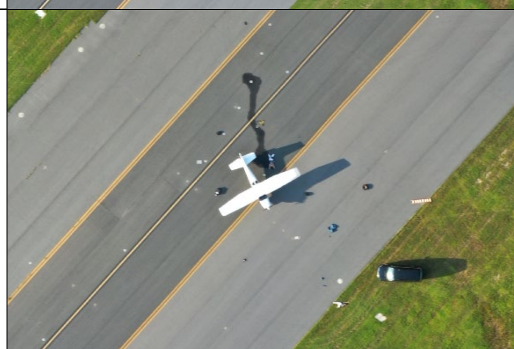
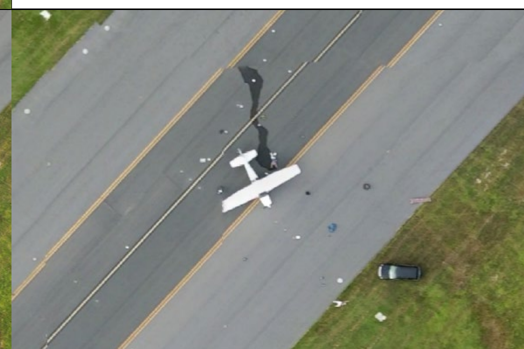
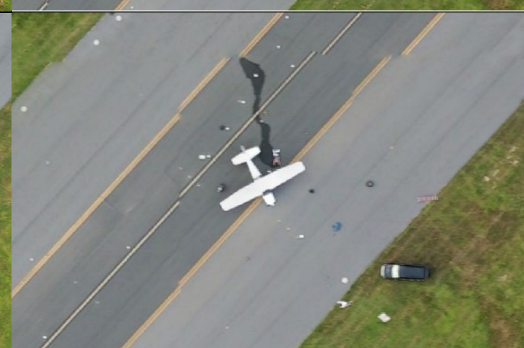
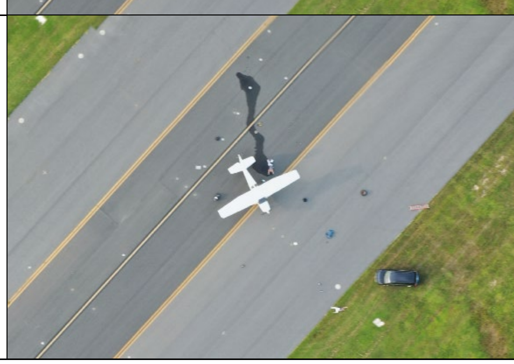
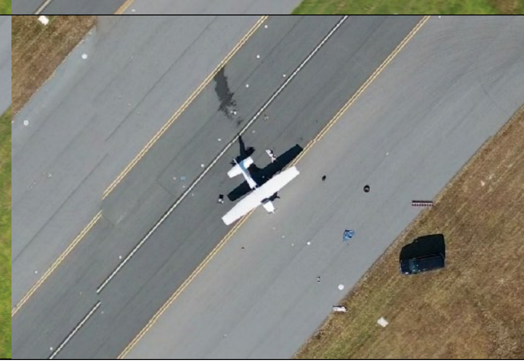
Data Set	Pix4DReact	DroneDeploy Live Map
Test 1: Mavic 2 Pro 70%/60% 0.39-in. GSD 147 ft AGL		
Test 2: M2ED 70%/60% 1-in. GSD 236 ft AGL		N/A
Test 3: ANAFI USA 70%/60% 1-in. GSD 249 ft AGL		N/A
Test 4: eBee X/ S.O.D.A. 3D 60%/60% 1-in. GSD 368 ft AGL		N/A

Table 9. Phase 2 Processing Errors/Distortion Comparison (Continued)

	Pix4DReact	DroneDeploy Live Map
Test 5: Mavic 2 Pro 80%/70% 1-in. GSD 373 ft AGL		N/A
Test 6: Mavic 2 Pro 60%/60% 1-in. GSD 373 ft AGL		
Test 7: Mavic 2 Pro 50%/50% 1-in. GSD 373 ft AGL		
Test 8: Mavic 2 Pro 40%/40% 1-in. GSD 373 ft AGL		

Overall Pix4DReact produced less distortion than DroneDeploy Live Map, with most of the distortion limited to the C172 wing, as shown in Figure 36. Of the eight maps generated using Pix4DReact, three had small portions of the C172's wingtip cut off or misaligned (eBee X/S.O.D.A. 3D 60%/60%, 1-in. GSD; ANAFI USA 70%/60%, 1-in. GSD; and DJI Mavic 2 Pro 70%/60%, 0.39-in. GSD). Additionally, it was observed that the C172 was blurrier in the DJI

Mavic 2 Pro 50%/50%, 1-in. GSD map compared to other data sets collected with this UAS platform. This was likely due to focus issues with the sensor during data collection rather than a product of data processing.

Figure 36. C172 Wingtip Distortion in Pix4DReact Orthomosaics from (a) Test 1A (70%/60% overlap and 0.39-in. GSD) and (b) Test 3 (70%/60% overlap and 1-in. GSD)

All four maps processed using DroneDeploy Live Map had distorted or misaligned taxiway surface markings. Two of the DroneDeploy Live Map maps (Mavic 2 Pro 1-in. GSD 60%/60% and DJI Mavic 2 Pro 70/60, 0.39-in. GSD) also had small sections of the C172's wingtip cut off.

Figure 37 compares the distortion present in orthomosaics generated by each processing software from Test 6. This data set was collected using the Mavic 2 Pro with a 1-in. GSD and overlap settings of 60%/60%. The red boxes overlaying each image indicate where distortion is present. As shown in Figure 37, DroneDeploy Live Map produced several minor instances of distortion that could be seen on the C172 wingtip, taxiway markings, and the edge of the taxiway pavement.

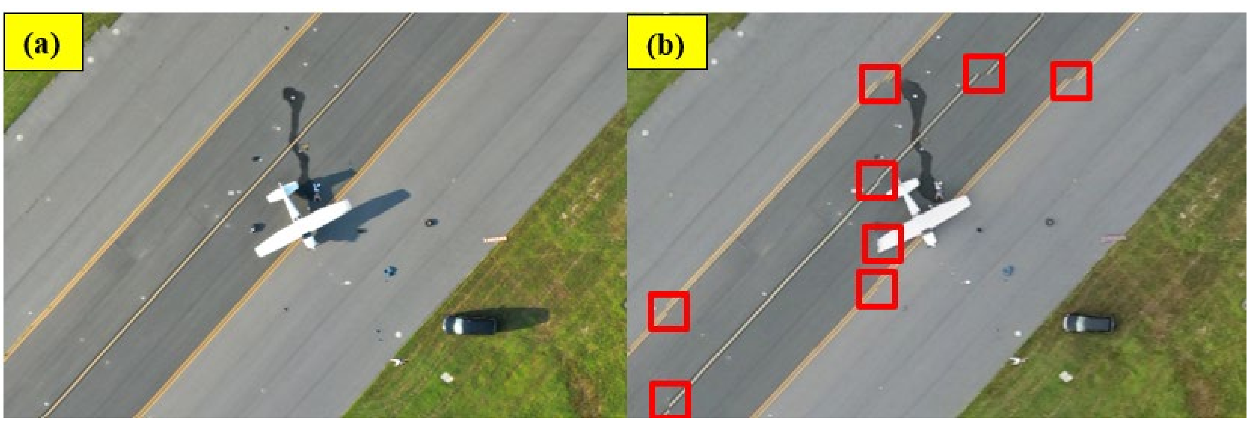


Figure 37. Comparison of Distortion in Orthomosaics Generated from Test 6 (60%/60% overlap and 1-in. GSD) by (a) Pix4DReact and (b) DroneDeploy LiveMap

Varying overlap values did not appear to have a determining effect on the presence of distortion in the orthomosaics. Figure 38 compares screenshots of orthomosaics generated using Pix4DReact from data sets collected by the Mavic 2 Pro with a 1-in. GSD and overlap settings of 80%/70% and 40%/40%. As shown in Figure 38, neither orthomosaic contains significant distortion. This indicated that lower overlap settings did not increase the level of distortion in the resulting orthomosaic.

Figure 38. Comparison of Distortion in Orthomosaics Generated by Pix4DReact from Data Sets Collected by the Mavic 2 Pro with Overlap Settings of (a) 80%/70% and (b) 40%/40%

Altitude/GSD did appear to have an effect on the amount of distortion present in the imagery, specifically regarding the wingtip of the C172. Figure 39 compares screenshots taken from the orthomosaics generated from Test 1A and Test 5A. Both data sets were collected with the same UAS, payload, and overlap settings and processed with Pix4DReact. Test 1A was collected at an altitude of 147 ft AGL (0.39-in. GSD) while Test 5A was collected at an altitude of 373 ft AGL (1-in. GSD). The red boxes indicate where there was a discrepancy in the amount of distortion observed in the orthomosaics. As shown in Figure 39, the data set collected at a lower altitude produced distortion of the C172 wingtip, while the data set collected at a higher altitude did not experience this issue.

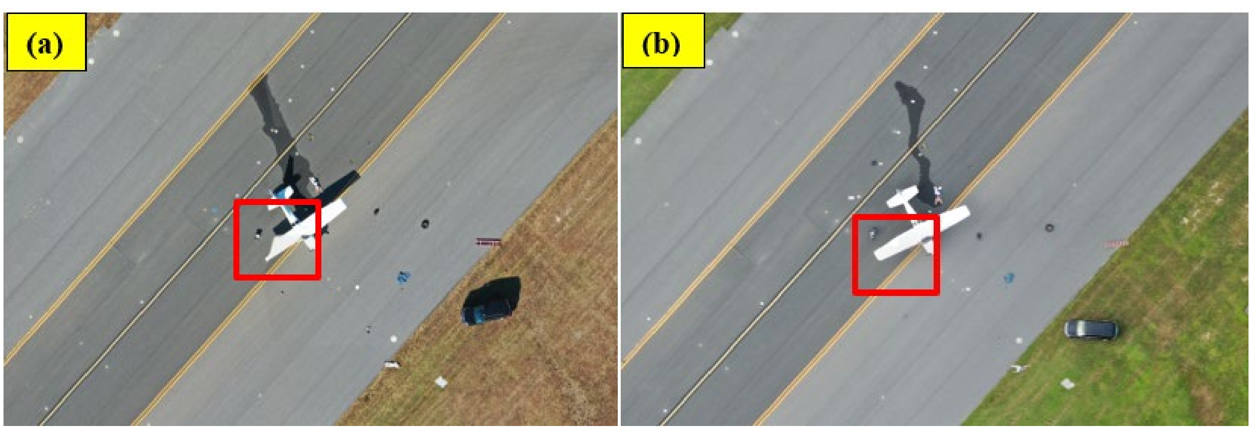


Figure 39. C172 Wingtip Distortion in Pix4DReact Orthomosaics from (a) Test 1A (70%/60% overlap and 0.39-in. GSD) and (b) Test 5A (70%/60% overlap and 1-in. GSD)

5.3.3.2 Orthomosaic Quality/Level of Detail

FAA researchers next compared the image quality and level of detail present in each map. Table 10 shows a representative sample from each data set showing a manikin and various tools. As noted in Section 5.2.2, images were taken on two different dates, so objects were arranged slightly differently in each image. The forward and side overlap did not have any visible effect on the level of detail of the resulting map. All maps generated using Pix4DReact had sufficient level of detail to identify all objects placed in the test area, including small tools and handheld radio. As expected, the Mavic 2 Pro data set captured with a 0.39-in. GSD had a higher level of detail than the 1-in. GSD data sets. Among the 1-in. GSD data sets, the eBee X/S.O.D.A. 3D and ANAFI USA had the highest level of detail.

Table 10. Phase 2 Image Quality Comparison

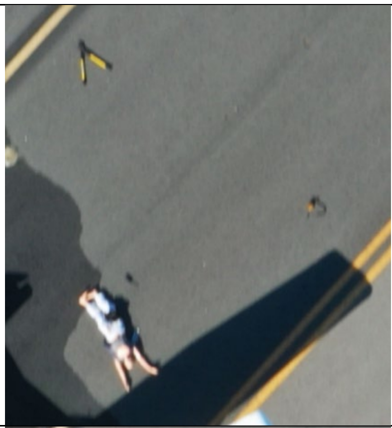
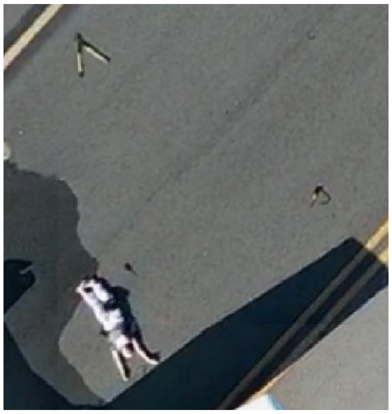
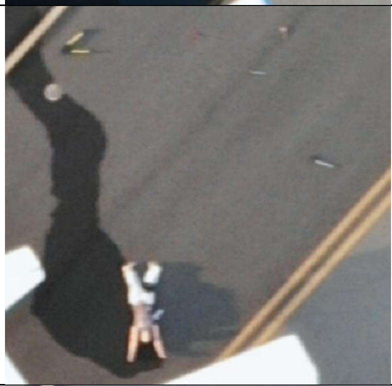
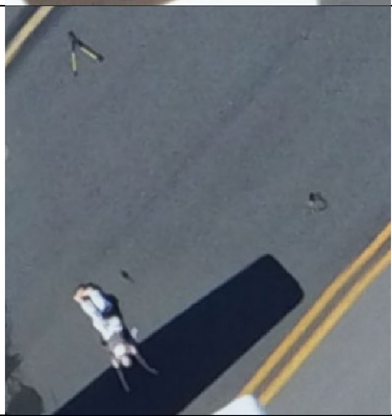
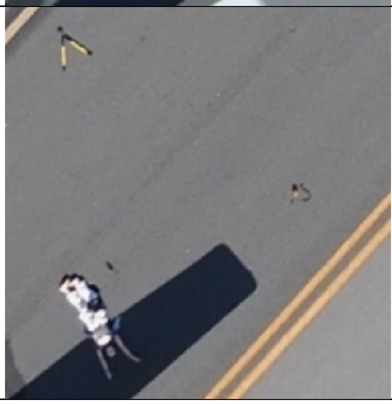
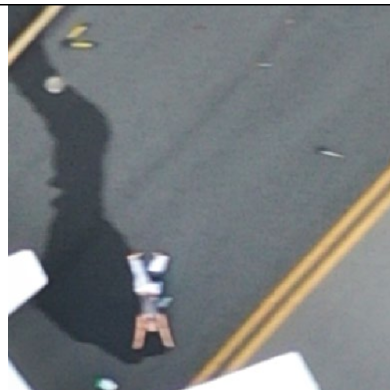
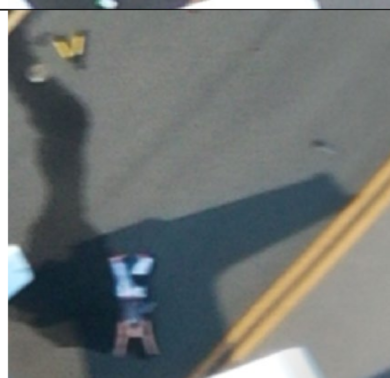
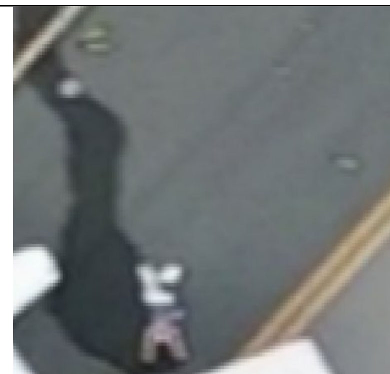
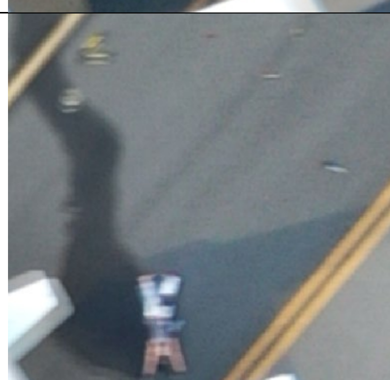
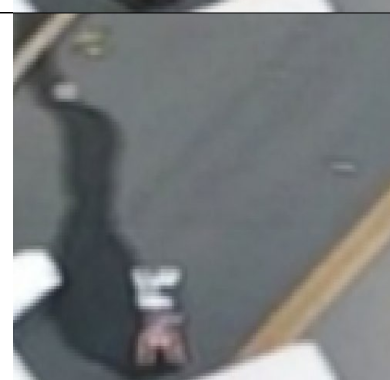
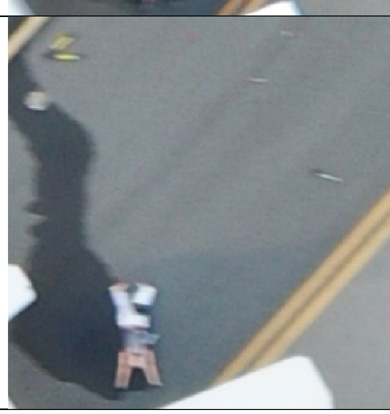
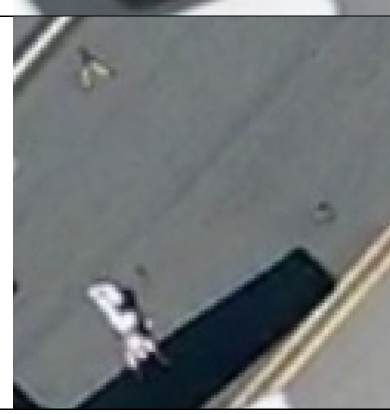
	Pix4DReact	DroneDeploy Live Map
Test 1: Mavic 2 Pro 70%/60% 0.39-in. GSD 147 ft AGL		
Test 2: M2ED 70%/60% 1-in. GSD 236 ft AGL		N/A
Test 3: ANAFI USA 70%/60% 1-in. GSD 249 ft AGL		N/A
Test 4: eBee X/ S.O.D.A. 3D 60%/60% 1-in. GSD 368 ft AGL		Sensor not compatible.

Table 10. Phase 2 Image Quality Comparison (Continued)

	Pix4DReact	DroneDeploy Live Map
Test 5: Mavic 2 Pro 80%/70% 1-in GSD 373 ft AGL		N/A
Test 6: Mavic 2 Pro 60%/60% 1-in. GSD 373 ft AGL		
Test 7: Mavic 2 Pro 50%/50% 1-in. GSD 373 ft AGL		
Test 8: Mavic 2 Pro 40%/40% 1-in. GSD 373 ft AGL		

Tables 11 and 12 compare the difference in clarity between Pix4DReact and DroneDeploy Live Map when viewing a manikin and the tire tread markings. As these tables show, the maps captured and processed using DroneDeploy Live Map provided less detail and were somewhat more pixelated than data sets processed using Pix4DReact. This was likely due to these maps being generated from the live-stream video from the UAS, rather than full-resolution still images. Despite any discrepancies, the manikin and tire markings on the pavement could be detected and identified in each data set.

Table 11. Phase 2 Detail Comparison: Manikin

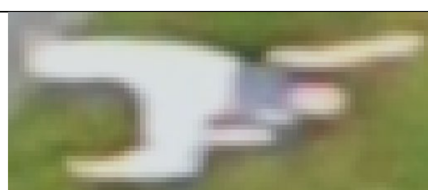
	Pix4DReact	DroneDeploy Live Map
Test 1: Mavic 2 Pro 70%/60% 0.39-in. GSD 147 ft AGL		
Test 2: M2ED 70%/60% 1-in. GSD 236 ft AGL		N/A
Test 3: ANAFI USA 70%/60% 1-in. GSD 249 ft AGL		N/A
Test 4: eBee X/ S.O.D.A. 3D 60%/60% 1-in. GSD 368 ft AGL		Sensor not compatible.
Test 5: Mavic 2 Pro 80%/70% 1-in GSD 373 ft AGL		N/A
Test 6: Mavic 2 Pro 60%/60% 1-in. GSD 373 ft AGL		

Table 11. Phase 2 Detail Comparison: Manikin (Continued)

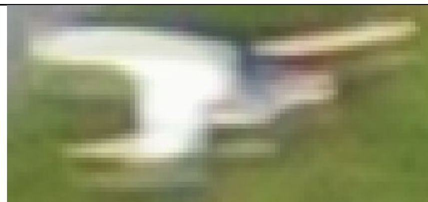
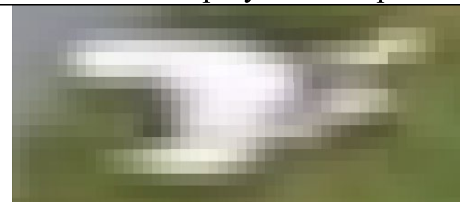
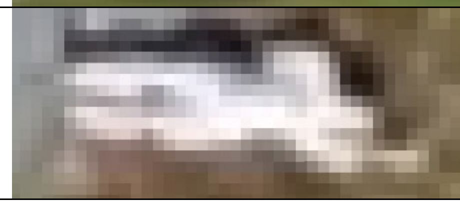
	Pix4DReact	DroneDeploy Live Map
Test 7: Mavic 2 Pro 50%/50% 1-in. GSD 373 ft AGL		
Test 8: Mavic 2 Pro 40%/40% 1-in. GSD 373 ft AGL		

Table 12. WWD Detail Comparison: Tire Markings

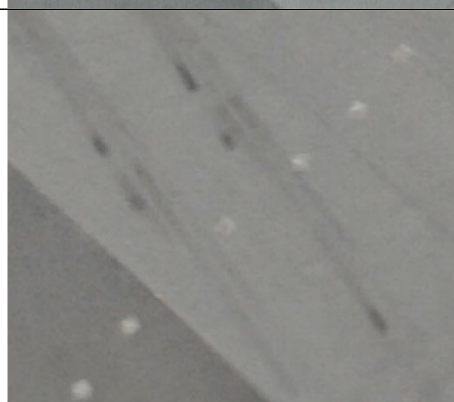
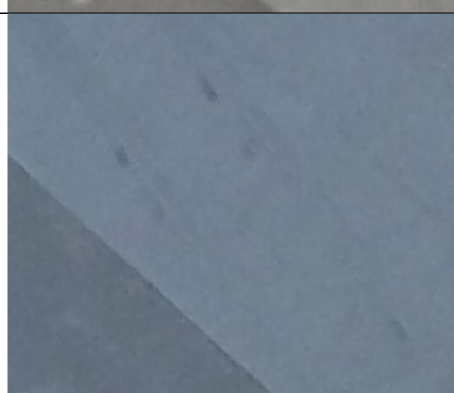
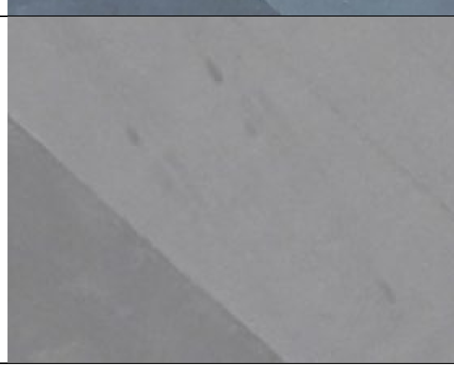
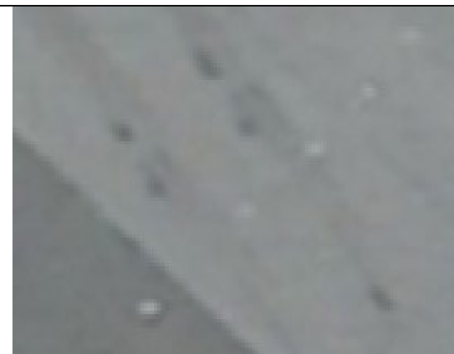
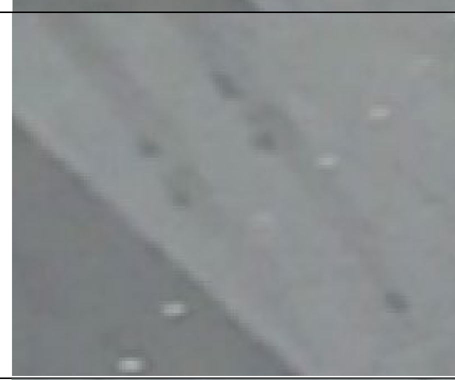
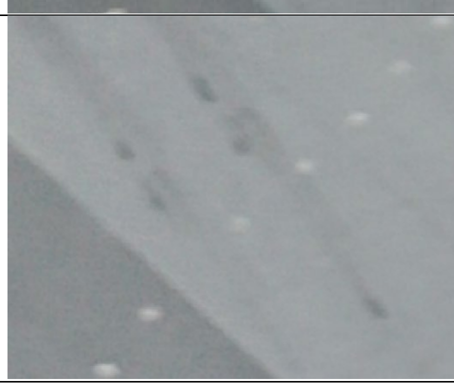
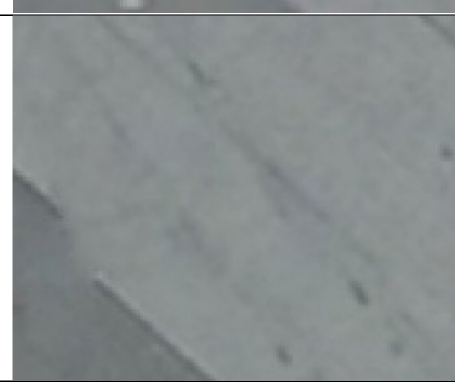
	Pix4DReact	DroneDeploy Live Map
Test 1: Mavic 2 Pro 70%/60% 0.39-in. GSD 147 ft AGL		
Test 2: M2ED 70%/60% 1-in. GSD 236 ft AGL		N/A
Test 3: ANAFI USA 70%/60% 1-in. GSD 249 ft AGL		N/A
Test 4: eBee X/ S.O.D.A. 3D 60%/60% 1-in. GSD 368 ft AGL		Sensor not compatible

Table 12. WWD Detail Comparison: Tire Markings (Continued)

	Pix4DReact	DroneDeploy Live Map
Test 5: Mavic 2 Pro 80%/70% 1-in GSD 373 ft AGL		N/A
Test 6: Mavic 2 Pro 60%/60% 1-in. GSD 373 ft AGL		
Test 7: Mavic 2 Pro 50%/50% 1-in. GSD 373 ft AGL		
Test 8: Mavic 2 Pro 40%/40% 1-in. GSD 373 ft AGL		

5.3.4 Additional Features/Capabilities

When processing the data collected at WWD with Pix4DReact, the software package's marking and annotation feature was used to identify objects and features in the orthomosaics. Figure 40shows examples of this marking feature. It should be noted that, when using this feature, the PDF views of the accident site are scaled to focus on the specific feature marked, causing a loss of image detail. FAA researchers also demonstrated the linear measurement tool to measure the lengths of tire markings, as shown in Figure 41.

Figure 40. Examples of Markers/Annotations for Manikins, Aircraft, and Liquid Spill Locations

Figure 41. Tire Marking Measurement Examples

5.4 FINDINGS

Following are the primary findings from Phase 2 UAS testing at WWD:

- A 1-in. GSD provided sufficient detail for aircraft accident and incident documentation, confirming the findings from Phase 1. Tests conducted at lower altitudes and smaller GSDs were able to provide enhanced clarity and detail but took significantly longer to collect and process. Tests conducted at higher altitudes and greater GSDs resulted in faster data collection and processing and fewer processing errors and distortion.

- Forward and side overlaps of 50%/50% were the minimum values for generating complete orthomosaics of the surveyed area. The data set collected with overlap values of 40%/40% were unable to reconstruct certain locations within the mapping area that had dense vegetation.

- All UAS platforms and payloads used during Phase 2 were able to capture acceptable imagery for aircraft accident and incident documentation, confirming the findings from Phase 1.

- Sensor resolution had a significant effect on data collection times, confirming the finding from Phase 1.

- Both processing software packages used were able to consistently generate orthomosaics that were acceptable for aircraft accident documentation. However, since DroneDeploy Live Map did not collect still imagery that could be included as evidence, it is not recommended for further testing.

- The computer hardware used to process data had a significant effect on processing times. Pix4DReact processing speeds for WWD were more than 4.5 times faster than processing times at ACY.

- In general, the orthomosaics of the simulated GA accident exhibited less distortion than the orthomosaics generated during the Phase 1 simulated commercial aircraft accident. This is believed to be due to the shorter height of the objects and structures in the orthomosaic.

- Pix4DReact produced orthomosaics with less distortion than DroneDeploy Live Map.

- DroneDeploy Live Map generated orthomosaics in less time than Pix4DReact because the software package instantly creates the map during flight. However, this time benefit was deemed negligible since Pix4DReact processed all data sets in approximately 2 minutes or less.

- The marking and annotation tools in Pix4DReact were found to provide a significant benefit for preserving insights and intelligence gained from assessing the orthomosaics.

6. PHASE 3 TESTING: ACY

Phase 3 aircraft accident and incident documentation testing followed a similar approach as the previous phases and included collecting aerial mapping data sets with various UAS platforms, payloads, and flight parameters over a simulated aircraft accident scene. Phase 3 was conducted at the same location as Phase 1 at ACY. This test effort expanded upon previous testing by including a wider variety of overlap settings with each UAS platform and payload, and conducting testing in low-light conditions during twilight and nighttime. In addition, tests were conducted over areas with varying elevations and with dense vegetation to assess the effects of these factors on the orthomosaics. In total, Phase 3 testing included 32 tests. Due to scheduling limitations and weather, testing was conducted across two nonconsecutive days.

6.1 UAS AND PAYLOADS

Sections 6.1.1 through 6.1.2 describe the UAS platforms and payloads used to conduct Phase 3 testing.

6.1.1 UAS Platforms

The following UAS platforms were used during Phase 2 UAS flight testing:

- DJI M210
- DJI Mavic 2 Pro
- Parrot ANAFI USA
- SenseFly eBee X

Figure 6 in Section 3.2.1.2 depicts these UAS platforms. Table 1 in Section 3.2.1.2 presents a comparison of key specifications for these UASs, and detailed specifications for each platform are presented in Appendix A.

The M210 was reintroduced into testing for Phase 3 to assess the suitability of the Zenmuse X5S payload, which is compatible with Pix4DReact, unlike the previously tested Zenmuse X7. In addition, the M210 was used to capture data with the XT2 payload, whose visual camera could make a meaningful contribution to the refinement of minimum performance specifications, and whose thermal camera was used to perform a proof-of-concept for thermal mapping.

6.1.2 Payloads

The following camera payloads were used to collect imagery during Phase 3 UAS testing at ACY:

- DJI Mavic 2 Pro Hasselblad Camera (visual camera)
- DJI Zenmuse XT2 13mm (dual visual and thermal camera)
- DJI Zenmuse X5S (visual camera)
- Parrot ANAFI Triple (dual visual cameras and one thermal camera)
- SenseFly S.O.D.A. 3D (visual camera)

Figure 7 in Section 3.2.1.3 depicts the camera payloads included in this testing. Table 2 in Section 3.2.1.3 compares key specifications of each payload. Detailed specifications for each payload are presented in Appendix B.

6.2 TEST METHODS AND PROCEDURES

Sections 6.2.1 through 6.2.5 describe the test setup and procedures employed during Phase 3 UAS testing at ACY.

6.2.1 Mapping Area

Phase 3 testing took place at the same location at ACY as Phase 1. While the primary focus of the mapping and analysis was the ARFF test area and retired aircraft, the total mapping area was significantly increased from Phase 1 from approximately 16 acres to approximately 51 acres. The mapping area was increased to include areas with dense vegetation to the north and a construction site with elevation changes to the southeast. This mapping area is pictured in Figure 42.

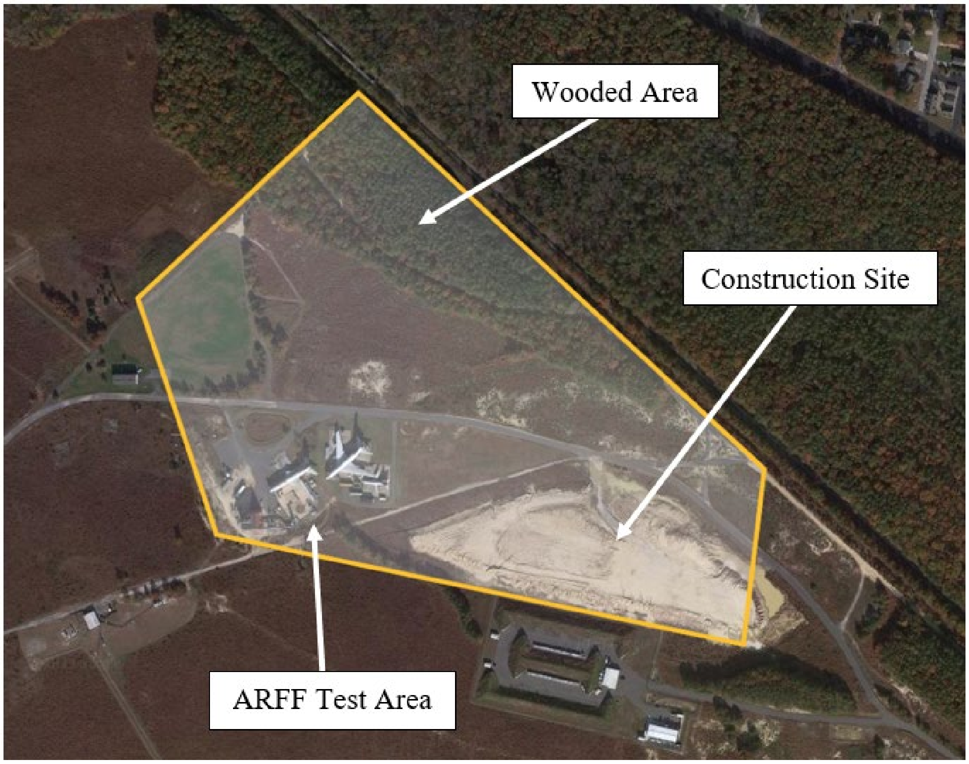


Figure 42. Phase 3 UAS Mapping Area

In addition to the full mapping area, several flights, including those conducted during twilight, used a condensed mapping area to make more efficient use of time. This mapping area focused on the ARFF test area. Figure 43 shows this condensed mapping area.

Figure 43. Condensed Phase 3 Mapping Area

6.2.2 Site Setup

Prior to testing, a variety of objects were placed adjacent to the L-1011 to simulate an accident site and debris field and provide a means to assess the quality of the resulting maps. These items included an ARFF vehicle, two full-size manikins, an aircraft wheel, a suitcase, various pieces of metal, and aircraft seat cushions. Additional manikins were placed in the construction site area to assess any effect the increased elevation had on the map quality. Figure 44 shows the layout of these objects, and Figure 45 shows a view of the scene from the ground.

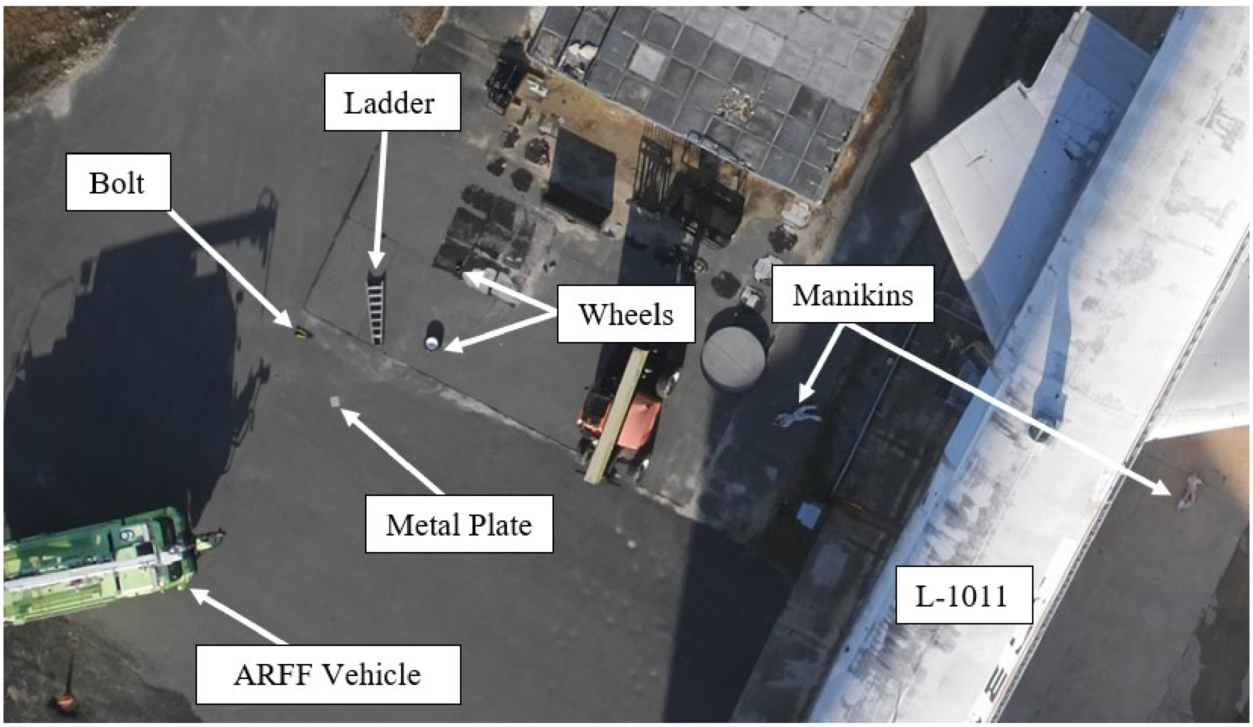


Figure 44. Aerial View of Phase 3 Debris Layout

Figure 45. Ground View of Phase 3 Debris

6.2.3 Flight Parameters

Phase 3 testing focused on evaluating various overlap values ranging from 40%/40% to 80%/80% with each UAS platform and visual camera payload. Testing included 32 flights conducted during daylight, twilight, and nighttime conditions. Based on previous findings, all flights were conducted with a 1-in. GSD. In addition, to evaluate mapping in low-light conditions, the Mavic 2 Pro was used to conduct continuous repeated mapping of the condensed mapping area with its visual camera payload from 30 minutes prior to sunset until 30 minutes after sunset (the end of civil twilight). After dark, an additional data set of thermal imagery was collected with the M210 and XT2 payload to serve as a proof of concept for conducting thermal mapping.

In addition to standard mapping missions, a data set was collected with the ANAFI USA to evaluate the usefulness of conducting a low overlap flight to save time while the RPIC took additional photos manually over areas that were critical or expected to present a challenge for the processing software. In this case, the ANAFI conducted a test with overlap values of 40%/40% and took an additional 10 photos over the ARFF Test Laboratory and aircraft to aid in their reconstruction. Table 13 presents the test parameters used during Phase 3 testing at ACY.

Table 13. Phase 3 Test Parameters

Test #	UAS	Payload	Overlap % (Forward/Side)	Altitude (AGL)	GSD (in.)	Lighting Condition
1	ANAFI USA	ANAFI Triple	80/80*	249 ft	1	Day
2	M210	XT2 Visual	80/80	350 ft	1	Day
3	eBee X	S.O.D.A. 3D	80 80*	369 ft	1	Day
4	Mavic 2 Pro	Hasselblad	80/80*	373 ft	1	Day

Test #	UAS	Payload	Overlap % (Forward/Side)	Altitude (AGL)	GSD (in.)	Lighting Condition
5	M210	X5S	80/80	379 ft	1	Day
6	ANAFI USA	ANAFI Triple	80/70	249 ft	1	Day
7	eBee X	S.O.D.A. 3D	80/70	369 ft	1	Day
8	Mavic 2 Pro	Hasselblad	80/70	373 ft	1	Day
9	M210	X5S	80/70	379 ft	1	Day
10	ANAFI USA	ANAFI Triple	60/60	249 ft	1	Day
11	eBee X	S.O.D.A. 3D	60/60	369 ft	1	Day
12	Mavic 2 Pro	Hasselblad	60/60	373 ft	1	Day
13	M210	X5S	60/60	379 ft	1	Day
14	ANAFI USA	ANAFI Triple	50/50	249 ft	1	Day
15	eBee X	S.O.D.A. 3D	50/50	369 ft	1	Day
16	Mavic 2 Pro	Hasselblad	50/50	373 ft	1	Day
17	M210	X5S	50/50	379 ft	1	Day
18	ANAFI USA	ANAFI Triple	40/40	249 ft	1	Day
19	eBee X	S.O.D.A. 3D	40/40	369 ft	1	Day
20	Mavic 2 Pro	Hasselblad	40/40	373 ft	1	Day
21	M210	X5S	40/40	379 ft	1	Day
22	ANAFI USA	ANAFI Triple	40/40 + add'l	249 ft	1	Day
23	Mavic 2 Pro	Hasselblad	80/80*	373 ft	1.00	Twilight
24	Mavic 2 Pro	Hasselblad	80/80*	373 ft	1.00	Twilight
25	Mavic 2 Pro	Hasselblad	80/80*	373 ft	1.00	Twilight
26	Mavic 2 Pro	Hasselblad	80/80*	373 ft	1.00	Twilight
27	Mavic 2 Pro	Hasselblad	80/80*	373 ft	1.00	Twilight
28	Mavic 2 Pro	Hasselblad	80/80*	373 ft	1.00	Twilight
29	Mavic 2 Pro	Hasselblad	80/80*	373 ft	1.00	Twilight
30	Mavic 2 Pro	Hasselblad	80/80*	373 ft	1.00	Twilight
31	Mavic 2 Pro	Hasselblad	80/80*	373 ft	1.00	Twilight
32	M210	XT2 Thermal	70/60*	200 ft	1.00	Night

* Indicates condensed flight area

6.2.4 Data Processing

Sections 6.2.4.1 through 6.2.4.3 describe the specific software, hardware, and settings used to process the ACY data.

6.2.4.1 Processing Software

Based on the findings from previous testing, FAA researchers processed data using one locally installed software, Pix4DReact, and one cloud-based software package, DroneDeploy.

The standard cloud-based DroneDeploy was used rather than the locally processed Live Map because of findings from Phase 2 testing. During that test effort it was found that Live Map produced significantly more distortion and provided less clarity and detail than Pix4DReact.

Despite generating the map during the flight, the time savings from Live Map was minimal because Pix4DReact processed all data sets in approximately 2 minutes or less. The cloud-based DroneDeploy, by contrast, was used in Phase 1 and produced the highest quality orthomosaics among the software packages tested, however processing could take significantly longer. The ARFF subject matter expert supporting this research program provided feedback suggesting that, despite the longer processing times, the high-quality orthomosaics generated by DroneDeploy could be of use to accident investigators since they generally do not arrive at the scene for at least several hours if not the following day.

6.2.4.2 Processing Hardware

The primary device used for processing and/or uploading data was a Dell laptop. Following are the specifications for the Dell laptop:

- Processor: Intel i5-1145G7 CPU @ 2.60Ghz
- RAM: 16GB
- Video card: Intel Iris X^e
- Operating System: Windows 10 Enterprise 64bit
- Power source: Alternating current power supply

In the interest of time, the data sets processed using DroneDeploy were completed using a wireless office internet connection.

6.2.4.3 Processing Settings

Following are the processing settings used for each processing application/service:

- Pix4DReact:

  Imagery was post-processed via the Pix4DReact downloadable suite with no changes to the default processing options. If a data set exceeds a certain threshold in size or resolution, Pix4DReact asks the user if they would like to process the data set at a lower resolution. For these tests, this option was declined, and the data sets were all processed at the "full" resolution offered by Pix4DReact.

- DroneDeploy:

  Imagery was post-processed via the online "MapEngine." The "Turbo Upload" option was turned off due to its compression of imagery. The "Processing Options" slider was moved to the quickest speed setting. The information listed by the MapEngine states the "Processing Options" slider reduces 3D model quality while also reducing processing time.

6.2.5 Regulatory and Safety Considerations

Phase 3 UAS testing followed all the safety and coordination procedures from Phase 1, described in Section 4.2.5; however, the addition of UAS testing in nighttime conditions required additional protocols. Title 14 C.F.R. Part 107.29 allows operation of UASs during civil twilight or at night only if the RPIC received their initial certification or recurrent training after April 6, 2021, and the UAS is equipped with anti-collision lighting that is visible for at least 3 statute miles (SMs). Both conditions were met for all RPICs and UASs during Phase 3 testing. In addition, prior to night operations, the RPIC gave an additional safety briefing informing all those present of the risks, safety protocols, and emergency procedures specific to night UAS operations (Operation at Night, 2022).

6.3 RESULTS AND DISCUSSION

Sections 6.3.1 through 6.3.4 provide results and additional discussion from Phase 3 testing at ACY. These sections address data acquisition and processing times, orthomosaic quality, and additional software features.

6.3.1 Data Acquisition Times

As shown in Figure 46, data acquisition times during Phase 3 ranged from 8 minutes to 39 minutes to cover the approximately 51-acre test area. (Note: This comparison only includes flights that covered the entire mapping area, excluding flights that only covered the condensed mapping area.) These results confirmed findings from previous phases that overlap settings have a significant effect on data acquisition time. Flights conducted with lower overlaps were generally completed in less time than missions with higher overlaps. For example, lowering the forward/side overlap parameters for the eBee X from 80%/70% to 50%/50% resulted in a 53% reduction in acquisition time (from 17 minutes to 8 minutes), however the lower overlaps experienced more distortion. In most cases, however, this distortion was relatively minor and did not impact the usability of the orthomosaics for aircraft accident and incident documentation.

6.3.2 Data Processing Times

Figure 47 shows the upload and processing times for each data set. DroneDeploy did not provide processing times in the reports generated; therefore, only upload times are shown. The results from Phase 3 data processing validated results from previous testing. As indicated by the blue bars in Figure 47, Pix4DReact processed each data set significantly faster than DroneDeploy. This was directly because it processes the photos locally and is not dependent on an internet connection or the speed of the host servers. Processing and upload times generally correlated to the size of the data set; data sets with more images require more time for processing. Pix4DReact generated maps in 1 to 5 minutes, while DroneDeploy data upload and processing times ranged from 31 to 140 minutes.

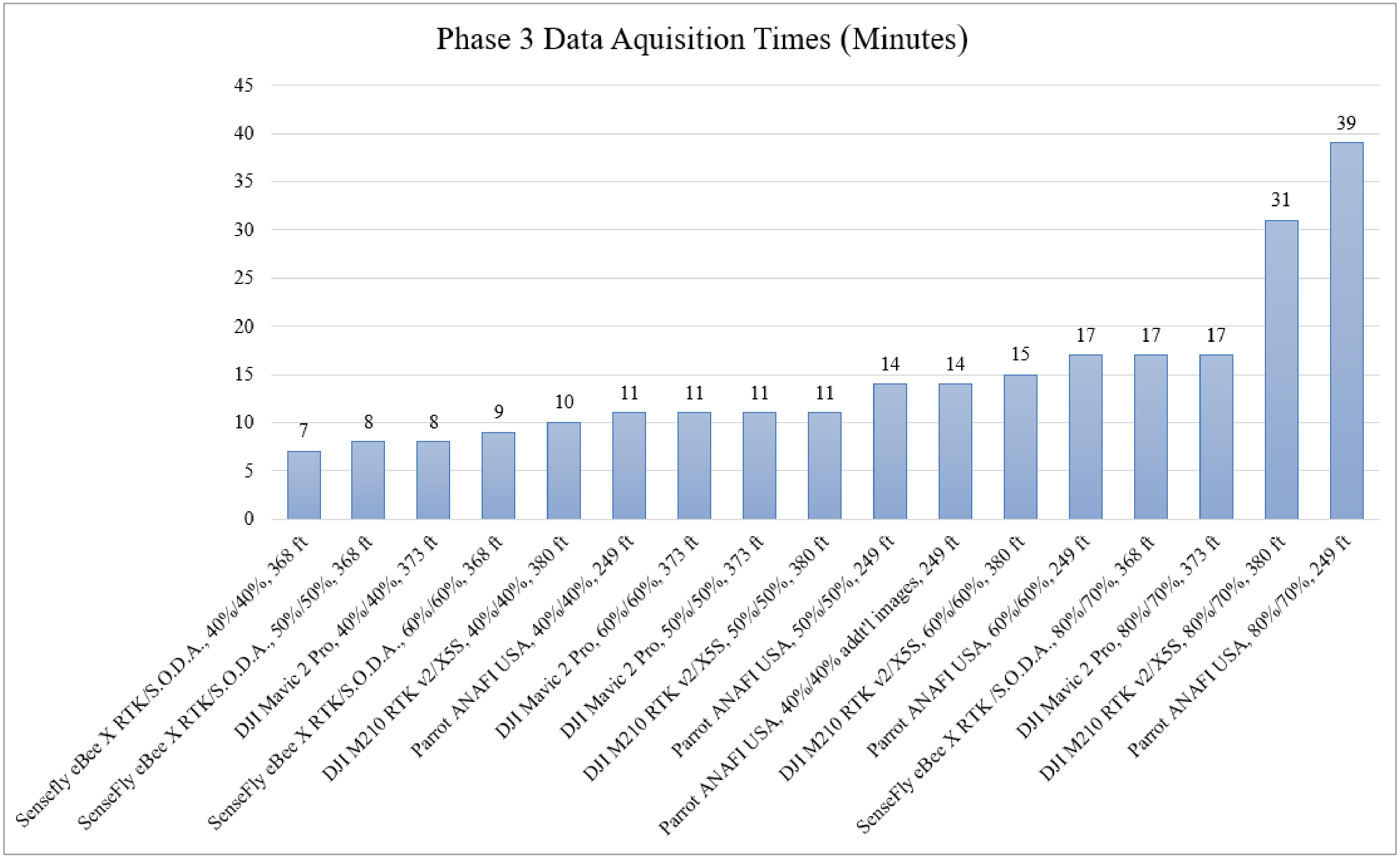


Figure 46. Phase 3 Data Acquisition Times

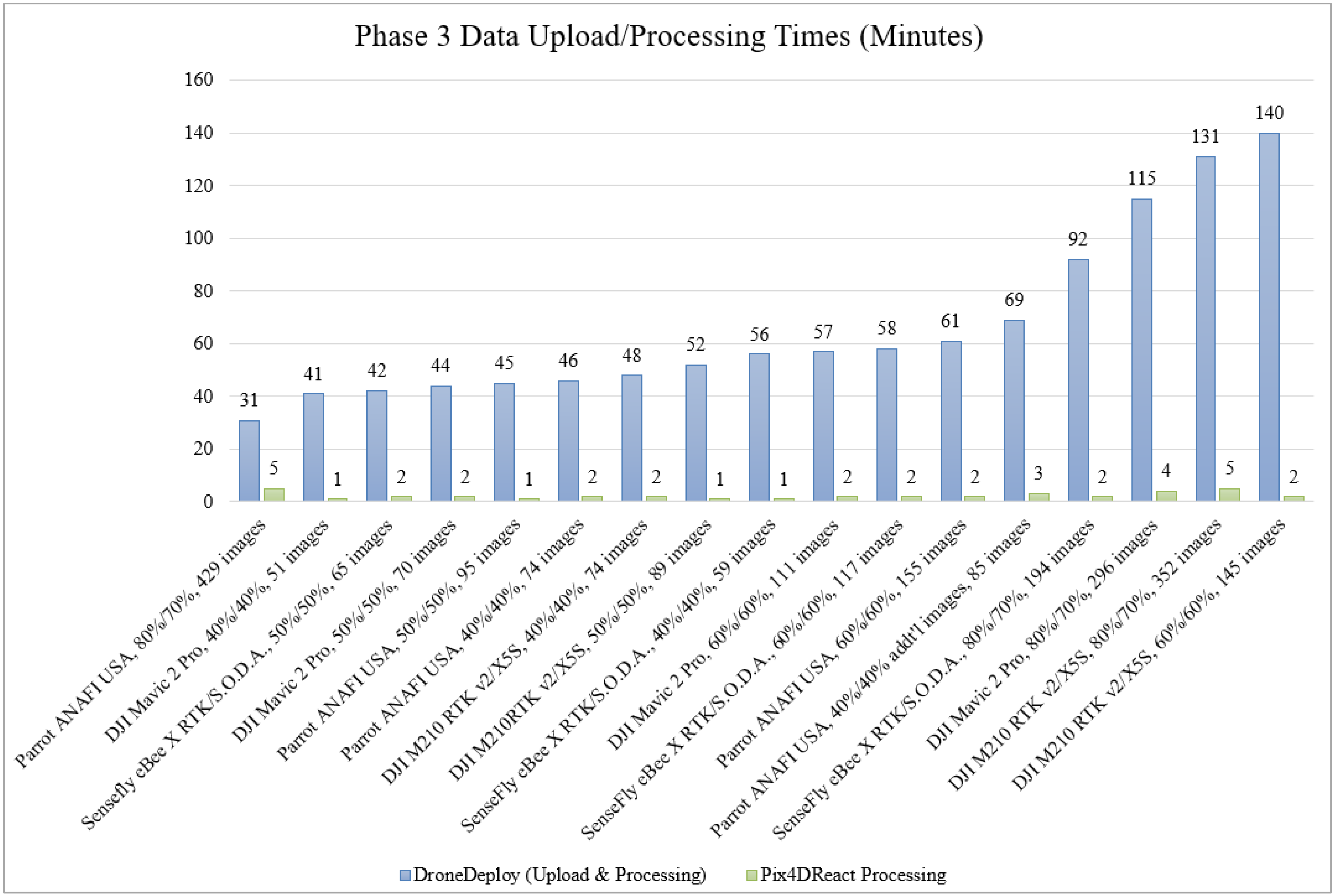


Figure 47. Phase 3 Data Processing Times

6.3.3 Orthomosaic Analysis

After processing was complete, each orthomosaic was assessed to identify any distortion or processing errors. Section 6.3.3.1 presents these results.

6.3.3.1 Processing Errors/Distortion

Each orthomosaic was analyzed to look for signs of distortion or other processing errors. Similar to the results from Phase 1 testing at ACY, all maps were found to have some degree of distortion, and most of this distortion occurred on and around vertical structures, such as aircraft fuselages and the ARFF fire testing research facility. In most cases, the distortion was relatively minor and did not impact the usability of the map for situational awareness purposes. Table 14 presents a screenshot of each orthomosaic processed during Phase 3.

Table 14. Phase 3 Processing Outputs

	DroneDeploy	Pix4DReact
Test 1: ANAFI USA 80%/80% 1-in. GSD 249 ft AGL		
Test 18: M210/XT2 80%/80% 1-in. GSD 350 ft AGL		Sensor not compatible with processing software.

Table 14. Phase 3 Processing Outputs (Continued)

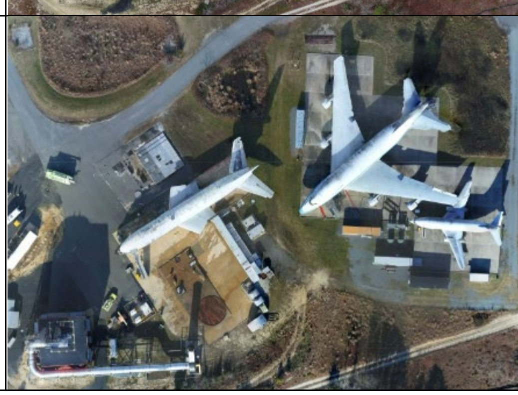
	DroneDeploy	Pix4DReact
Test 3: eBee X/ S.O.D.A. 3D 80%/80% 1-in. GSD 369 ft AGL		
Test 4: Mavic 2 Pro 80%/80% 1-in GSD 373 ft AGL		
Test 5: M210/ X5S 80%/80% 1-in. GSD 379 ft AGL		
Test 6: ANAFI USA 80%/70% 1-in. GSD 249 ft AGL		

Table 14. Phase 3 Processing Outputs (Continued)

	DroneDeploy	Pix4DReact
Test 7: eBee X/ S.O.D.A. 3D 80%/70% 1-in. GSD 369 ft AGL		
Test 8: Mavic 2 Pro 80%/70% 1-in. GSD 373 ft AGL		
Test 9: M210/ X5S 80%/70% 1-in. GSD 379 ft AGL		
Test 10: ANAFI USA 60%/60% 1-in. GSD 249 ft AGL		

Table 14. Phase 3 Processing Outputs (Continued)

	DroneDeploy	Pix4DReact
Test 11: eBee X/ S.O.D.A. 3D 60%/60% 1-in. GSD 369 ft AGL		
Test 12: Mavic 2 Pro 60%/60% 1-in. GSD 373 ft AGL		
Test 13: M210/ X5S 60%/60% 1-in. GSD 379 ft AGL		
Test 14: ANAFI USA 50%/50% 1-in. GSD 249 ft AGL		

Table 14. Phase 3 Processing Outputs (Continued)

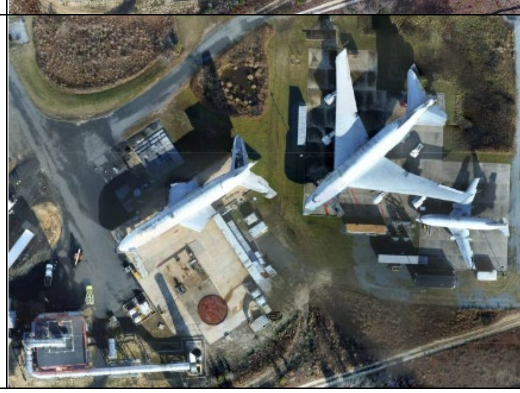
	DroneDeploy	Pix4DReact
Test 15: eBee X/ S.O.D.A. 3D 50%/50% 1-in. GSD 369 ft AGL		
Test 16: Mavic 2 Pro 50%/50% 1-in. GSD 373 ft AGL		
Test 17: M210/ X5S 50%/50% 1-in. GSD 379 ft AGL		
Test 18: ANAFI USA 40%/40% 1-in. GSD 249 ft AGL		

Table 14. Phase 3 Processing Outputs (Continued)

	DroneDeploy	Pix4DReact
Test 19: eBee X/ S.O.D.A. 3D 40%/40% 1-in. GSD 369 ft AGL		
Test 20: Mavic 2 Pro 40%/40% 1-in. GSD 373 ft AGL		
Test 21: M210/ X5S 40%/40% 1-in. GSD 379 ft AGL		
Test 22: ANAFI USA 40%/40% Addt'l Photos 1-in. GSD 249 ft AGL		

6.3.3.1.1 Overlap Settings Comparison

The orthomosaics were also evaluated to further discern the relationship between overlap and the presence of distortion. Results from Phase 2 indicated that for a GA accident where there are no particularly tall structures or objects, low overlaps do not significantly degrade mapping performance versus higher overlaps. A similar comparison was performed regarding overlap values when mapping large commercial aircraft during Phase 3. Figure 48 presents a comparison of the distortion present in data sets collected with various overlap settings with the ANAFI USA.

Figure 48. Comparison of Distortion Present in Data Sets Collected with Various Overlap Settings with the ANAFI USA and Processed with Pix4DReact

As shown in Figure 48, distortion and visual errors generally decreased as overlap values were increased. The test conducted at 40%/40% (shown in Figure 48(a)) resulted in severe distortion of the L-1011, while the 50%/50% test (shown in Figure 48(b)) resulted in severe distortion of the Boeing 747. Distortion was still present in both airframes in the 60%/60% data set (shown in Figure 48(c)) but was significantly decreased. Distortion of the airframes was further reduced in the data set collected with 80%/70% overlap (shown in Figure 48(d)), and the test conducted with 80%/80% overlap (shown in Figure 48(e)) contained no significant distortion.

6.3.3.1.2 Processing Software Performance

When comparing the results of data sets processed by each software package, it was found that DroneDeploy produced significantly less distortion than Pix4DReact. Figure 49 compares the distortion present in a data set collected with the ANAFI USA with overlap settings of 40%/40% when processed with each software package. While both orthomosaics have examples of distortion, as indicated by the red boxes, DroneDeploy resulted in an orthomosaic with relatively minor distortion present only on the Boeing 747 airframe, while Pix4DReact resulted in distortion on the 747, L-1011, and ARFF Test Laboratory.

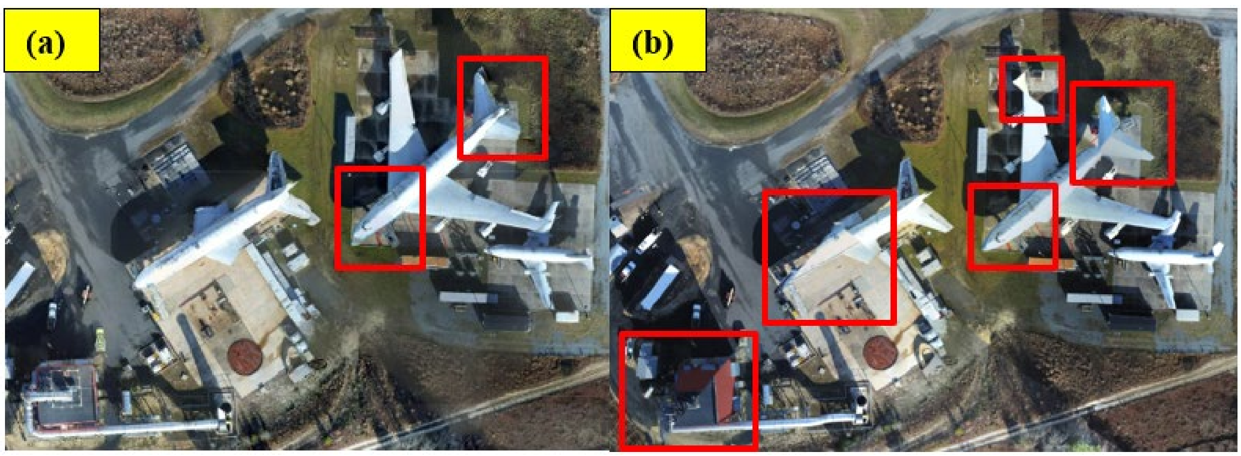


Figure 49. Comparison of Distortion in 40%/40% Overlap ANAFI USA Data Set Processed with (a) DroneDeploy and (b) Pix4DReact

6.3.3.1.3 Effect of Additional Photos

Following the initial data set collected with the ANAFI USA with overlap values of 80%/80%, the RPIC assumed manual control of the aircraft and took an additional 10 photos while flying over the areas that were known to have an increased chance of creating distortion in the orthomosaic, including the aircraft and the ARFF Test Laboratory building. This manual data collection took approximately an additional 4 minutes of flight time. Figure 50 compares these data sets when processed with Pix4DReact.

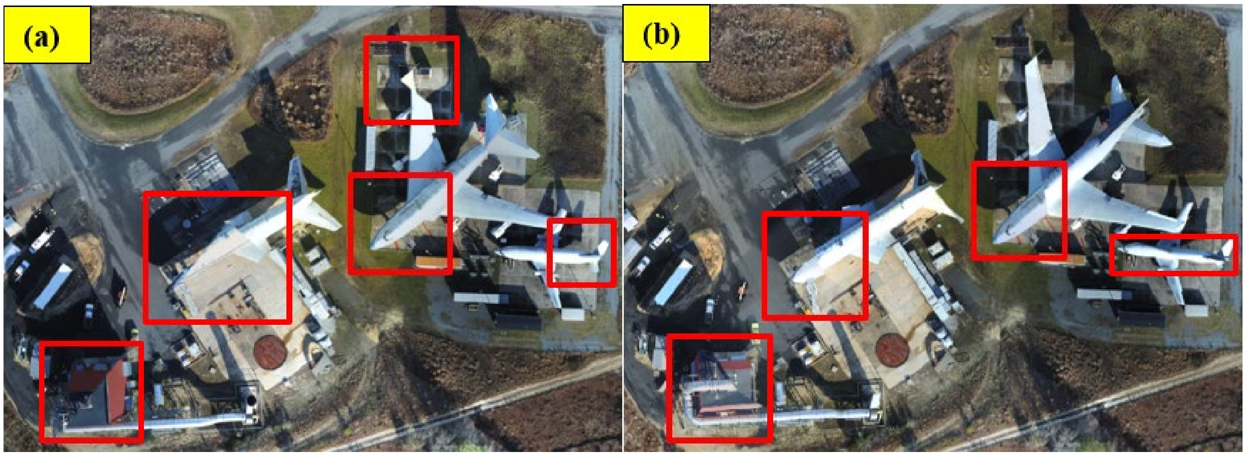


Figure 50. Comparison of Distortion in ANAFI USA Data Sets Processed with Pix4DReact: (a) Standard 40%/40% and (b) 40%/40% with Additional Images

While a considerable amount of distortion is present in both orthomosaics, it is significantly reduced in the data set that included the 10 additional images and is particularly visible when comparing the L-1011 aircraft and ARFF Test Laboratory. If the total area that requires mapping is relatively small, it might be more beneficial to conduct the flight with higher overlap settings to reduce distortion. However, if the mapping area is large with only a few limited areas that could prove troublesome for reconstruction, the addition of several additional images might be beneficial.

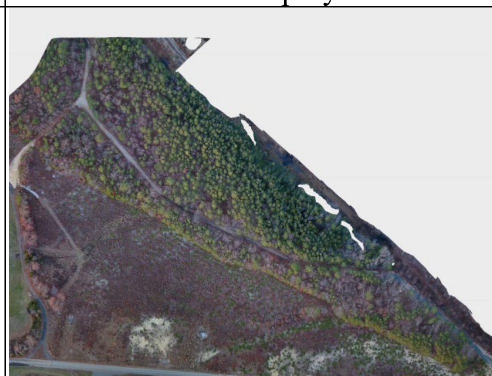
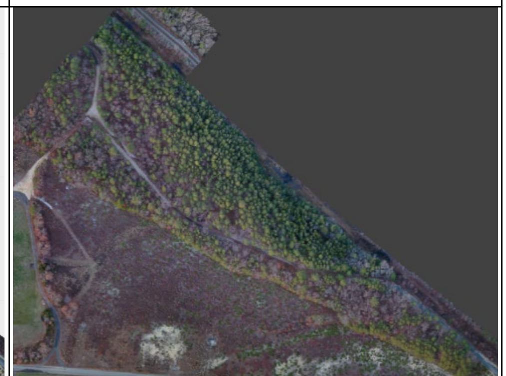
6.3.3.1.4 Wooded Area Reconstruction

Similar to previous phases, orthomosaics were first examined for completeness, particularly in the densely vegetated portion of the mapping area along the northern boundary. A number of datasets were unable to support the complete reconstruction of this area, particularly during tests conducted with lower overlap settings. Table 15 compares the gaps present in data sets collected with various overlap settings with the Mavic 2 Pro and ANAFI USA. The gray areas in the top right portion of each image in Table 15 indicate areas that failed to be reconstructed.

Table 15. Comparison of ANAFI USA and Mavic 2 Mapping Performance of Wooded Area

	DroneDeploy	Pix4DReact
Test 20: Mavic 2 Pro 40%/40% 1-in. GSD 373 ft AGL		
Test 18: ANAFI USA 40%/40% 1-in. GSD 249 ft AGL		
Test 16: Mavic 2 Pro 50%/50% 1-in. GSD 373 ft AGL		
Test 14: ANAFI USA 50%/50% 1-in. GSD 249 ft AGL		

Table 15. Comparison of ANAFI USA and Mavic 2 Mapping Performance of Wooded Area (Continued)

	DroneDeploy	Pix4DReact
Test 12: Mavic 2 Pro 60%/60% 1-in. GSD 373 ft AGL		
Test 10: ANAFI USA 60%/60% 1-in. GSD 249 ft AGL		
Test 8: Mavic 2 Pro 80%/70% 1-in. GSD 373 ft AGL		
Test 6: ANAFI USA 80%/70% 1-in. GSD 249 ft AGL		

As shown in this comparison, the Mavic 2 Pro data were able to completely reconstruct the wooded area with the higher overlap settings and were still able to build the majority of the area with lower overlap. The ANAFI USA data, on the other hand, were completely unable to be processed to reconstruct the wooded area at lower overlap settings but were able to successfully reconstruct most of the area with the higher 80%/70% overlap settings. FAA researchers believe this is due to the significantly lower altitude at which the ANAFI must fly to achieve a 1-in. GSD versus the Mavic 2 Pro. Flying at a higher altitude minimizes the change in perspective between photos and increases the chances processing software will be able to stitch the images together.

With regard to software, both DroneDeploy and Pix4DReact performed similarly. Generally, Pix4DReact was able to reconstruct a larger portion of the wooded area, particularly with data sets captured with the ANAFI USA. Data sets processed with DroneDeploy, however, displayed less distortion than Pix4DReact, which was most evident when observing the railroad tracks running from the northwest to the southeast in the orthomosaics.

6.3.3.1.5 Effect of Terrain

The varying vertical terrain presented by a construction site within the mapping area was used to assess its potential effect on the quality of the orthomosaics generated. This terrain was found to have no effect on the quality of the orthomosaics generated by either software package in any of the data sets collected. Figure 51 shows screenshots of the manikins placed along a slope taken from data sets processed with each software package.

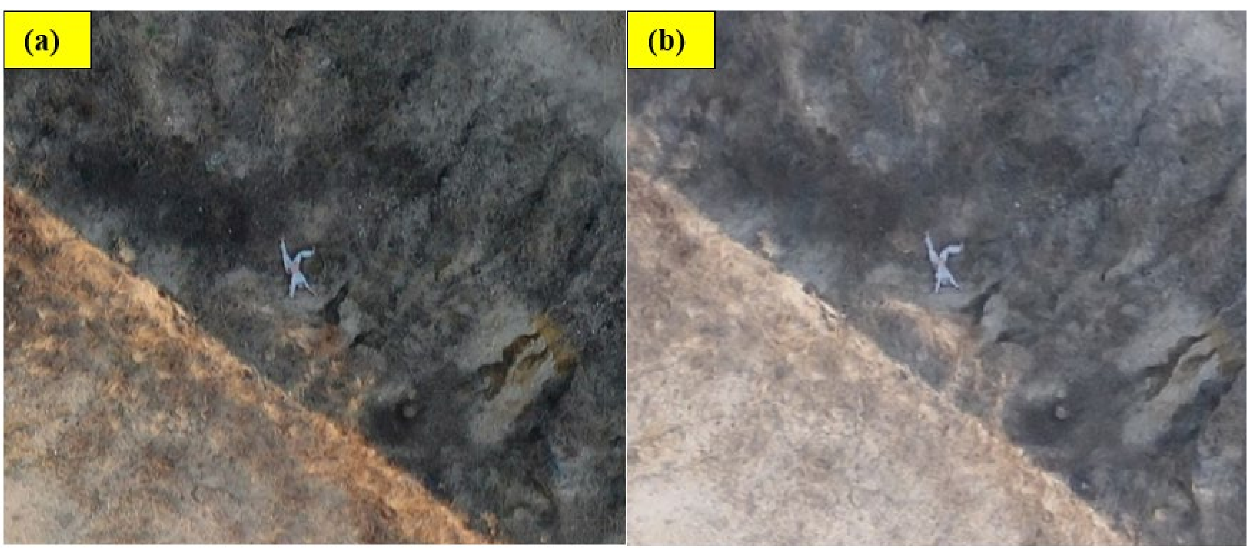


Figure 51. Effect of Terrain on Data Sets Collected with the (a) Mavic 2 Pro at 80%/70% and (b) eBee X at 50%/50%

6.3.3.1.6 Lowlight Mapping Performance

On the day of lowlight testing, sunset occurred at 4:34 p.m. and civil twilight ended at 5:04 p.m. Lowlight testing took place from 4:16 p.m. until 5:05 p.m. As expected, the imagery collected during these tests was significantly less sharp when compared to tests conducted when the sun was higher in the sky, and the quality of the data sets further degraded as the sun continued to set. In particular, the quality of the data sets significantly degraded following sunset. Each successive data set collected following sunset exhibited more blurriness and distortion than the previous, and the final data set captured at the end of civil twilight was deemed unacceptable for aircraft accident and incident documentation. Table 16 compares screenshots of each data set collected during lowlight testing during Phase 3.

Table 16. Comparison of Lowlight Mapping Performance

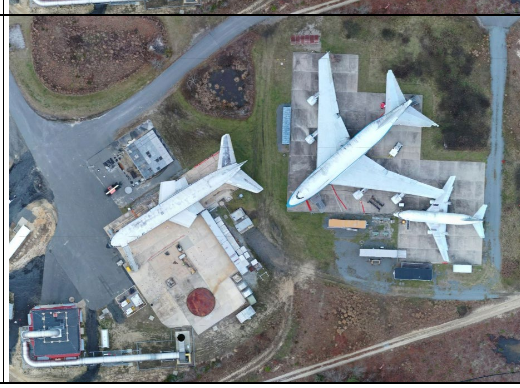
	DroneDeploy	Pix4DReact
Test 23: 4:16 p.m. 18 min before Sunset Mavic 2 Pro 80%/80% 1-in. GSD 373 ft AGL		
Test 24: 4:21 p.m. 13 min before Sunset Mavic 2 Pro 80%/80% 1-in. GSD 373 ft AGL		
Test 25: 4:25 p.m. 9 min before Sunset Mavic 2 Pro 80%/80% 1-in. GSD 373 ft AGL		

Table 16. Comparison of Lowlight Mapping Performance (Continued)

	DroneDeploy	Pix4DReact
Test 26: 4:30 p.m. 4 min before Sunset Mavic 2 Pro 80%/80% 1-in. GSD 373 ft AGL		
Test 27: 4:38 p.m. 4 min after Sunset Mavic 2 Pro 80%/80% 1-in. GSD 373 ft AGL		
Test 28: 4:42 p.m. 8 min after Sunset Mavic 2 Pro 80%/80% 1-in. GSD 373 ft AGL		
Test 29: 4:46 p.m. 12 min after Sunset Mavic 2 Pro 80%/80% 1-in. GSD 373 ft AGL		

Table 16. Comparison of Lowlight Mapping Performance (Continued)

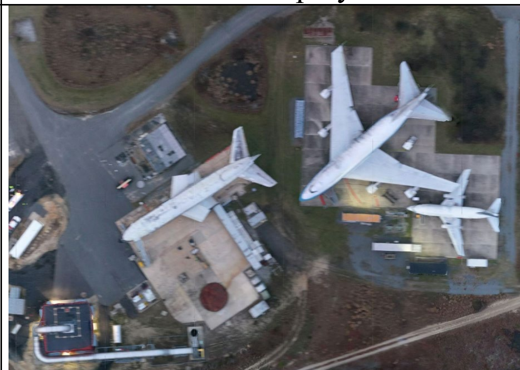
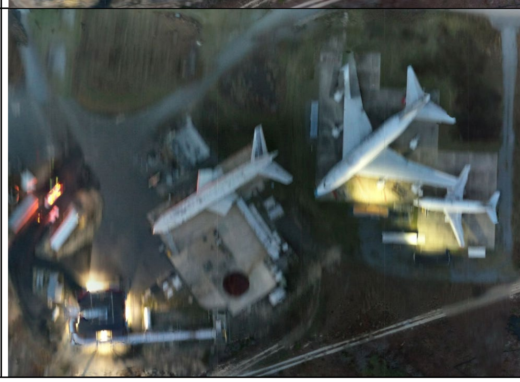
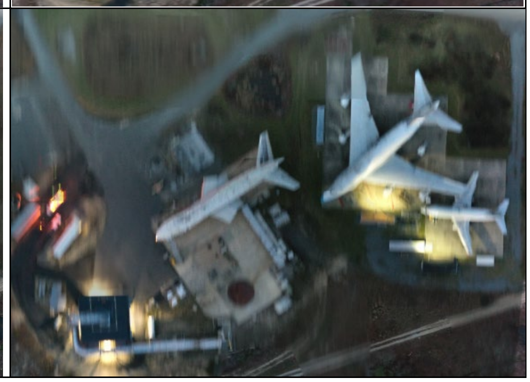
	DroneDeploy	Pix4DReact
Test 30: 4:51 p.m. 17 min after Sunset Mavic 2 Pro 80%/80% 1-in. GSD 373 ft AGL		
Test 31: 5:01 p.m. 27 min after Sunset Mavic 2 Pro 80%/80% 1-in. GSD 373 ft AGL		

Figure 52 compares screenshots showing the manikins and debris field taken from four tests conducted in increasingly low-light conditions. The first test, shown in Figure 52(a), commenced at 4:16 p.m. and was able to retain sufficient clarity to identify the manikins and objects in the simulated debris field. Figure 52(b) shows the results from a test conducted at sunset, and while the orthomosaic is less clear than earlier flights, it retains enough clarity to identify the manikins and some of the debris, including the ladder and wheel. The seventh low-light test, shown in Figure 52(c), took place from 4:46 p.m. to 4:50 p.m. The manikins and ladder are still visible in the imagery, but the clarity continued to degrade. When viewing the full orthomosaic, however, as shown in Table 16, FAA researchers concluded that it retained enough clarity to provide a meaningful benefit as a high-level overview of the scene. Figure 52(d) shows the final low-light data set collected, which began at 5:01 p.m. This data set provides little value, as only the airframes can be identified in the imagery.

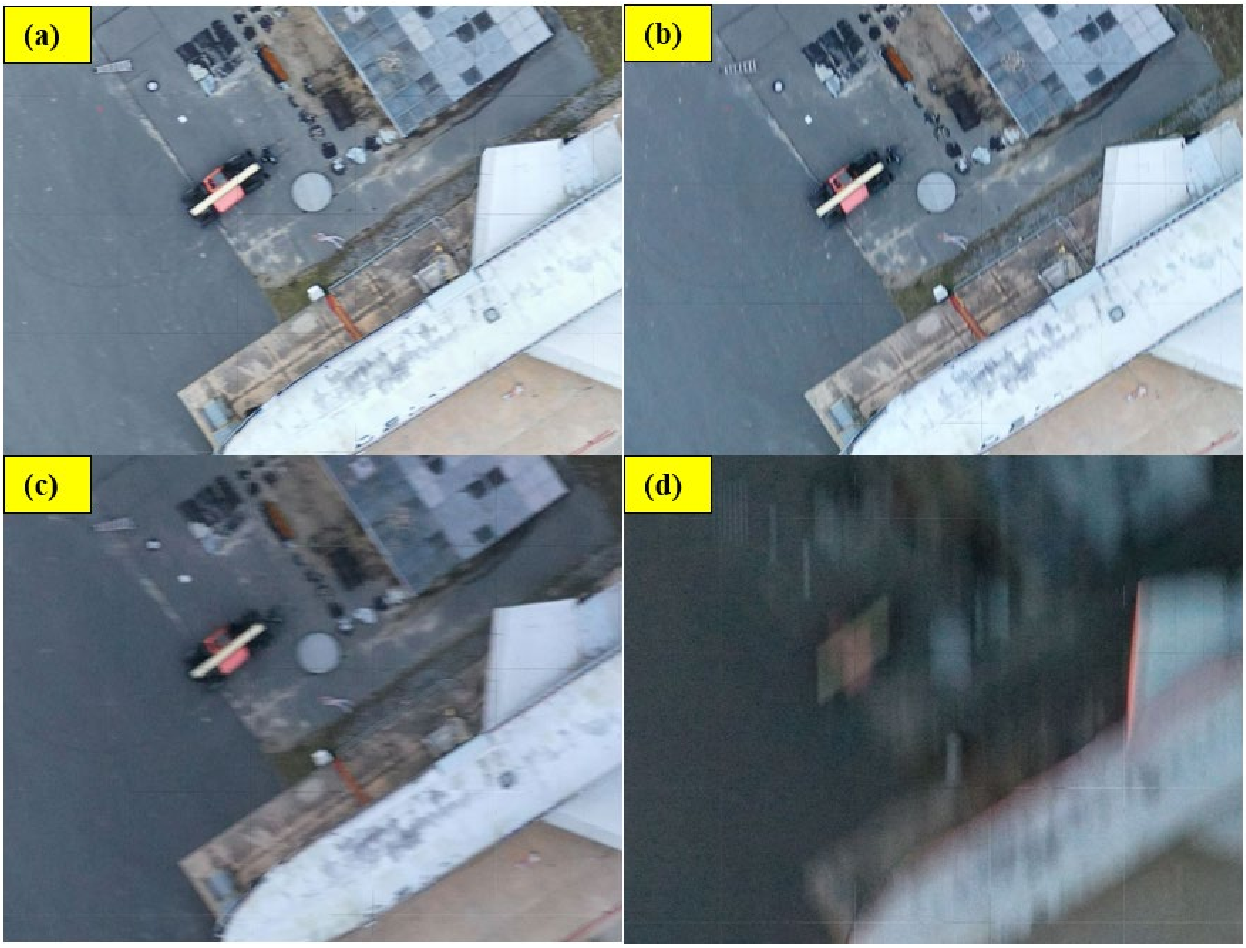


Figure 52. Comparison of Clarity in Data Sets Collected in Low-Light Conditions with the Mavic 2 Pro

6.3.4 Additional Features/Capabilities

In addition to the quality of the orthomosaics, FAA researchers also evaluated additional features and capabilities of the software packages as they relate to aircraft accident and incident documentation. These evaluations focused on the capability of DroneDeploy to create an orthomosaic using thermal imagery, and each software package's annotation and measuring tools. Sections 6.3.4.1 and 6.3.4.2 present these evaluations.

6.3.4.1 Thermal Mapping Performance

A single data set (Test 32) was collected with the M210 and XT2 payload after dark as a proof of concept for the use of thermal imagery in aircraft accident and incident documentation. This data set was only processed with DroneDeploy since Pix4DReact does not currently have the capability to generate orthomosaics using thermal imagery. A screenshot of this orthomosaic is shown in Figure 53.

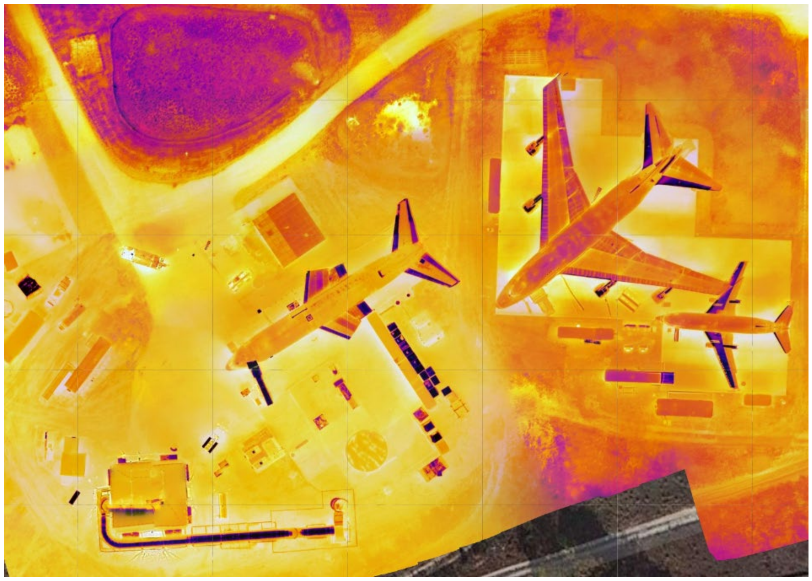


Figure 53. Orthomosaic Generated with Thermal Imagery

The thermal orthomosaic showed minimal distortion and allowed FAA researchers to clearly identify the ARFF vehicle, aircraft, and buildings in the mapping area. While there were several standing humans within the mapping area, they could not be clearly identified due to their reduced cross section. The varying heat signatures of different structures, such as the cooler metal exhaust piping on the ARFF Test Laboratory, are clearly distinguishable. This shows that thermal mapping could provide value for ARFF responders during and immediately following the response to ensure there are no lingering heat signatures that might indicate possible reignition sources.

6.3.4.2 Software Annotation and Measuring Tools

In addition to thermal mapping, FAA researchers also evaluated each software package's annotation feature to identify objects and measure features in the orthomosaics. Both software packages provide the capability to place markers to identify objects/subjects in the maps and measure features. Figure 54 shows an example of these capabilities in each software package. In Figure 54, the markers are placed to identify the location of manikins, while the blue line along the aircraft is from the measurement tool. The measurement tool was accurate in both software packages. An L-1011 airframe is 177.7 ft long. DroneDeploy measured the aircraft within a margin of error of 6 in., at 178.25 ft, and Pix4DReact provided a measurement of 179.73 ft.

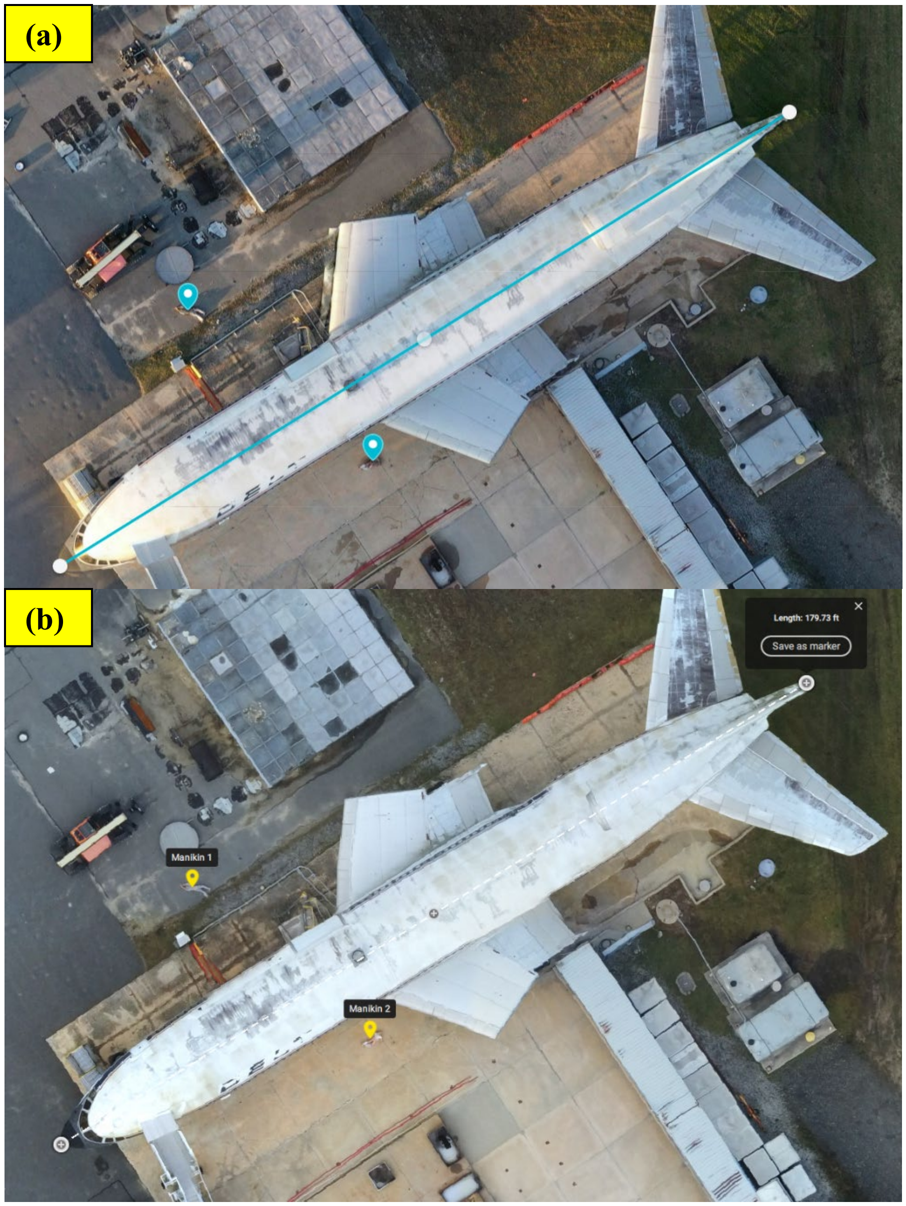


Figure 54. Annotation and Measurement Features in (a) DroneDeploy and (b) Pix4DReact

6.4 FINDINGS

The primary findings from Phase 3 UAS testing at ACY include the following.

- Phase 3 confirmed findings from previous phases that a 1-in. GSD is sufficient for generating acceptable orthomosaics.
- Forward/side overlap values of 80%/70% were found to produce the most complete orthomosaics, producing less distortion, particularly in the area of dense vegetation.

- The varying vertical terrain within the mapping area did not affect the quality of the orthomosaics generated.
- Supplementing data sets with additional images of areas known to present challenges for data processing were found to reduce distortion.
- All UAS platforms and payloads used during Phase 3 were able to capture imagery that was of sufficient resolution and quality to be used to generate orthomosaics that were acceptable for aircraft accident documentation.
- The thermal camera payload was effective for conducting thermal mapping of the accident area.
- All data processing software packages tested, including cloud-based ones locally installed on a GCS or computer, produced some level of distortion in areas with vertical structures such as buildings and aircraft. Overall, the orthomosaics were still acceptable for overview purposes.
- Confirming findings from Phase 1, DroneDeploy produced orthomosaics with less distortion than Pix4DReact, while Pix4DReact processed the data sets significantly faster than DroneDeploy.
- The marking and annotation tools in the software packages provided a significant benefit for preserving insights and intelligence gained from assessing the orthomosaics, confirming findings from previous testing phases.

7. SUMMARY

Sections 7.1 through 7.3 summarize the findings regarding the benefits and limitations of UASs for aircraft accident and incident documentation, recommended minimum performance specifications, and additional technical and operational considerations.

7.1 BENEFITS AND LIMITATIONS

Sections 7.1.1 and 7.1.2 summarize benefits and limitations of using UASs for aircraft accident and incident documentation.

7.1.1 Benefits

Orthomosaics generated with a 1-in. GSD resolution UAS imagery provided sufficient detail to see aircraft and ground vehicle positions and orientations, and additional features of a scene including people, liquid spills, tire marking, and debris of various sizes. These maps can be used to supplement the required photographic coverage of the accident or incident scene as required under AC 150/5200-12. This includes showing the layout and locations of objects and witness marks such as tire tracks and land scars. In addition, the maps could document actions taken during the response by capturing agent discharge patterns and fuel release tracks.

- UAS aerial mapping allows for the timely documentation of an accident or incident before the NTSB or other investigators and stakeholders can arrive on site to begin their own documentation. The early documentation of these data, relative to what the NTSB or others could capture a day or more later, provides a more accurate picture of the accident or incident by minimizing the amount of time, weather, wildlife, people, the environment, or other factors can alter the scene. In addition, these mapping software packages allow for real-time analysis, including the labeling and measuring of items of interest that can be easily preserved and shared during the investigation by using their annotation features. This allows investigators to begin analyzing the scene prior to arrival on site.

- UAS-generated orthomosaics provide a scaled, accurate depiction of the accident or incident scene. These maps can be provided to ARFF ICs or other stakeholders during the response to improve their ability to coordinate and allocate resources when managing the scene, such as the identification and placement of ingress and egress routes, as well as triage areas. In addition, these maps can be provided to investigators or stakeholders prior to their arrival to aid in their familiarization with the environment and to expedite their own actions once on site.

- Collecting maps at various points during the response and recovery creates a detailed record of the incident and the response, providing timeline for internal review of the event and training.

7.1.2 Limitations

There are currently several regulatory and technical limitations that could affect the deployment of UASs for accident and incident documentation:

- Orthomosaics generated with UAS aerial imagery do not provide an equivalent level of detail or clarity as photography captured from the ground. In addition, aerial imagery cannot see underneath certain structures, such as aircraft wings, nor can it see as well in areas that are shadowed. For these reasons it is recommended that the orthomosaics generated by UAS imagery be used to supplement, rather than replace, other investigation and documentation techniques.

- The ability to deploy a UAS might be limited by the available staffing at the incident or accident scene. The preservation of human life is always the priority during a response. Many airports operate with minimal ARFF personnel on duty at a single time and would lack the staffing required to support UAS operations in addition to fulfilling existing ARFF requirements. UAS operations generally require at least one RPIC, who is responsible for the safety of the operation and maintaining visual line-of-sight of the UA in accordance with 14 C.F.R. Part 107.31. The RPIC will likely be prevented from carrying out any other duties during the ARFF response.

- UAS operations could be limited by weather and lighting conditions at the time of the operation. Conducting an aerial survey at night and during civil twilight can significantly diminish the quality of the resulting orthomosaic, rendering UASs less effective after sunset. The RPIC must also consider the operating limitations of the UAS platform and the current weather conditions, including the temperature, precipitation, and wind speed, to ensure operations can be safely conducted (refer to Section 7.3.1.4 for additional information regarding UAS environmental tolerances). Also, 14 C.F.R. §107.51 requires no less than 3 SMs of visibility and 500-ft vertical/2,000-ft horizontal separation from clouds (Operating Limitations for Small Unmanned Aircraft, 2017), 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.

- UAS operations could be limited by ATC and airspace restrictions. The ATC facility might disapprove, restrict, or delay UAS flight operations covered by an airspace authorization at any time. Additionally, UAS operations might 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 C.F.R. §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.

- UAS operations could be limited by the presence of nonparticipating individuals at the accident or incident scene. 14 C.F.R. §107.39 restricts UASs from being operated over any human being who is not directly participating in the operation (Operation over Human Beings, 2021). Aircraft accident and incident scenes are often complex and can potentially involve dozens of nonparticipants including passengers, airport operations personnel, ARFF personnel, and other first responders. Since the priority is always the preservation of human life, UAS operations might have to be postponed until the scene is clear of any nonparticipating individuals; however, it is possible to obtain an operational waiver of this requirement from the FAA.

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7.2 RECOMMENDED MINIMUM PERFORMANCE SPECIFICATIONS

Based on the findings derived from testing conducted at ACY and WWD, and analysis of the capabilities of current technologies, FAA researchers created recommended UAS performance specifications for aircraft accident and incident documentation. These performance specifications address general UAS platform (features and capabilities), payload, and data acquisition parameters. Appendix C presents a comprehensive summary of these minimum performance specifications in table format.

7.2.1 UAS Platform

The following are the recommended minimum requirements for the UAS platform:

- The UAS must be capable of stable and predictable flight behavior. This minimizes the task load on the operator.

- The UAS must be capable of conducting preprogrammed mapping flight plans with specific data parameters, including camera orientation, altitude, and forward/side overlap values.

- 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 operations during civil twilight or night, the UAS must be equipped with an anti-collision light visible from at least 3 SMs. This lighting requirement is based on Title 14 C.F.R. § 107.29, Paragraph (b) (Operation at night, 2022).
- When stored, all components of the UAS must be resistant to the typical shocks and forces experienced by a vehicle driving on an airport, including off-road driving.

7.2.2 Payload

The following are the recommended minimum requirements for the UAS payload:

- The UAS payload must include a visual camera capable of collecting still imagery.
- The payload camera and gimbal must be capable of capturing nadir imagery (pointing straight down at -90 degrees).
- The camera payload used for data acquisition should have a minimum image resolution of 12 MP.
- The camera must be capable of automatically adjusting the image focus and exposure.

7.2.3 Minimum Data Acquisition Parameters

Table 17 provides a summary of the recommended minimum parameters for data acquisition. Based on the test results, FAA researchers recommend that mapping data be collected with the camera in a nadir orientation with a minimum GSD of 1-in., and forward/side overlap values of 80%/70%.

Table 17. Recommended Minimum Performance Specifications Summary

Parameter	Minimum Performance Specification
Flight Pattern	Single grid
Camera Angle	Nadir
GSD	1 in. or better
Forward/Side Overlap	80%/70%

7.2.4 Data Processing Software

The recommended minimum requirements for data acquisition parameters are:

- Processing software must be capable of generating orthomosaics.

- If real-time processing software is used, the software should also include an option to capture still images in case the live feed connection is lost.

- Data export formats must include, at a minimum, PDF and GeoTIFF.

7.3 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 aerial mapping to enhance aircraft accident and incident scene documentation. These considerations address UAS platform selection, payloads, data acquisition, and data processing.

7.3.1 UAS Platform Selection

Sections 7.3.1.1 through 7.3.1.4 provide considerations for selecting a UAS platform, including airframe configuration, endurance, cybersecurity, and environmental tolerances.

7.3.1.1 Airframe Configuration

Different UAS types provide contrasting capabilities and limitations on conducting aerial surveys and operating in the airport environment. The most appropriate UAS for a given survey area will be dependent on the details of the environment.

Multirotor UASs have the greatest maneuverability, enhancing safety by allowing for quick avoidance of obstacles or aircraft in the flight path. In addition, multirotor UASs require a smaller flight operations area versus fixed-wing or hybrid UASs for a given survey area because they are capable of VTOL and have no turning radius. Multirotor UASs should be used in smaller survey areas or dense areas where maneuverability is a higher priority than collection speed.

Fixed-wing UASs can typically fly faster and longer than multirotors and provide the most benefit for larger mapping areas. In addition, fixed-wing UASs also require a larger land area for takeoff and landing, and a larger flight operations area to accommodate their larger turning radii. In addition, operators should consider that fixed-wing UASs are more susceptible to being affected by winds during flight. Hybrid VTOL UASs perform as a fixed-wing, but their VTOL capability allows them to operate in areas with less open space than a typical fixed-wing aircraft would require to take off and land safely.

7.3.1.2 Endurance

Operators should consider the flight endurance (i.e., the length of time a UA can remain airborne before needing to replace batteries) when selecting a UAS. These typically range from 20 to 40 minutes. 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%).

7.3.1.3 Cybersecurity

UASs used for aircraft accident and incident scene documentation should feature secure, encrypted connections between the aircraft, GCS, and any other devices that receive data to prevent outside persons from knowingly or unknowingly accessing or interrupting data communications. These include data used for command and control of the aircraft and payload footage.

7.3.1.4 Environmental Tolerances

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

- 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 18, 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).

  It is recommended that UASs used to support aircraft accident documentation have a minimum 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.

Table 18. The IP Rating Matrix (IEC, n.d.)

Dust (First Number)	Moisture (Second Number)
IP 0x—No protection	IP x0—No protection
IP 1x—Objects ≥ 50 mm	IP x1—Vertically falling water
IP 2x—Objects ≥ 12 mm	IP x2—Vertically falling water when enclosure tilted up to 15 degrees
IP 3x—Objects ≥ 2.5 mm	IP x3—Sprayed water (up to 60 degrees from vertical)
IP 4x—Objects ≥ 1 mm	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. Based on market research, two recommended operating temperature range targets were identified: 32 °F to 110 °F for warmer climates, and -40 °F to 110 °F for colder climates that require winterization. These ranges are based on the operating temperature range for ARFF vehicles specified in AC 150/5220-10, *Guide Specification for Aircraft Rescue and Fire Fighting Vehicles*. However, because no UAS platforms are currently capable of operating at -40 °F as stated in AC 150/5220-10, the minimum recommended operating temperature for colder climates was raised to 14 °F (FAA, 2011).

- 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.

7.3.2 Payload Camera Selection

The following are considerations regarding the UAS payloads:

- Payload camera specifications will determine the necessary flight plan altitude to achieve a given GSD. In addition to the resolution of a payload, the GSD is also affected by the lens and focal length. For example, Table 19 shows the altitude that must be flown with various payloads to capture data with a 1-in. GSD. Higher altitudes generally result in shorter data acquisition times and less distortion; however, they also result in higher GSDs that limit the amount of clarity in the imagery. Generally, the UAS should capture imagery as high as possible while maintaining a GSD of less than or equal to 1-in.

Table 19. Payload GSDs

Payload Camera	Altitude required to achieve 1-in. GSD (AGL)
DJI M2ED Visual Camera	236 ft
Parrot ANAFI Triple	249 ft
DJI X7 16mm	340 ft
SenseFly S.O.D.A. 3D	369 ft
DJI Mavic Pro 2 Hasselblad	373 ft
Sony RX1R-II	642 ft

- Operators should check the focus of the UAS camera during the mission by monitoring the live video feed on the GCS screen and, if able, perform a field check of the raw imagery prior to processing to ensure the quality of the imagery. After processing, operators should perform an additional field check of the 2D map output to verify processing success. All field checks should be performed as soon as possible to account for the possibility that a mapping mission needs to be flown again.

7.3.3 Data Acquisition

The following are general considerations for conducting aircraft accident and incident documentation flight planning and data acquisition:

- Firefighting or other critical tasks should not be delayed to conduct aerial mapping—the saving of lives is the primary objective. If the RPIC has an active role in firefighting or rescue, the UAS mapping mission should be conducted as soon as practical after initial firefighting and lifesaving efforts are completed.

- The orthomosaics generated for aircraft accident and incident documentation do not use ground control points and, therefore, are not tied to an exterior coordinate system. These orthomosaics are intended only to provide immediate situational awareness to responders and investigators enroute to the scene and are not a replacement for more detailed mapping by NTSB accident investigators.

- The area(s) being mapped should encompass as many relevant elements of the scene as possible (e.g., aircraft, ground vehicles (if involved in accident), foam/fuel discharge, debris fields, airport signs/markings, and witness marks [e.g., ruts, tire marks, structures impacted by aircraft]).

- If the accident or incident occurs at night or during inclement weather, imagery acquisition should be accomplished as soon as practical during daylight hours and when conditions are safe for flight. The amount of ambient light present during data collection has a significant effect on the quality of the orthomosaic generated from the imagery.

- For each map generated, record the date and time captured.

7.3.4 Data Processing

Following are considerations regarding data processing:

- The processing software used affects the amount of time required to create the orthomosaic and the amount of distortion present. The type of processing software should be chosen based on the use case for the orthomosaic and how quickly it is needed:

    - Locally installed processing software provides significantly faster data processing and should be used if the orthomosaic is intended to be provided to the ARFF IC during an ongoing response. Rapid processing solutions are designed for relatively flat terrain; therefore, these solutions could have issues with areas with tall vertical structures or severe vertical terrain variation.

    - Cloud-based processing services should be used if the orthomosaic is not needed immediately, whether because it is intended to be provided to the NTSB or used to document the evolution of the scene and response over time. While the processing speeds of these services are dependent on internet connectivity strength and bandwidth, and can take considerably longer than locally installed software, they produce orthomosaics with less distortion and provide more output options and capabilities.

- Software should have the ability to annotate key features and points of interest.

- All UAS images and map files must be preserved in accordance with AC 150/5200-12, *First Responders' Responsibility for Protecting Evidence at the Scene of an Aircraft/Incident*.

- Airport operators should develop specific plans and chain-of-custody procedures for UAS images and map files in accordance with their existing policies and standard operating procedures.

- Computer specifications have a significant effect on the speed of local data processing. The computer used to perform data processing with locally installed software should have a minimum of 16GB of RAM.

- The strength and stability of the internet connection used to upload images to cloud-based processing software services have a significant effect on the total processing time. If possible, it is recommended that data uploads be performed using a hard-wired or Wi-Fi internet connection in an office or residence. If processing is performed in the field, a hotspot with priority access for first responders is preferred to minimize upload times.

8. CONCLUSIONS

The Federal Aviation Administration (FAA) Airport Technology Research and Development Branch conducted a research effort to explore the use of small unmanned aircraft systems (UASs) for documenting aircraft accident and incident scenes at airports. The objectives of this research effort were to assess the benefits and limitations of UASs for this application, and to develop minimum performance specifications and technical and operational considerations for using UASs to document aircraft accidents and incidents.

This research effort consisted of outreach to the National Transportation Safety Board (NTSB) and three phases of UAS flight testing. Phase 1 consisted of the testing of various UASs, payloads, and processing software packages by conducting aerial mapping over a simulated commercial air carrier accident scene staged at the FAA's William J. Hughes Technical Center, which is collocated with the Atlantic City International Airport (ACY). The goal of this phase was to develop initial performance specifications and best practices on how to use UASs to generate two-dimensional (2D) orthomosaic maps of aircraft accident scenes in daylight conditions. Eight data sets were collected during Phase 1 in daylight conditions. Phase 2 testing followed a similar approach, consisting of 12 mapping flights over a simulated general aviation accident staged at the FAA's Research Taxiway (Taxiway C) at Cape May County Airport (WWD) during daylight conditions. The goal of this phase was to further refine the initial findings and evaluate their applicability for a smaller scale accident. Phase 3 testing was conducted at the same location as Phase 1, and consisted of 32 tests conducted during daylight, twilight, and nighttime conditions. In addition to validating previous findings, daylight testing during Phase 3 focused on evaluating various overlap settings with each platform and evaluating the effect dense vegetation and varying terrain elevations had on the orthomosaics. Tests conducted during twilight and nighttime conditions served as an initial proof of concept to evaluate the efficacy of conducting data collection in less-than-optimal lighting.

Following each phase of testing, FAA researchers evaluated the times required to acquire and process each data set, in addition to the quality and level of detail present in each orthomosaic to determine which UAS hardware, processing software, and flight parameters resulted in the most efficient flight operations and the highest quality outputs.

FAA researchers found that UASs equipped with camera payloads were effective tools for generating orthomosaics of aircraft accident and incident scenes for documentation purposes. These orthomosaics can benefit accident investigators by providing them with an overview of the scene prior to their arrival on site, by which time key details could be lost due to the dynamic and changing environment. In addition, when provided to ARFF incident commanders during the response, these maps could enhance their situational awareness and logistical management of the response. These benefits were limited, however, by the availability of staffing required to operate the UAS, inclement weather conditions, and current federal restrictions on UAS operations in controlled airspace.

Based on the testing results, FAA researchers set minimum performance specifications, including a minimum camera image resolution of 12 megapixels. FAA researchers recommend that mapping data be collected with the camera in a nadir orientation with a minimum GSD of 1-in., and forward/side overlap values of 80%/70%. FAA researchers also developed technical and operational considerations to maximize the benefits of UASs for aircraft accident documentation. These considerations address technical aspects such as the UAS platform, payloads, data acquisition, and data processing.

This report provides a summary of the outreach with the NTSB and the testing conducted at ACY and WWD and provides benefits and limitations, minimum performance specifications, and technical and operational considerations for using UASs for aircraft accident and incident documentation at airports.

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APPENDIX A—UAS PLATFORM SPECIFICATIONS

A.1 INTRODUCTION

This appendix provides the specifications for the 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 (M210); Table A-2 shows the specifications for the SenseFly eBee X; Table A-3 shows the specifications for the Parrot ANAFI USA; Table A-4 shows the specifications for the DJI Mavic 2 Pro; Table A-5 shows the specifications for the Wingtra WingtraOne PPK; Table A-6 shows the specifications for the DJI Mavic Enterprise Dual System (M2ED).

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

DJI M210	
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, preprogramed flight area prohibits flying outside of predetermined Geofence.
Obstacle Avoidance	Forward, Down, Above, DJI Airsense (ADS-B Receiver)
Ingress Protection Rating	IP-43

Table A-2. Specifications for the SenseFly eBee X (SenseFly, 2019)

SenseFly eBee X	
Type	Fixed-Wing
Wingspan	45.7 in.
Weight	3.1 lb
Maximum Flight Time	90 minutes
Average speed of flight during image capture	25–50 mph (wind speed & direction dependent)
Operating Temperature Range	5° F–95 °F
Transmitter Range	5 miles
Communication with Transmitter	Radio (2.4 GHz)
Maximum sustained wind speed limit for safe flight	Up to 29 mph
Lost Link Procedure (if > 30 seconds)	Autonomous return-to-home point, circular loiter until battery drain, then automatically land at predetermined landing spot if communication is not reestablished.
Low Battery Procedure	Autonomous return-to-home at predetermined AGL, then autonomous landing following predetermined parameters. Drone has 30% reserved and hidden by user, so landing with what flight controller says is 15% is actually 45%.
Operational Area Procedure	On-board, preprogrammed, radial flight area prohibits flying outside of predetermined geofence. If drone reaches the geofence, automatic return to home is triggered.
Obstacle Avoidance	Down, ADS-B Receiver

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	Pilot override from autonomous to manual control and return UAS to launch location and land when battery percentage reaches 20%. If battery decreases to level where flight computer can no longer maintain current altitude, UAS will initiate autonomous land and current position.
Operational Area Procedure	No built-in limitation for NFZ (no-fly zone), On-board, preprogramed flight area prohibits flying outside of predetermined, cylindrical geofence.
Obstacle Avoidance	Down
Ingress Protection Rating	IP-53

Table A-4. Specifications for the DJI Mavic 2 Pro (DJI, 2020b)

DJI Mavic 2 Pro	
Type	Rotary Aircraft (4)
Wingspan	13.9-in. motor-to-motor cross measurement
Weight	2.00 lb (without accessories)
Maximum Flight Time	31 minutes
Average speed of flight during image capture	TBD
Operating Temperature Range	14°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	Pre-programed flight area prohibits flying outside of predetermined geofence.
Obstacle Avoidance	Omnidirectional—Forward, Backward, Upward, Downward, Sides, DJI Airsense (ADS-B Receiver)

Table A-5. Specifications for the Wingtra WingtraOne PPK (Wingtra, 2022)

Wingtra WingtraOne PPK	
Type	Fixed-Wing
Wingspan	4.1 ft
Weight	9.9 lb
Maximum Flight Time	55 minutes
Average speed of flight during image capture	35.8 mph (wind speed & direction dependent)
Operating Temperature Range	-4 °F–122 °F
Transmitter Range	5 miles
Communication with Transmitter	2.404–2.479 GHz
Maximum sustained wind speed limit for safe flight	Up to 28 mph in cruise, up to 18 mph for landing
Lost Link Procedure (if > 30 seconds)	Autonomous return-to-home point, then automatically land at predetermined landing spot if communication is not reestablished.
Low Battery Procedure	Warning when battery at <45%, return to home initiated at 38% battery. If the battery reaches <2%, it will land on spot.
Operational Area Procedure	On-board, preprogrammed, radial flight area prohibits flying outside of predetermined geofence. If drone reaches the geofence, automatic return to home is triggered.
Obstacle Avoidance	Set transition height 65 ft above obstacles. Terrain following feature recommended. Assisted mode available with tablet and RC.

Table A-6. Specifications for the DJI M2ED (DJI, 2021)

DJI M2ED	
Type	Rotary Aircraft (4)
Wingspan	13.9-in. motor-to-motor cross measurement
Weight	1.98 lb (without accessories)
Maximum Flight Time	31 minutes
Average speed of flight during image capture	TBD
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	Pre-programed flight area prohibits flying outside of predetermined geofence.
Obstacle Avoidance	Omnidirectional—Forward, Backward, Upward, Downward, Sides, DJI Airsense (ADS-B Receiver)

APPENDIX B—PAYLOAD SPECIFICATIONS

This appendix provides the specifications for the small unmanned aircraft system (UAS) payloads used during this research effort. Table B-1 shows the specifications for the Da-Jiang Innovations (DJI) Zenmuse X7; Table B-2 shows the specifications for the DJI Zenmuse X5S; Table B-3 shows the specifications for the DJI Zenmuse XT2; Table B-4 shows the specifications for the SenseFly S.O.D.A. 3D; Table B-5 shows the specifications for the Parrot ANAFI Triple; Table B-6 shows the specifications for the DJI Mavic 2 Pro Hasselblad Camera; Table B-7 shows the specifications for the Sony RX1R-II; Table B-8 shows the specifications for the M2ED Visual Camera.

Table B-1. Specifications for the DJI Zenmuse X7 (DJI, 2018b)

DJI Zenmuse X7	
Airframe Compatibility	Inspire 2, M210
Gimbal Control (3D Stabilized)	Pitch: -125° to +40° Pan: ±300° Roll: +90° to -50°
Still Image Resolution	24.0 MP (6016x4008)
Aspect Ratio	3:2
Sensor Type	CMOS—Super 35
Sensor Size	APS-C (23.5 mm × 15.7 mm)
Focal Length	16 mm (35 mm equivalent: 24 mm)
Still Image Format	JPEG, RAW, RAW + JPEG
Shutter Mode	Electronic Rolling
GSD @ 400 ft AGL	1.18 in.

3D = Three dimensional
CMOS = Complementary metal-oxide semiconductor
GSD = Ground sample distance
M210 = Matrice 210 RTK v2
MP = Megapixel

Table B-2. Specifications for the DJI Zenmuse X5S (DJI, 2018a)

DJI Zenmuse X5S	
Airframe Compatibility	Inspire 2, M210
Gimbal Control (3D Stabilized)	Pitch: -125° to +40° Pan: ±300° Roll: +90° to -50°
Still Image Resolution	20.8 MP (5280x3956)
Aspect Ratio	4:3
Sensor Type	CMOS
Sensor Size	4/3 (17 mm × 13 mm)
Focal Length	15 mm (35 mm equivalent: 30 mm)
Still Image Format	JPEG, RAW, RAW + JPEG
Shutter Mode	Electronic Rolling
GSD @ 400 ft AGL	1.05 in.

Table B-3. Specifications for the DJI Zenmuse XT2 (DJI, 2018c)

DJI Zenmuse XT2	
Gimbal control (3D Stabilized)	Tilt: +45° to -130° Pan: ±330° Roll: -90° to +60°
Visual camera sensor	1/1.7″ CMOS, 12 MP
Visual camera resolution	4K; 1080p
Visual camera frame rate	29.97 fps
Visual camera FOV	57.12° × 42.44°
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: 336 x 256 13mm/19mm/25mm: 640 x 512
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: 640 × 512: -13 °F to 275 °F 336 × 256: -13 °F to 212 °F Low gain: -40 °F to 102°F
Thermal camera spectral band	7.5–13.5 µm
Thermal camera sensitivity	<50 mK
Photo formats	Thermal—JPEG, TIFF, R-JPEG Visual—JPEG

FLIR = Forward-looking infrared
FOV = Field of view

Table B-4. Specifications for the SenseFly S.O.D.A. 3D (SenseFly 2020)

SenseFly S.O.D.A. 3D	
Airframe Compatibility	eBee X
Gimbal Control (2D Stabilized)	Roll: 45° Left to 45° Right
Still Image Resolution	20 MP (5472x3648)
Aspect Ratio	3:2
Sensor Type	CMOS
Sensor Size	1 in. (13.2 mm x 8.8 mm)
Focal Length	10.6 mm (35 mm equivalent: 29 mm)
Still Image Format	JPG, JPG+DNG
Shutter Mode	Mechanical Global
GSD @ 400 ft AGL	1.08 in.

Table B-5. Specifications for the Parrot ANAFI USA Triple (Parrot, 2020)

ANAFI USA Triple	
Airframe Compatibility	Parrot ANAFI USA
Gimbal Control (3D Stabilized)	Pitch: -140° to +110° Pan: TBD Roll: TBD
Visual Camera Sensors	2x, 1 / 2.4
Digital Zoom	32x
Electronic Shutter Speed	1s to 1/10000s
ISO Range	100–3200
Photo Resolution	Wide: 21 MP (84° FOV), Rectilinear: 16 MP (75.5° FOV)
Photo Formats	JPEG, DNG
IR Image Chain	FLIR Boson, -40 °F to +302 °C temperature range
Thermal Resolution	320 x 256

Table B-6. Specifications for the Mavic 2 Pro Hasselblad Camera

Mavic 2 Pro Hasselblad Camera	
Airframe Compatibility	DJI Mavic 2 Pro
Gimbal Control (3D Stabilized)	Tilt: -135–+45° Pitch: -90–+30 ° Pan: -100–+100°
Image Sensors	1-in. CMOS
Digital Zoom	3x
Electronic Shutter Speed	8-1/8000s
ISO Range	Video：100–3200 Photo：100–1600(Auto), 100–12800(Manual)
Video Resolution, Format	MP4, MOV (MPEG-4 AVC/H.264)
Photo Resolution	Thermal—12 MP, Horizontal FOV: 57° Aperture: f/1.1 Visual—12 MP, FOV: approx. 85° Aperture: f/2.8 Focus: 0.5 m to ∞
Photo Formats	JPEG

Table B-7. Specifications for the Sony RX1R-II

Sony RX1R-II	
Airframe Compatibility	WingtraOne
Gimbal Control	None
Still Image Size	42.18 MP (7952x5304)—3:2
Ground Sample Distance (GSD) @ 400 ft AGL	0.64 in.
Sensor Type	Full Frame 35mm
Still Image Format	JPG, DNG, JPG+DNG
Shutter Mode	Mechanical Global
Max Video Resolution	None
Zoom Capability	None
Video Format	None

Table B-8. Specifications for the M2ED Visual Camera

M2ED Visual Camera	
Airframe Compatibility	DJI Mavic 2 Enterprise Dual
Gimbal Control (3D Stabilized)	Tilt: -135–+45° Pitch: -90–+30 ° Pan: -100–+100°
EO Sensors	1/2.3" CMOS; Effective pixels: 12M
Lens	
Digital Zoom	3x
Electronic Shutter Speed	8-1/8000s
ISO Range	Video：100–3200 Photo：100–1600(Auto), 100–12800(Manual)
Video Resolution, Format	MP4, MOV (MPEG-4 AVC/H.264)
Lens	FOV: approx. 85° Aperture: f/2.8 Focus: 0.5 m to ∞
Photo Formats	JPEG

APPENDIX C—RECOMMENDED MINIMUM PERFORMANCE SPECIFICATIONS

This appendix presents the minimum performance specifications for unmanned aircraft systems (UASs) for conducting aircraft accident documentation operations. Minimum performance specifications are presented regarding UAS platforms (Table C-1), payloads (Table C-2), data acquisition parameters (Table C-3), and data processing software (Table C-4).

Table C-1. UAS Performance Specifications

Item	Specification
Flight Performance	The UAS should be capable of stable and predictable flight behavior, including the capability to loiter at/around a fixed position at a commanded altitude with no control input.
Flight Planning	The UAS must be capable of conducting aerial mapping using preprogrammed flight plans with specific data parameters, including camera orientation, altitude, and forward/side overlap values.
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 operations during civil twilight or night, the UAS must be equipped with an anti-collision light visible from at least 3 statute miles.
Durability	When stored, all components of the UAS must be resistant to the typical shocks and forces experienced by a ground vehicle when driving on an airport, including off-road driving.

Table C-2. UAS Visual Camera Performance Specifications

Item	Specification
Payload Type	The UAS must be equipped with a visual camera payload.
Data Type	The payload must collect still image data.
Vertical Range of Motion	The payload camera and gimbal must be capable of capturing nadir imagery (pointing downward at -90 degrees).
Image Resolution	The payload must have a minimum image resolution of 12 megapixels.
Auto Focus	The visual camera must include auto focus.
Auto Exposure	The visual camera must include auto exposure.

Table C-3. Data Acquisition Parameters Performance Specifications

Item	Criteria
Camera Orientation	Image data must be collected in a nadir (straight downward) orientation.
Ground Sample Distance (GSD)	Image data must be collected with a minimum GSD of 1 in. or better.
Image Overlap	Image data must be collected with minimum forward/side overlap values of 80%/70%.
Flight Pattern	Mapping flights must consist of at least a single grid pattern over the mapping area.

Table C-4. Data Processing Software Performance Specifications

Item	Criteria
Software Optimization	Processing software must be capable of generating orthomosaics.
Data Export File Types	Data should be exported in PDF and GeoTIFF orthomosaic file formats.
PDF Report Information	The exported PDF report should include notes of relevant information for the map, including date and time generated, the UAS platform and payload used, and data collection parameters, including GSD and forward and side overlap.