RESEARCH & DEVELOPMENT

Unmanned Aircraft Systems: A New Tool for DOT Inspections [Final Report]

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Unmanned Aircraft Systems: A New Tool for DOT Inspections Final Report

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16. Abstract

The NextGen Air Transportation Program (NGAT) at North Carolina State University (NCSU) collaborated with the NCDOT departments (Location and Surveys, Photogrammetry, Aviation, etc.) to analyze the potential role of small Unmanned Aerial Systems (UAS) in transportation environments such as structural inspections, small area surveys, rockslide assessments, and other situations. This project provided insight into UAS integration as an additional tool for situational assessment and surveying during inspection activities, especially for smaller areas and difficult to reach places. Multiple aircraft were used for data capture. Data sets captured included orthophotos, DEMs, traffic videos, thermal imagery, and flight logs.

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The Photogrammetry and Location and Survey Units have been incredibly patient, understanding, and committed to this project. The entire aviation community has been experiencing the most dynamic period in UAS integration history over the last two years. The timing of this project to coincide with the rapid technology maturation and regulatory expansion was both unfortunate, because we could not move as fast as wanted to, and fortunate, because we (collectively) learned many valuable lessons during this research effort. The Research Advisory Committee was always available for a discussion and guidance: Keith Johnston, Charlie Brown, Earl Dubin, Brian Hanks, John Pilipchuk, Jody Kuhne, Greg Perfetti, Tony Wyatt, and Neil Mastin.

The NGAT Team also wants to thank the NCDOT Division of Aviation Team- Bobby Walston, Chris Gibson, and Basil Yap- for their support of this project.

The NGAT Consortium at NC State University is proud to acknowledge the in-kind support from members that are committed to UAS integration and advancement. The Duke University Marine Lab (DUML) and Duncan Parnell contributed time and resources to provide additional data sets in support of this project.

Final "thanks" to the NC State University Center for Geospatial Analytics for data processing and analysis support of this project and the College of Agriculture and Life Sciences for the access to the Lake Wheeler Field Lab areas for flight testing and hours of data collection.

EXECUTIVE SUMMARY

Bridges, pipelines, tunnels, highways, and roads require maintenance and regular inspections. Inspections provide safety, repair, performance condition, and status updates. Most inspections are manually performed by a trained professional with tools, a camera, and an activity sheet. North Carolina Department of Transportation (NCDOT) uses manned aircraft to capture images for airborne surveys but the process can be expensive ($2,000 per flight) and has its limitations like weather, cloud cover, sun angle, time, etc. The generally accepted cost for a manned aircraft imaging sensor is around $1,000,000 for a complete system. These flights are often a cost effective resource for large areas but not for small roads or bridges.

The NextGen Air Transportation Program (NGAT) at North Carolina State University (NCSU) collaborated with NCDOT (Location and Surveys, Photogrammetry, Aviation, etc.) to analyze the potential role of small Unmanned Aerial Systems (UAS) in transportation environments such as structural inspections, small area surveys, rockslide assessments, and other situations. This project has provided insight into UAS integration as an additional tool for situational assessment and surveying during inspection activities, especially for smaller areas and difficult to reach places. This Report summarizes the research and general analyses process used to evaluate potential UAS integration in the NCDOT inspector survey operations. The scope of this project evolved as regulations changed, opportunities were presented, and lessons were learned. The research team conducted over 100 flights capturing large amount of images and flight performance data to support the assessment objectives of the project.

This project started in August 2014 to provide NCDOT data to demonstrate UAS potential in a range of applications and evaluate integration strategies. The goals of the project included three primary objectives: capturing data, analyzing data, and making recommendations for routine integration. The NGAT and NCDOT flight teams captured quantitative and anecdotal data over the two years regarding aircraft performance, sensor performance, data accuracy, and UAS operational metrics. Despite numerous delays, authorization hurdles, a major flight incident, and some unplanned misfortune, the research team has collected and analyzed a large amount of data on this project and related projects to justify the recommendation for NCDOT to consider UAS operations to support specific types of projects. The research team was flexible and able to adapt to changing regulations while also taking advantage of strategic partners that are committed to

UAS growth and maturation. This flexibility is evident in the report and data captured throughout this project.

The summary conclusion from the data analysis is that small UAS are not a viable option yet for small area, high resolution surveys. Due to flight time limitations, varying confidence in system performance across a range of products, image limitations from nonmetric cameras, and data processing requirements, this project provided NCDOT a detailed assessment of current UAS capabilities. For highly accurate orthophotos, too many Ground Control Points were required for UAS data capture. The point cloud data sets developed in the image analysis processing produced such large numbers of points that computing requirements were challenged beyond traditional aerial image analysis. This experience and reference data were primary objectives of this project to assist NCDOT with future UAS integration planning.

Not all the UAS operations were considered nonviable for NCDOT however. The data sets captured for non-precise applications including traffic monitoring, structure analysis, and volumes were considered adequate for engineering use. These would be beneficial for accident reconstruction, workflow monitoring, and ramp metering. Video data sets and larger area orthophotos were provided as additional UAS products for consideration as part of this project.

UAS are just beginning to demonstrate efficiency and cost benefits in real world applications. The technologies will continue to evolve just as the regulations are changing. Based on the analysis of this project, NCDOT will benefit from UAS integration in specific applications and business units, but not all departments immediately. UAS expectations must be defined at the beginning to determine products, operational requirements (i.e. using internal resources or contract services), and feasibility.

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1 INTRODUCTION

Rock slides, bridges, tunnels, quarries, earthworks, culverts, highways and rural roads all require scheduled maintenance and inspections. Major storms, minor storms, regular maintenance procedures, and federal requirements all contribute to the subset of inspection activities routinely performed by North Carolina Department of Transportation (NCDOT) field units. Inspections provide safety, repair, performance, and status data. Most inspections are conducted visually, using a set of standard processes and procedures, by a trained inspector with basic tools, i.e., a camera, hammer, and inspection logs for conducting each type of investigation. The addition of small Unmanned Aircraft Systems (UAS), commonly referred to as drones, has the potential of giving NCDOT field units another tool to complement and complete their missions by providing an on-demand aerial view of transportation infrastructure, operations, and survey areas.

This research evaluated the feasibility of small UAS to compliment a DOT inspector's current process while meeting required approvals to operate. Feasibility analysis included functionality of the technology, utility of the data, and usage requirements to operate the UAS. The FAA regulations in place at the beginning of the project delayed and restricted many of the originally proposed operations. However, the FAA regulations rapidly evolved over the duration of the project and the current FAA Part 107 Rule now enables broad commercial and civilian routine operations. This change in regulations will be described later. All North Carolina UAS flight related regulations were also met during the course of this research project.

In addition to flight regulations, RP2015-16 studied the technical requirements for accomplishing NCDOT missions. Image quality (resolution and accuracy) was assessed against current NCDOT methods. Multiple aircraft were flown to evaluate UAS operations and data collection for small area surveys, bridge inspection, and traffic monitoring. Many lessons were learned through these flights that will aid NCDOT integration of UAS capabilities.

The NextGen Air Transportation Program (NGAT) at North Carolina State University is a research group in the Institute for Transportation Research and Education (ITRE). The NGAT research team is a collection of engineers, flight operations staff, and researchers assembled to support the statewide integration of UAS into the National Airspace System and modernize aviation transportation in the state. The research team began conducting UAS flight research under FAA approval in March 2013 and now has over 900 flights and 200 hours of flight time with small UAS. The NGAT research team is supporting the FAA UAS Center of Excellence research activities as a core member of the ASSURE Team (www.assureuas.org). The team is also supporting the NCDOT Division of UAS Aviation UAS Program Office with policy development, integration exercises, and research services. The research team included the NGAT Consortium membership of 35+ organizations committed to advancing aviation in the region. This Consortium includes industry members Trimble, Precision Hawk, and Duncan Parnell. Other members are the Duke University Marine Lab (DUML), East Carolina University, City of Raleigh, and North Carolina Emergency Management.

The format for this report is a review of regulatory changes during the timeframe of the research, a brief review of NCDOT photogrammetry and survey processes, then a detailed summary of the research conducted followed by results and conclusions. This review includes sample flight data, imagery, and test scenarios to accomplish the research objectives of this project.

2 CURRENT UAS REGULATIONS

2.1 Overview

Current Federal Aviation Agency (FAA) regulations differentiate between recreational, public agency, and commercial UAS use. As of August 28, 2016 operations conducted for NCDOT may be conducted as a public agency or as commercial operations. Over the lifetime of this project flight operation regulations evolved from public agencies utilizing Certificates of Authorization for exclusive access to the National Airspace System (NAS), to more than 5,500 commercial operators using Section 333 Exemptions for providing a wide range of UAS services nationwide, to the release of the Part 107 Small Unmanned Aircraft System regulations (August 2016) which formalizes Small UAS Operations in the NAS with a newly created Remote Pilot certificate. A brief summary of the FAA UAS timeline during the course of this project can be seen in Figure 1:

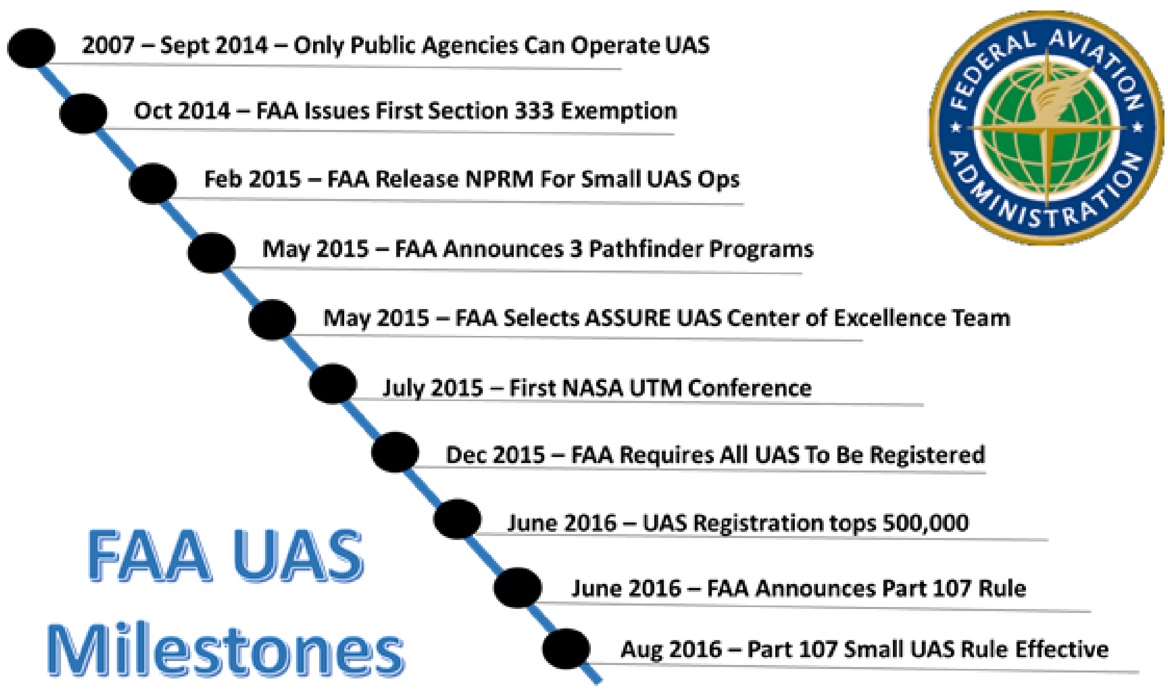

Figure 1: UAS Regulatory Milestones 2014-2016

“Small” aircraft are defined by the FAA as larger than 0.5 lbs. and less than 55 lbs. takeoff weight. As of December 2015 <u>all</u> unmanned aircraft are required to be registered with the FAA before UAS operations can commence, that includes hobbyists, commercial aircraft, and government-owned public unmanned aircraft. Beginning January 2016 all UAS operators, commercial and government, which intend to operate in North Carolina, are required to obtain the NCDOT UAS Permit from the NCDOT website. These rules are intended to protect the safety and integrity of the NAS, the citizens on the ground, and the performance of the air transportation system.

2.2 Aircraft Registration

Shortly after this project started, the FAA began requiring an aircraft N Number registration, just as how a manned aircraft is registered with the FAA. This process is time consuming (60 days on average) and cumbersome, especially for aircraft made outside the United States. Registering a UAS can now be completed in under an hour through an online process that immediately generates a unique registration number. As of June 2016 more than 500,000 UAS registration numbers were issued by the FAA. The technology and regulations continue to evolve at an exponential rate to meet market demand and commercial opportunities.

2.3 Certificate of Authorization

For public aircraft operations, the FAA issues a Certificate of Waiver or Authorization (COA) that permits public agencies and organizations to operate a particular aircraft, for a specific purpose, in a well-defined area. The COA allows the proponent to self-certify aircraft and pilot qualifications, but these must be documented and approved by the FAA. In addition to aircraft and pilot certification, the proponent must provide detailed analysis of the airspace, operation procedures, and safety measures. The NGAT research team applied for and received 5 COAs for RP2015-06 in 2015. COAs typically take 2 weeks to prepare and were granted in 60-90 days. The latest NCSU COA for the NGAT research team is the Blanket Area Public Agency COA, 2016-ESA-29-COA, that was issued in April 2016. This COA allows NGAT operation of small UAS weighing less than 55 lbs., in Class G airspace at or below 400 above ground level, greatly expanding our research team's operational capabilities. The Blanket COA structure did not exist in the FAA toolbox as an option when this project started. By the time the Blanket COA option was available for the research team to request, most of the resources of this project were spent and the coordination timeline with active NCDOT field projects was lost.

2.4 FAA Section 333 Exemptions

Beginning in October of 2014 commercial UAS operations were allowed under a Section 333

Exemption from the FAA. Unlike COA operations the applicant was not self-certifying the pilot and aircraft; instead the applicant was requesting to operate an aircraft without a certification of airworthiness in the NAS. Section 333 exemption holders are granted a blanket COA with operational parameters similar to the blanket public agency COA. For 333 Exemption operations, the UAS pilot in command is required to have at least a sport pilot's license, and the UAS must maintain at least 500 feet separation from any non-participants. These were significant barriers to UAS operations for most of the desired NCDOT missions, but the Exemption process provided more flexibility to choosing flight locations and aircraft to meet specific flight objectives. NGAT worked with a local law firm to request a 333 Exemption to conduct aerial surveying and flight research using six different aircraft. The first 333 Exemptions took at least 120 days for the FAA to process and approve. NGAT applied for a 333 Exemption July 2015 and received the Exemption in February 2016. The Duke University Marine Lab (DUML), an NGAT consortium member, began operating under a 333 Exemption in August of 2015 for marine science research. They used their exemption to collect imagery at the Gallants Channel Bridge to support this project in the summer of 2016.

To date there are over 100 companies in North Carolina with FAA approved 333 exemptions for providing commercial services. When this project began there were none, the process had not been established by the FAA.

2.5 Part 107 Small Unmanned Aircraft Regulations

The FAA Part 107 Rule formalizes operations for small unmanned aircraft in the National Airspace System. The operational parameters are similar to those of the 333 Exemption and Blanket COAs. Fortunately most of the restrictive issues that constrained 333 and COA operations have been redefined or removed. These include the requirement to have a Part 61 Pilots Certificate, 2nd Class Medicals, Visual Observers and airworthiness statements. While operations over non-participants are still prohibited, the 500 foot separation requirement is not included in the rule. The FAA is also allowing for waivers of some of the limitations if a proponent can provide a safety case to mitigate the additional risk. The basic highlights of 14 CFR Part 107 are listed below:

Part 107 Operational Limitations

- Aircraft less than 55 lbs
- Visual Line of Sight only
- Daylight hours only
- Max airspeed: 100 mph
- Max altitude: 400' AGL
- Requires preflight inspection
- No careless and reckless operations
- 1 aircraft per 1 operator
- Pilots must avoid aircraft operations over people
- Can fly in Class B,C,D and E airspaces with ATC permission
- Can fly in Class G airspace without ATC permission
- No transportation of hazardous materials

Part 107 Operator Requirements

- Pass an aeronautical knowledge test for small UAS Type Certificate under Remote Pilot License
- Vetted by TSA

Part 107 Aircraft Requirements

- No airworthiness certification
- Aircraft registration number
- Small (less than 55lbs) tethered powered UAS are also included in the Part 107 definition for needing registration and compliance with operational limitations

The FAA has announced that individuals or organizations can apply for waivers that will allow UAS operations to deviate from some the Part 107 operating requirements which include rules that restrict operations around transportation infrastructure. Waivers may be requested for the following:

- Operation from a moving vehicle or aircraft (§ 107.25)
- Daylight operation (§ 107.29)
- Visual line of sight aircraft operation (§ 107.31)
- Visual observer (§ 107.33)

- Operation of multiple small unmanned aircraft systems (§ 107.35)
- Yielding the right of way (§ 107.37(a))
- Operation over people (§ 107.39)
- Operation in certain airspace (§ 107.41)
- Operating limitations for small unmanned aircraft (§ 107.51)

In December of 2016 the FAA is expected to release the Notice of Proposed Rule Making (NPRM) for the rule that allows for small UAS operations over people, also known as "The Micro Rule." This is expected to be a change to Part 107, but may be a separate regulation entirely. The NPRM will present the FAA's current plans for enabling small UAS operations over nonparticipants. This will include weight restrictions, communication requirements, aircraft design requirements, safety requirements (such as a parachute), and other guidelines for enabling safe operations over dense populations. NGAT is actively monitoring the progress of the NPRM announcement.

2.6 North Carolina State UAS Regulations

As of January 1, 2016 a permit is required for commercial and government UAS operations in North Carolina. Anyone operating a UAS for other than hobbyist purpose must pass the UAS Knowledge Test on the NCDOT Division of Aviation website to receive the Operator Permit (Figure 2) before beginning operations. The knowledge test covers NC State laws covering UAS operations, and airspace knowledge. https://www.ncdot.gov/aviation/uas/

Figure 2: NCDOT UAS Government Operator Permit Example

3 NCDOT SURVEYING CURRENT METHODS

3.1 NCDOT Photogrammetry

The North Carolina Department of Transportation (NCDOT) uses photogrammetry techniques in conjunction with traditional ground surveying to provide data for transportation facility planning, design, and construction. Applications of photogrammetry in aerial surveying practice include topographic mapping, site planning, and earthwork volume estimation, compilation of digital elevation models (DEM), and image base mapping (orthophotography). The NCDOT photogrammetric process consists of project planning, image acquisition, image processing, and control data for image orientation, data compilation and a project presentation. The results of the photogrammetric process are georeferenced to the North Carolina State Plane Coordinate System.

3.2 UAS Imagery vs. Traditional Practices

Images used for photogrammetry can originate from a metric camera, non-metric camera or from digital sensors. The image can be captured by traditional methods like a device mounted on a satellite, an airplane (including helicopters), or a tripod (terrestrial photogrammetry). The first element in photogrammetry is choosing the correct sensor. The sensor is the most important photogrammetric instrument since it records the images of the applied photogrammetric principles. The sensor must be able to produce very sharp images, minimal distortion, in rapid succession under the adverse conditions of a moving aircraft. Any error, distortion, or compromise in the clarity of the image will result in mapping and positioning errors.

A second element of the photogrammetric process is establishing control points. They are used to establish the position and orientation of the camera at instant of exposure. In order to establish a stereo model, there must be at least two points with known horizontal positions (for scaling) and three points with known elevations (for orientation). Standard practices recommend use of additional control points to process a stereo model.

Photographs can be controlled using three different methods:

1. **Ground Control Points** - Ground control points that are placed using a survey grade GPS unit.

2. **Aerial Triangulation** - Aerial triangulation is used to bridge control over multiple images using fewer ground surveyed control points. Bridging is accomplished by measuring on the photographs common points that appear in three consecutive photographs or in two adjacent strips and computing their 3D coordinate values.
3. **Kinematic GPS** - Aerial photography control through kinematic a GPS technique in which the position and the attitude of the camera are computed without ground control.

Currently NCDOT aerial imagery is collected using an Intergraph DMC digital mapping sensor. This aerial sensor is interfaced to an Applanix Global Positioning System/Inertial Measurement Unit (GPS/IMU) for precision aerial imagery operations. The GPS/IMU data is used to recreate the coordinates and attitudes of each aerial image. Upon completion of an aerial imagery mission, the raw digital imagery, along with the GPS/IMU data are post-processed into aerial digital images and associated image positions and attitudes.

4 RESEARCH PROJECT SUMMARY

In order to accomplish the primary research objectives of this project, the research team divided the UAS feasibility analysis into three elements: applications, locations, and platforms. The value of UAS technologies is a combination of applying the proper capability in the desired environment to accomplish a specific set of defined objectives. NGAT and NCDOT identified a set of applications of interest for evaluating UAS performance in typical NCDOT applications at a specific set of locations across the state of North Carolina. With the locations and applications selected, the NGAT Flight Operations Team identified the aircraft and payloads necessary to accomplish the research agenda at each location. The research team used an iterative testing approach to provide the most flexibility for accomplishing the research objectives. Flexibility and adaptability were essential on this project due to the evolving regulatory landscape, the rapid technology maturation, the lessons learned and shared from the greater community, and the feedback from collaboration with NCDOT engineering.

The following research summary uses the following organization to review the research performed under this project:

4.1 Results of Literature Review
4.2 Requirements Analysis
4.3 Ground Testing
4.4 Flight Operations
4.5 Data Processing
4.6 Results

4.1 Results of Literature Review

A comprehensive literature review was conducted at the beginning of RP2015-06. The literature review indicated that commercially available technologies and related-applications demonstrate the potential of UAS technology to aid NCDOT field operations. These operations include surveys, bridge inspections, small area monitoring, as well as landslide detection and evaluation. Researchers around the world are conducting experiments and tests to demonstrate UAS commercial and civilian applications of the technology. Numerous reports describe the multi-billion dollar markets that UAS are creating for domestic operations in support of gathering precise data for agriculture analytics and public safety data integration for law enforcement and emergency response situations (Snow, 2016). The objective of this research is to explore how UAS could be cost effectively integrated into the NCDOT field engineer's resources for situational assessment both during and following survey activities. The following is an abbreviated version of the literature review results; complete review is available upon request.

UAS product considerations. There are two basic types of small UAS products available on the market today: fixed-wing aircraft and multicopter vertical take-off and landing (VTOL) designs. Although there are some hybrid designs with characteristics of each in development, fundamentally there are benefits and deficiencies to each. Selection is determined by payload, range, image accuracy, and operator qualification requirements. Also factored into aircraft selection are the mission navigation requirements, including autonomous verses manual control and GPS-limited conditions. Small systems that are tethered with power for navigation and sensing control are also considered small UAS by the FAA's definition under Part 107; therefore consideration of tethered systems uses the same evaluation criteria as other small UAS.

Sensor technology. The resolution, speed, weight, and type (RGB, thermal, 3D point clouds, etc.) of sensor capabilities available for small UAS applications was reviewed. This review focused on evaluating five forms of remote sensing that are potentially valuable for NCDOT inspections and surveys using an UAS. The sensor technologies considered in the review included: (1) high resolution photography and videography, (2) 3D photogrammetry, (3) thermal infrared, (4) radar, and (5) LiDAR. The first three technologies were determined applicable and within scope of this project.

Orthorectification and 3D Photogrammetry. Fundamental principles for imagery analysis and photographic reconstruction are briefly covered. There are a number of algorithms readily available to process aerial imagery, including: (1) Orthomosaic Photogrammetry, (2) Digital Image Correlation (DIC), (3) Feature

Extraction, (4) Simultaneous Localization and Mapping (SLAM), and (5) Structure from Motion (SFM).

UAS Applications. Prior research, example uses, and evidence of similar applications of UAS technology for transportation related data collection were reviewed. UAS have assisted inspectors by providing aerial imagery of hard to reach locations without significantly interrupting the flow of traffic. This literature review explored the use of UAS for surveying-related applications such as: (1) Landslide Monitoring, (2) Forest Exploration and Small Area Surveys, (3) Bridge Condition Assessment, (4) Road Intersection Traffic Monitoring, (5) Accuracy Assessments, and (6) 3D Modeling. Each application in the review includes a summary of relevance to this NCDOT project.

Current inspection requirements, tools, processes. References for standards, regulations, best practices, and major research initiatives were reviewed for currency of emerging trends and potential data sharing opportunities. These included but are not limited to: (1) Moving Ahead for Progress in the 21st Century (MAP-21), (2) Long-Term Bridge performance Program (LTBP), (3) Bridge Inspector's Reference Manual, (4) Models, Predictive Tools and Cost Reports from Austroads, (5) Reports from the American Association of State Highway and Transportation and Federal Regulations. UAS are not recognized in these references yet, but these reports provide the guidance that UAS operators will need to know to accomplish these missions.

4.2 Requirements Analysis

4.2.1 Scenario development

Through discussions with the multiple NCDOT teams that supported this project, the research team developed test scenarios to evaluate UAS feasibility in the following applications:

- Geotechnical surveys
- Earthwork Quality Determination
- Small Area Survey for Final Design
- High Accuracy Pavement Elevations

- Traffic Monitoring
- Structures Inspections, including bridge inspection

NCDOT identified specific locations in the state for testing UAS performance in these applications. These locations and applications were assembled into a list of potential flight test scenarios (Table 1) for capturing research data. This original list was prepared in the Fall of 2014 before the selected aircraft was acquired for the research, before any FAA approvals (COAs) had been requested, and before the option of subcontracting to Section 333 Exemption holding commercial services providers was an option to accomplish the research objectives. By understanding the application requirements and location constraints and aircraft performance requirements, the research team was able to evaluate aircraft and sensor payload options to accomplish the research objectives.

Table 1: UAS Research Scenarios

Location	Application	Decimal Degrees	State Plane* (m)	State Plane* (ft US)
I-40 at MP 6 in Haywood County (I-5508)	GeoTech Application	35.73936 N -83.02754 E	228071.474 N 245405.482 E	748264.493 N 805134.485 E
NC 209 at US 74 near Waynesville (R-4047)	Earthwork Quantity Determination	35.52307 N -82.95843 E	203844.583 N 250695.070 E	668780.101 N 822488.741 E
Lake Wheeler Site (Area 3) Wake County	Small Area Survey	35.72681 N -78.69559 E	219333.278 N 637139.287 E	719595.930 N 2090347.811 E
Kinston Regional Jetport	High Accuracy Pavement Surveys	35.32081 N -77.62011 E	175122.053 N 735055.698 E	574546.270 N 2411595.236 E
NC 73 (Sam Furr Rd) over I-77	Traffic Monitoring	35.44225 N -80.869671 E	189320.136 N 439876.507 E	621127.813 N 1443161.507 E
SR 1394 (Popular Tent Rd) over I-85	Traffic Monitoring	35.402278 N -80.698556 E	184607.331 N 455332.498 E	605665.884 N 1493870.036 E
		35.408056 N -80.714167 E	185272.585 N 453925.861 E	607848.472 N 1489255.094 E
NC 73 (Davidson Highway) over I-85	Traffic Monitoring	35.435338 N -80.656771 E	188210.181 N 459188.405 E	617486.236 N 1506520.625 E
I-85 (Exit 48) at I-485 (Exit 30)	Traffic Monitoring	35.348509 N -80.733465 E	178698.259 N 452058.108 E	586279.204 N 1483127.310 E

4.2.2 Aircraft selection

The research project team initially selected the fixed wing Trimble UX5 and the Leica Aibotix X6 as the platforms for RP2015-16 flights. These selections were determined by payload, range, image accuracy, operator certification expectations, and NGAT prior experience. Mission navigation requirements, including autonomous versus manual control, and potential GPS-limited flight conditions were also factors considered in aircraft selection.

The fixed wing option (UX5) was initially abandoned because its flight profile precluded it from operation safely and legally over most of the desired flight locations identified in the scenario list (Figure 3). The NGAT UX5 has been used for many projects since 2015, including a 150-acre earthworks imagery project outside of Wilmington that captured over 800 images at 4 cm resolution illustrating the potential usefulness of fixed wing aircraft to image larger areas.

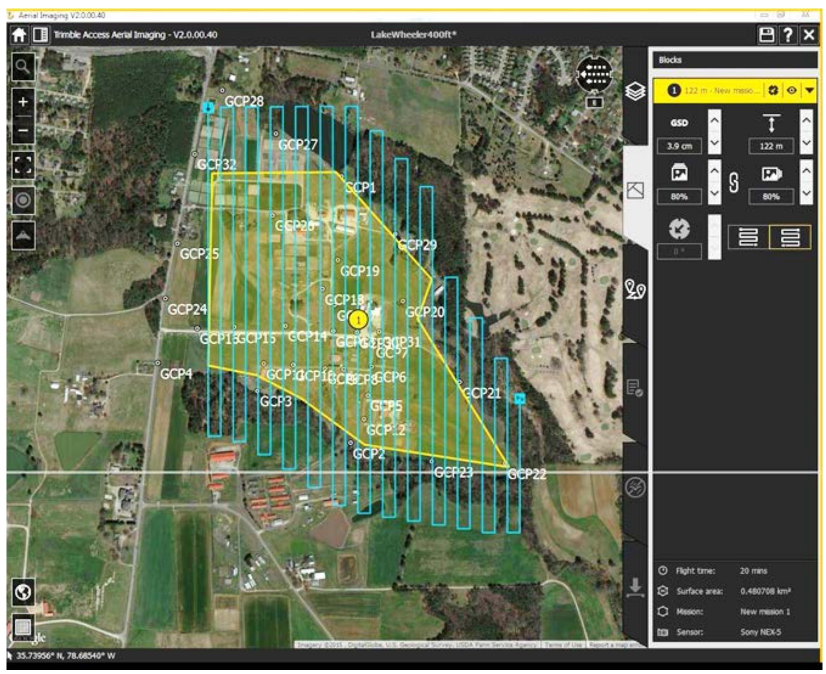

Figure 3: A Sample UX5 (fixed wing) Flight Profile at Lake Wheeler

The capability for vertical takeoff and landing, as well as the ability to hover, allow multirotor systems to operate effectively in congested areas around most transportation projects. These performance qualities drove the focus of this research toward multicopter evaluations and testing. The Leica Aibotix X6 was selected as the NGAT principle platform due to the use of many Leica products by NCDOT and its ability to carry the Samsung NX30 camera, a video camera, and thermal sensors. The X6 was envisioned to be used in all five test applications. The X6 was ordered in late 2014, and delivered in spring 2015, but several critical components were delayed without explanation by several months from the manufacturer.

In early 2015 the FAA updated the COA approval process requiring all UAS to have an N-Number before performing public operations. Obtaining the N-Number was a cumbersome process for several reasons: (1) the origin of the aircraft was Germany. As with all UAS manufactured outside the United States, the FAA paper registration process requires the COA operator to write to the Civil Aviation Authority from the aircraft origination country for a letter stating that the UAS had not been previously registered in that country. In the case of the Aibotix X6 this added several months from the factory delivering the X6, before the complete COA application was accepted by the FAA. (2) The N Number process assumes that there is an aircraft title, just as an owner would have with a manned aircraft. Since this title did not exist, the research team had to document the entire chain of custody from the manufacturer to delivery to NC State University referencing the serial number of the aircraft. For the X6 this document trail included a letter from the German government stating that the aircraft was never registered in Germany. Once the FAA had reviewed all of this, the N-Number (N116WP) was issued and the first X6 COA in NC was approved in August of 2015. This COA (COA # 2015-ESA-110) at the NC State Lake Wheeler Field Lab was used for initial training, flight testing, sensor integration, and data analysis.

Over the course of this project multiple aircraft were added to the NGAT research fleet or were made available by NGAT Consortium members for research support. All aircraft that were used during this project that provided sample data sets are briefly described in Appendix 9.2 Aircraft Descriptions. A summary analysis of those systems is included here in Table 2: UAS Comparison Data.

Table 2: UAS Comparison Data

Aircraft Requirements						
Evaluation Criteria / Aircraft Type	Flight Time (min)	Crew Experience	Payload Weight (kg)	Payload Integration	Availability	Potential Missions
X6	10	None	2	Advanced	Purchase	Survey, inspection, mapping
ZX5	20	None	2.3	Intermediate	Lease/Borrow	Survey, inspection, mapping
Inspire	20	Intermediate	1.7	n/a	Own	Aerial photography, inspection, video capture
Mikrocopter	15	None	4	Intermediate	Lease/Borrow	Survey, inspection, mapping
Cinestar	15	None	2	Intermediate	Lease/Borrow	Survey, inspection, mapping
UX5	50	Advanced	1	Limited	Own	Mapping, survey

4.2.3 Ground Control Points Integration

Ground Control Points (GCPs) are locations of known coordinates within the area of interest. Their coordinates have been measured with traditional surveying methods (survey grade GPS) or obtained by other sources (LiDAR, older maps of the area, Web Map Service). They are not required for processing raw data but they significantly increase the absolute accuracy of the final result. GCPs can also be used as check points to verify the accuracy of the results.

GCP integration into image analysis is dependent on two factors: (1) the number and distribution of GCP locations; and (2) the type of GCP markers.

Number and distribution of GCPs

Ground control points improve the spatial accuracy of photogrammetric products such as orthophotography and elevation point clouds derived from high resolution imagery. GCPs are locations on the surface of the earth with known X/Y (e.g. latitude and longitude) and Z (e.g. height above mean sea level) coordinates. They should be placed in a well distributed fashion within the area of interest.

In general, more GCPs are required if: (1) the area of interest grows in size; (2) there is tremendous topographic change throughout the areas; and (3) there are multiple overlapping images to rectify. An equidistant grid spacing of GCPs across the Area of Interest (AOI) should provide the best accuracy according to standard practice. It is important to include selected GCPs at or near the boundary of the AOI. The published formula calculating the appropriate number of GCPs for a location is:

Number of Ground Control Points = 10 + (Area Covered in Square Kilometers / 25) + (2 * Number of Overlapping Scene Edges) (McCarty, 2014)

The following figures display the GCPs used in the different flights at the Lake Wheeler Sediment and Erosion Control Research and Education Facility (SECREF) flight test location.

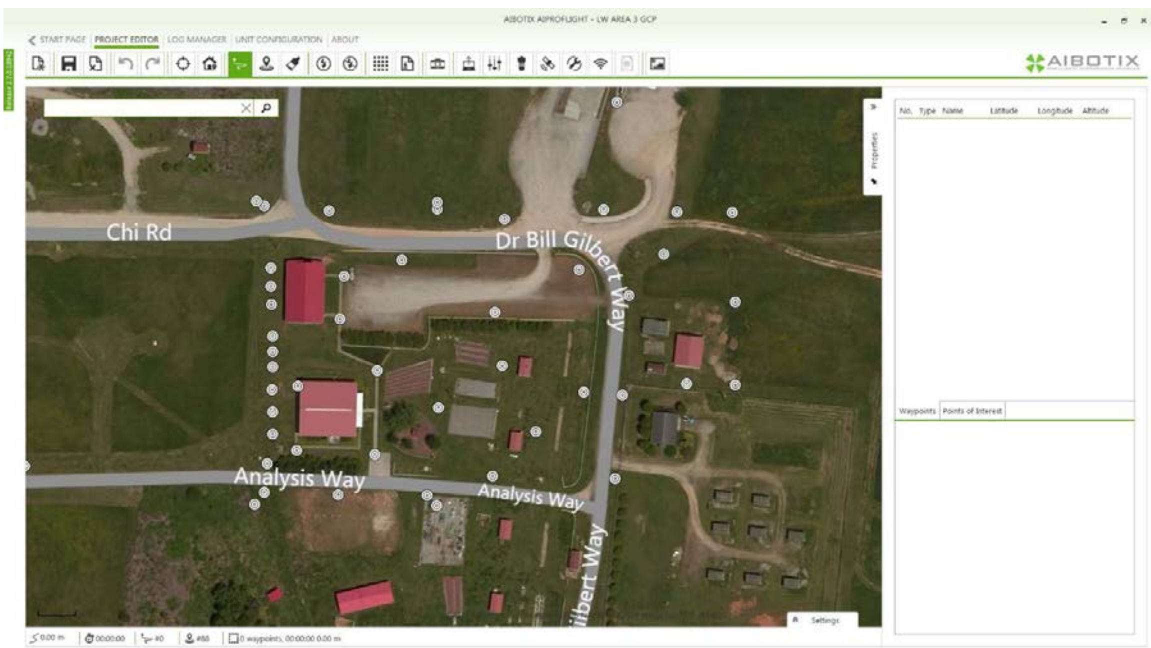

Figure 4: 67 feet flight, ground control points view on Aibotix AiProFlight

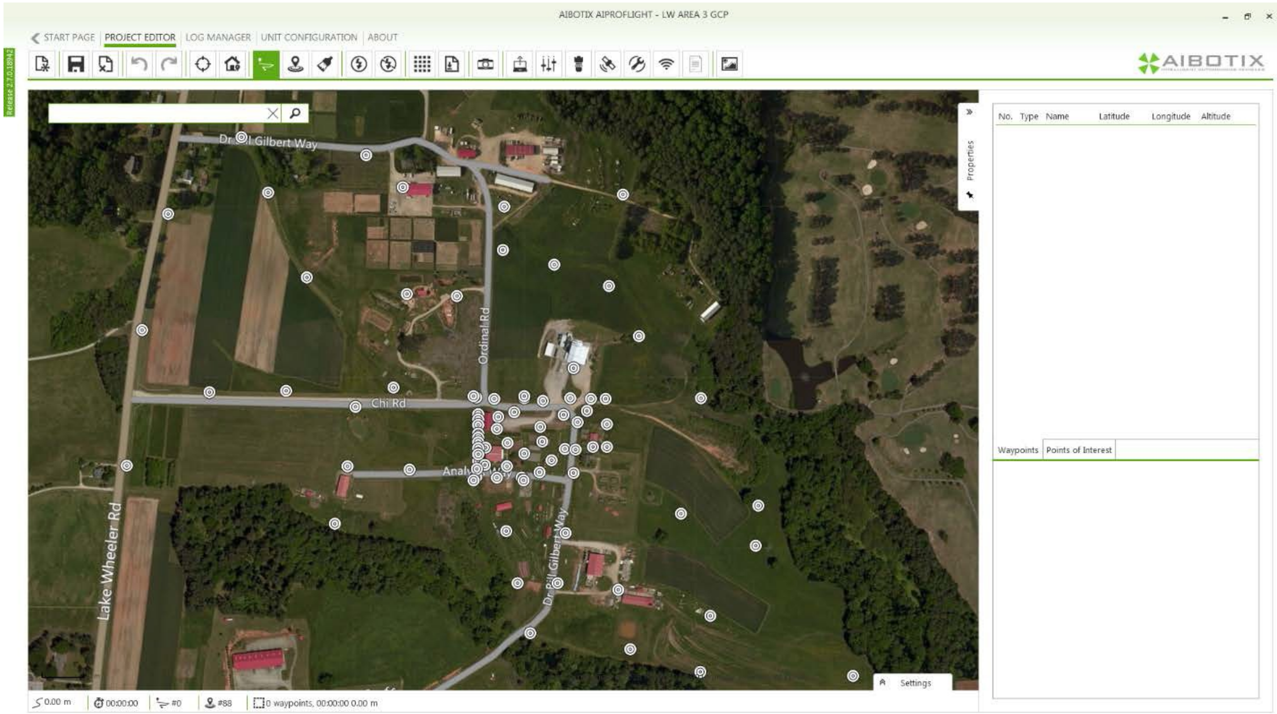

Figure 5: 200 feet flight, ground control points view on Aibotix AiProFlight

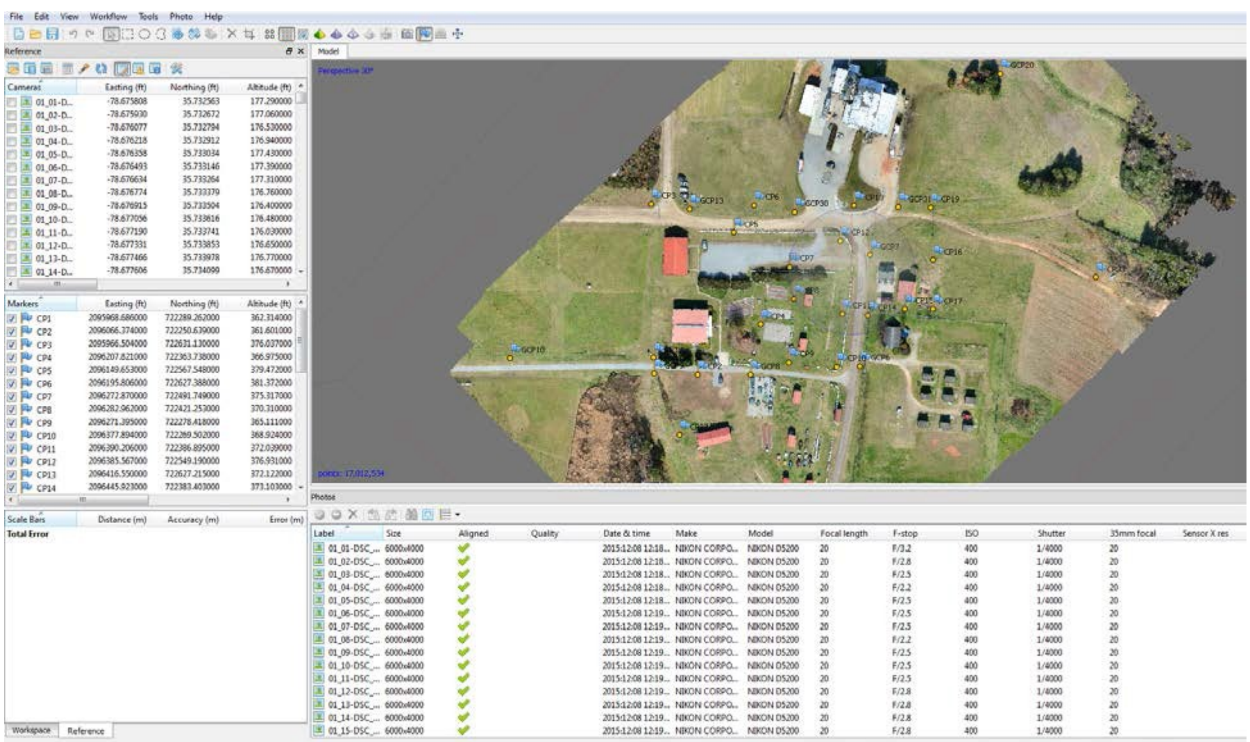

Figure 6: Ground control points view in Agisoft PhotoScan

Other recommendations for working with GCPs:

- A minimum of 3 GCPs are required for reconstruction. Each point should appear in at least 2 images.
- Areas with complex topography will require more GCPs. If possible place GCPs in locations with high and low evaluations.
- It is recommended to use at least 5 GCPs, each of which is identified in 5 images, as it minimizes the measurement inaccuracies and helps to detect mistakes that may occur when inserting the GCPs.
- The GCPs should be placed evenly on the landscape to minimize the error in Scale and Orientation.
- GCPs near the edges of the area will only be visible in few images.

Type of GCP marker

GCPs must be clearly identifiable both on the ground and in the image being used. Ideally, the markers should be located on a flat surface and free from standing obstructions. Cultural features, such as road intersections, are often used as photo identified control points (PICPs). Depending on the planned ground resolution or Ground Sample Distance (GSD), it is important to maintain the size of the targets utilized in the images for surveying accuracy. One formula for determining the size of GCP marker is:

Target size = 5 - 15 * the anticipated GSD (Wang, 2016)

Discussion of the GCPs used in this project are in Section 4.5.1.

4.2.4 Software Selection

Three photogrammetry programs were evaluated to create orthophotos, digital surface models and 3D models through a process known as Structure from Motion (SfM). Using overlapping imagery the SfM process extracts 3D coordinates from the original data.

1. Trimble Business Center (TBC) allows for the integration of geospatial data, including total station, global navigation satellite systems (GNSS) data, and

airborne imagery. Trimble Business Center is designed to work with the Trimble UX5 and ZX5 aircraft. Unfortunately, using data from other unmanned systems is very problematic.

2. Pix4D is commercially available software used by Duke University to process imagery from the Gallants Channel Bridge. Pix4D is available as a desktop or cloud base applications. https://pix4d.com/.

3. Agisoft PhotoScan is stand-alone software that utilizes a semiautomatic workflow that can be customized by the user producing orthophotos, DEMs, and image quality assessments. Photoscan is relatively inexpensive $3500.00 compared to other software packages. http://www.agisoft.com/. Due to NCDOT and NCSU experience with PhotoScan, the flexibility of the tool for processing data sets from multiple sources, and the image quality assessment feature, PhotoScan was selected as the primary data processing software tool for this project.

The standard Photoscan data workflow uses the process in Figure 7 (Agisoft, 2013).

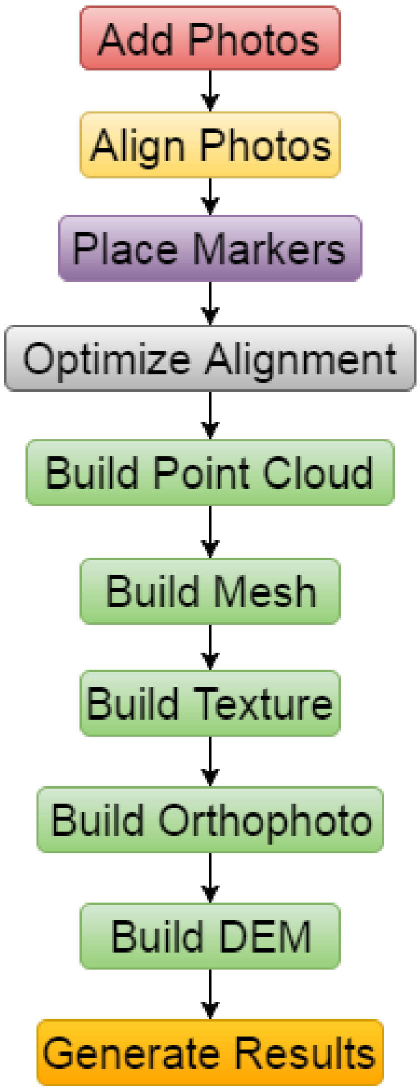

Figure 7: AgiSoft Workflow Process

Add Photos or **Add Folder** - The first step is to load all of the raw images into the software's interface.

Align Photos - This processing step compares the pixels in the photos to find matches and estimate camera locations, and 3D geometry within them.

Place Markers – In this step the ground control points are added, then optimized for alignment.

Build Dense Cloud - Once the alignment is complete, the sparse point cloud is processed into a dense cloud in which each corresponding pixel will get its own X, Y, Z location in 3D space.

Build Mesh - This step connects each set of three adjacent points into a triangular face. This combines to produce a continuous mesh over the surface model.

Build Texture - In the final step, the original images are combined into a texture map and wrapped around the mesh, resulting in a photorealistic model of your original object.

Build Orthophoto – The Orthophoto is built from the dense cloud and mesh.

Export Orthophoto & Flight Report – The final step is to export the data processed and generate a project report.

This project was completed in Agisoft PhotoScan. The following sections will provide greater detail of the workflow.

4.3 Ground Testing

4.3.1 Sensor Performance

The research team tested three types of sensors in this project: non-metric cameras, a high resolution video camera, and long wave thermal sensors. Unlike traditional metric cameras which are designed for the sole purpose of photogrammetric applications, non-metric cameras are consumer-off-the-shelf (COTS) products used for similar purposes. Photogrammetry departments are interested in non-metric cameras because they are much less expensive than metric cameras. The Olympus E-PL7 that was used in this project is approximately $1,200. According to NCDOT, a new metric airborne camera costs about $1,000,000 for a system installed in a survey airplane. The ability of these small inexpensive cameras to augment data collection of traditional metric airborne cameras is an emerging area for UAS imagery to fill.

There are a number of types of UAS sensor integration. The simplest form is to attach the payload to the UAS, set the camera to fire at a preprogrammed interval, turn it on, fly, then turn the payload off, and download the imagery. Optimally, the sensor integration should include the ability of the UAS to fire the camera based on a GPS location programmed into the flight plan. The research team tested a Samsung non-metric digital camera, a Nikon D5200, the Olympus E-PL7, and a Sony NEX-5 camera throughout the course of the project. The following analysis describes the performance of each of these cameras.

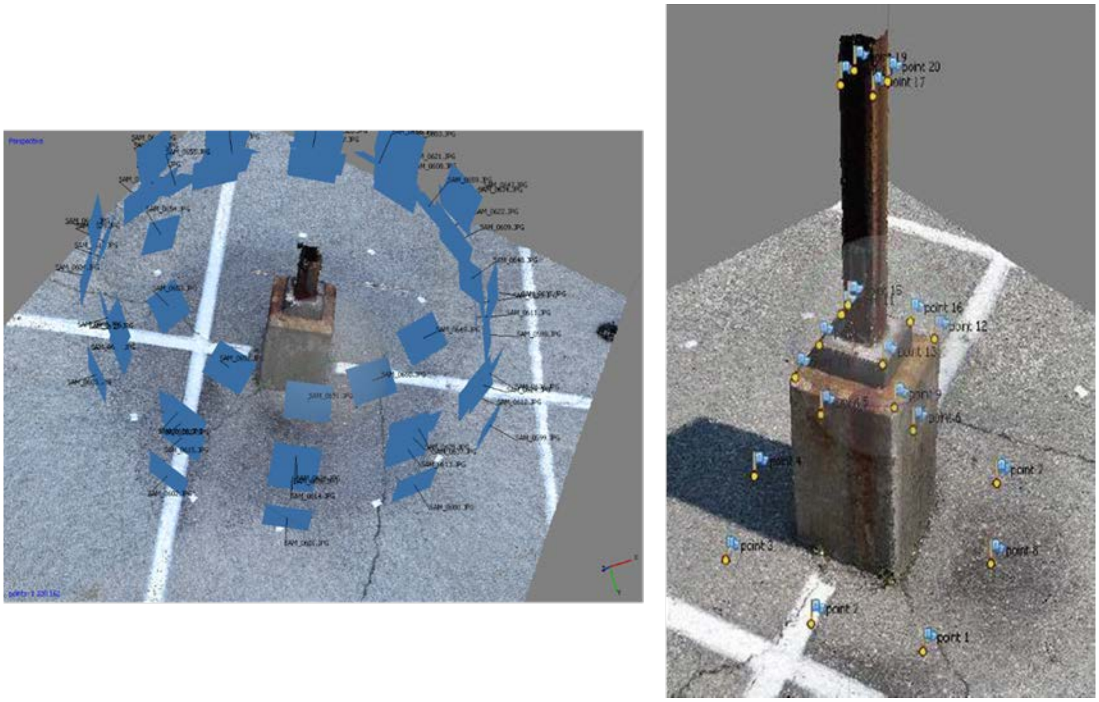

Figure 8: Camera Positions for Samsung NX30 16mm Lens Camera Calibration

NCDOT recommended purchasing the Samsung NX30 for this project based upon their imaging expectations and research goals. At the time the manufacturer's website stated that the NX30 was compatible with the X6. The NCDOT Photogrammetry team calibrated the Samsung 16mm lens. This was purchased off-the-shelf for the Samsung NX30 camera for use on the X6. The NCDOT team calibrated the lens using a subset of the control points (shown in Figure 8), while waiting for additional control points from the Location and Surveys Unit before "finalizing" the calibration. The preliminary calibrated focal length is reported at 16.825 mm which is quite different than the nominal 16 mm. The longer focal length provides a greater Ground Sample Distance (GSD) value from the same flying height; however, that comes with a smaller footprint for images. NGAT flight plans and analysis software (shown in Figure 9) were updated with this 16.825 mm calibrated focal length. The results of the NCDOT camera specs extraction is shown in Table 3. Ultimately the camera proved to be incompatible with the X6, even after discussions with the Aibotix engineers, because the camera's firmware was incompatible with the Aibotix firmware at the pre-programmed exposure points.

Table 3: Samsung NX30 Camera Specs

Sensor	Image Size (Mpixels)	Focal length (mm)	CMOS Element Size (um)	No. Pixels Cross Track	No. Pixels Along Track
Aibot X6 w/ Samsung NX30	20	16.825	4.38596	5472	3648

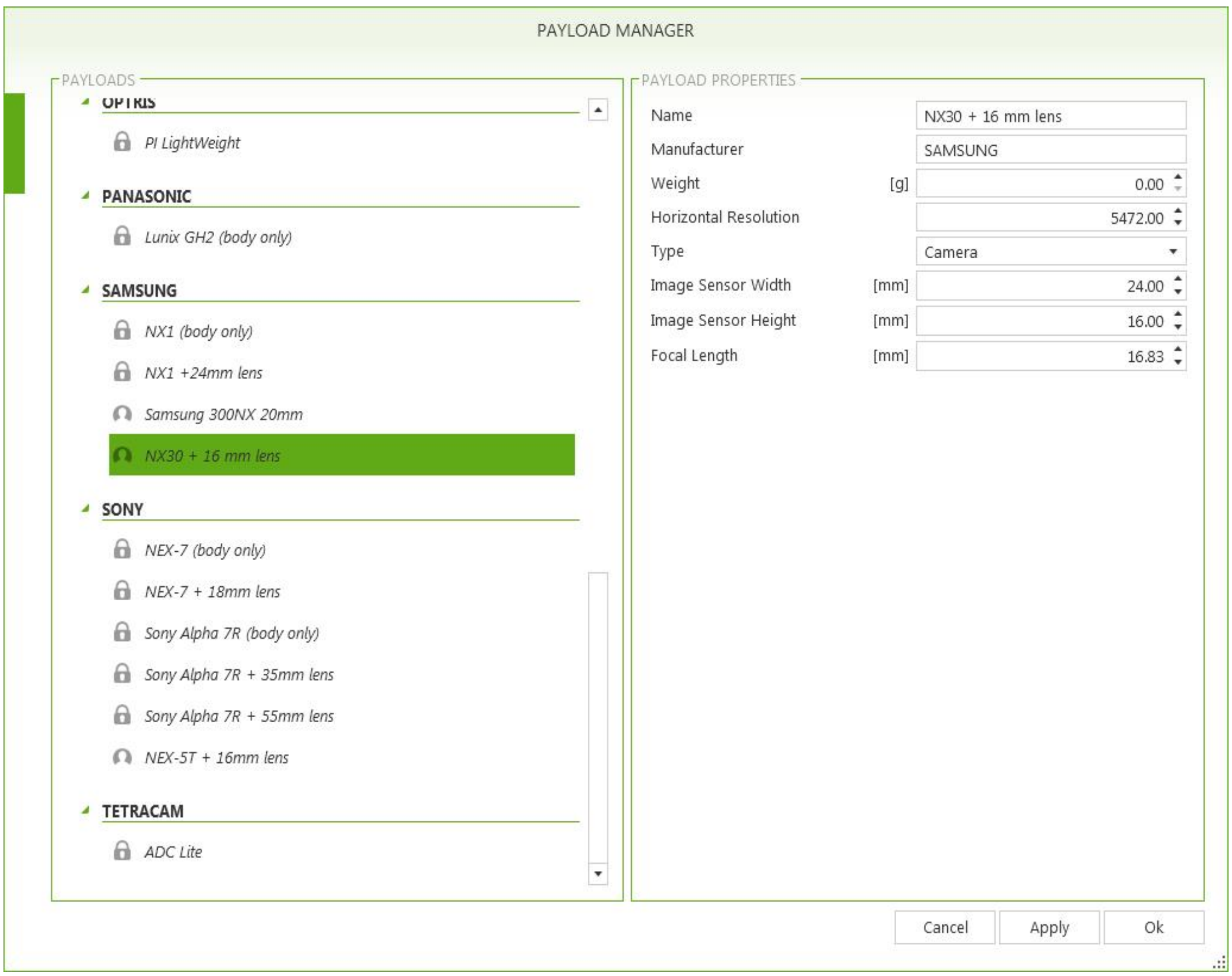

Figure 9: AiProFlight Payload Manager: NX30 16 mm lens Camera Calibration

After the failure of the Samsung integration effort, a Nikon D5200 was identified for the project research. This selection was available because NGAT owned the D5200 and it could be readily integrated with the X6. The Nikon D5200 is a 24 megapixel F-mount DSLR camera. The Nikon D5200 used an AF-S Nikkor 20 millimeter lens. The imagery for the Nikon was consistently clear and sharp on the ground but the team encountered issues in flight with the imagery. The issue was eventually isolated to vibration from the X6 camera mount, but the impact of the vibration could not be resolved.

Mirrorless SLRs are lighter, smaller, and simpler mechanically than DSLR cameras. The other platforms evaluated for this project used mirrorless cameras including the Olympus E-PL7 and Sony NEX-5. Analysis showed that the while the mirrorless cameras had to be flown lower and required more images to complete a mission, the quality of the imagery was comparable to the larger DSLR camera.

The lenses used for this project were pancake type lenses, primarily because they provided an optimal base to height ratio. This is the distance between the centers of overlapping images divided by the aircraft altitude. Photogrammetrists use the base height ratio to determine the vertical exaggeration allowing accurate vertical measurements of objects on the ground. Pancake lenses have fewer lens elements that other lens type which make them light and compact, ideal for UAS sensor integration.

4.3.2 Ground Sensor Test

Multiple cameras were tested at 67 feet and 200 feet away from the 12” and 36” ground control points. Due to different focal lengths and sensor sizes, the cameras cannot be directly compared to each other, but these conditions most accurately represent flights conducted by the NGAT team. The resolution difference from 67’ to 200’ can be seen through this comparison as well as the contrast and edge quality of the markers. See Figure 10 and Figure 11 for test examples.

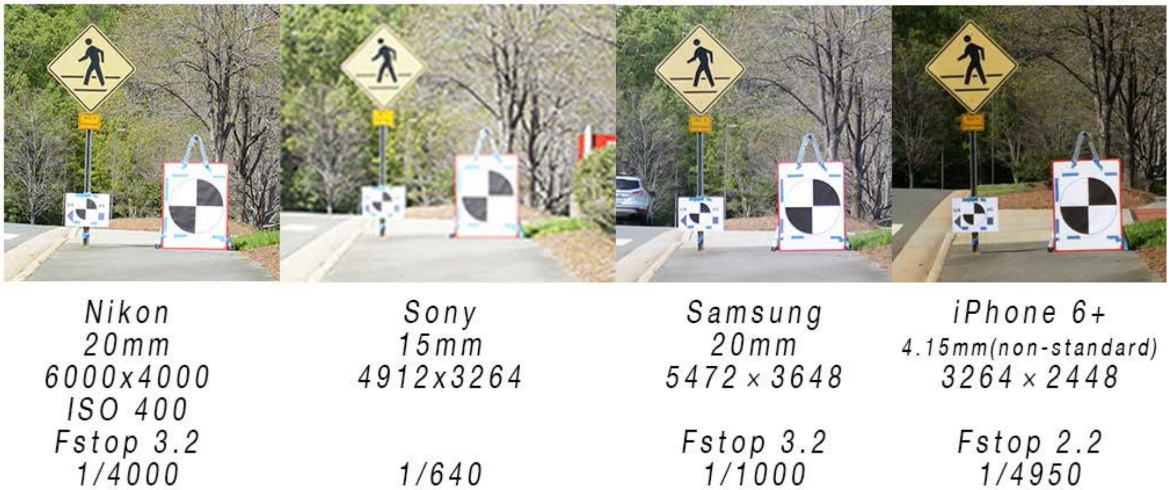

Figure 10: Ground Test with Multiple Sensors at 67 feet

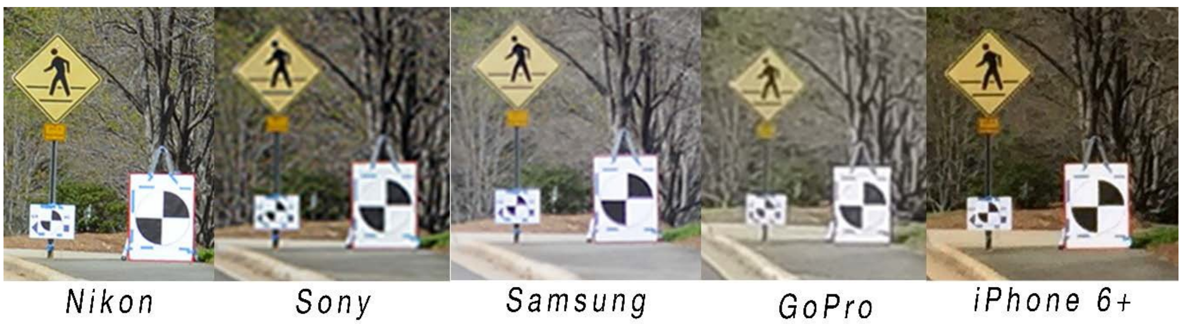

Figure 11: Ground Test with Multiple Sensors at 200 feet

4.4 Flight Operations

The NGAT Research team along with NCDOT personnel, Duke University Marine Lab (DUML), and NGAT consortium members, flew 118 flights that totaled 16.9 flight hours of research specifically for this project. All flight operations were conducted under two of the four COAs that NGAT obtained for this project and FAA approved Section 333 Exemptions (NGAT and DUML). Two COAs were submitted but were canceled while still in the approval process due to aircraft and location issues. Table 4 identifies the COA, aircraft, location, and application in the flight plan for accomplishing the project research objectives.

Table 4: Research Flight Agenda

COA	Aircraft	Location	Purpose
2015-ESA-110	Leica X6	Lake Wheeler, NC	Training, Small Area Survey
2015-ESA-111	Leica X6	Waynesville, NC	R-4047 Construction Project
2015-ESA-112	Leica X6	Haywood County, NC	Geotechnical Monitoring
2015-ESA-136	Leica X6	Henderson County, NC	Bridge Inspection
2015-ESA-138*	Leica X6	Concord, NC	Traffic Monitoring
2015-ESA-155*	Leica X6	Kinston, NC	High Resolution Survey
2016-ESA-29	UAS <55 lbs.	Nationwide	Traffic Monitoring, Bridge Inspection

Cancelled = *

Typical flight operations included three crew members: a pilot, visual observer, and data manager. The crew positions were typically changed between each flight to allow pilots to maintain currency with the UAS. Site managers were employed on more complex missions with more than a few non-participants to ensure safety. Observers and other active participants were presented a safety briefing and mission plan before all flight operations. The NGAT Flight Support Team included Site Managers, pilots (Aibotix X6, DJI Inspire), and visual observers. NCDOT Support included two NCDOT personnel that were trained as X6 pilots and visual observers. The NCDOT field team also surveyed the ground control points at the Lake Wheeler SECREF site and would set the markers for data collection missions.

Flight plans were developed for all anticipated study locations and were submitted to NCDOT Photogrammetry. There, a photogrammetrist used specialized software that projects the planned exposure points over the terrain of the study area to ensure there would be enough overlap and sidelap for accurate orthophoto and point cloud generation.

The following files were generated for each location:

- KMZ – Google Earth Project File
- XLSX – Geolocations of exposure points, ground control points (Highlighted Yellow), and check points in the NC State Plane Coordinate System
- XML – Aibotix AiProFlight Project File

The flight plans for the original project areas are explained in the following sections. The test missions that were defining the UAS application at each location precede the description of each location.

4.4.1 Lake Wheeler

Test Missions – Training, Small Area Surveys

Figure 12: SECREF (Area 3) at Lake Wheeler From Google Earth

Lake Wheeler is an active NGAT research COA location for the UX5 and most of the NGAT UAS research fleet. It was used for X6 Training and Small Area Survey for Final Design missions. The location is NC State University property and public access is limited. There are two primary flight test research locations at Lake

Wheeler: the Mid Pines Flight Research Area and Area 3 known as the SECREF. North Carolina Emergency Management surveyed and set the GCP for NGAT research use at the Mid Pines Flight research area. Estimated flight times for the entire 80 acre site (323,749 m^2) are between 30 to 50 minutes depending upon the winds for the UX5. But for the Aibot X6 it would take 120 to 140 minutes. Smaller areas have also been imaged. Figure 13 and Figure 14 are sample flight plans for the X6 at 50’ and 200’ altitudes at the SECREF area. The Mid Pines Flight area was the launch site of the X6 crash in January 2016.

The Sediment and Erosion Control Research and Education Facility (SECREF) is located on NCSU Lake Wheeler Road Field Laboratory (Figure 12). SECREF is used by NC State’s agriculture program for research and academic related activities including erosions studies and geographic analysis. SECREF includes various topographic features such as roads, buildings, fields, and wooded areas that make it an excellent location for evaluating UAS operations for small area surveys and inspections.

Using survey-grade GPS unit, NCDOT evenly placed 33 GCP markers around the 30 acre SECREF site. Four flights, at two different altitudes (67 feet & 200 feet) and two different overlaps (60-60 & 80-80), were processed in Agisoft PhotoScan with five GCPs and all GCPs (used as independent check points) to see which overlap configuration yielded better results.

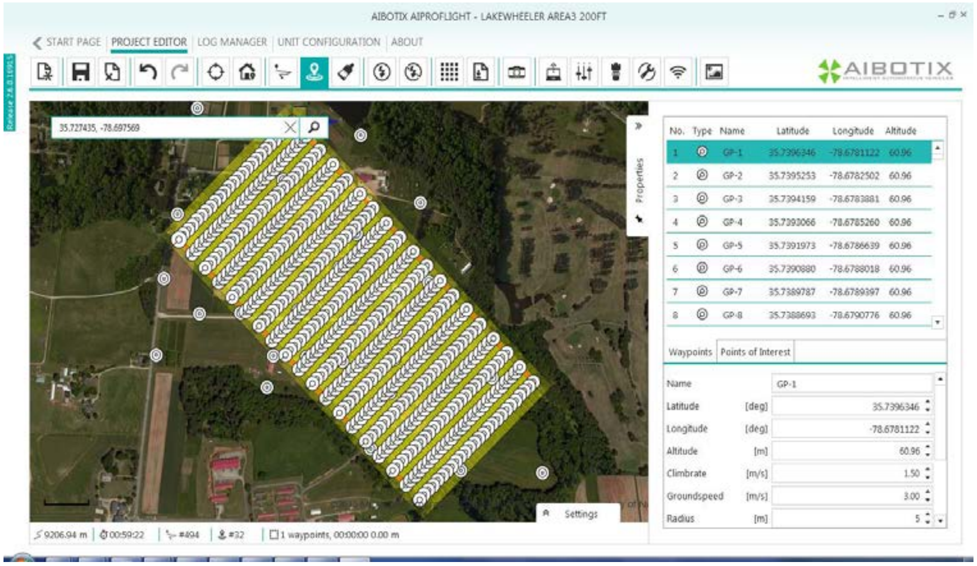

Figure 13: Lake Wheeler FP Elevation 60.96m [200 ft] (70/40% Overlap)

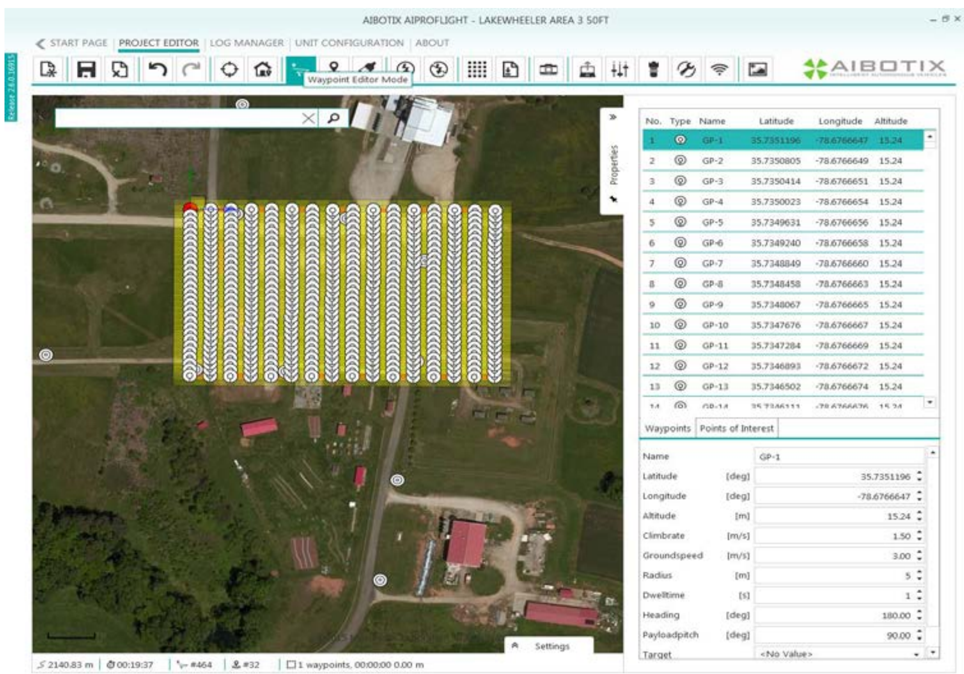

Figure 14: Lake Wheeler FP Altitude 15.24 m [50 ft] (70/40% Overlap)

4.4.2 Kinston Regional Jetport

<u>Test Mission</u>- High Resolution Survey

The Kinston Regional Jetport was intended for the High Accuracy Pavement Elevations Application research flights (Figure 15). NGAT contacted the airport management who was willing to support RP2015-06 by providing access to airport property. The flight profile called for the X6 to fly 20 meters or lower with both nadir and oblique views above the ramp at 80x80 percent overlap (Figure 16) to capture very high resolution imagery of the pavement. The imagery would be used to create a high resolution Digital Elevation Model of the pavement and compare the airborne DEM to data from terrestrial LIDAR measurements. A COA was filed and a Letter of Authorization was signed with the FAA to operate in Kinston Class D airspace. The project was not flown due to reliability concerns of the X6 UAS operating near an active runway. This project could be revisited in the future under the new NGAT Blanket COA to use a different aircraft such as the Trimble ZX5.

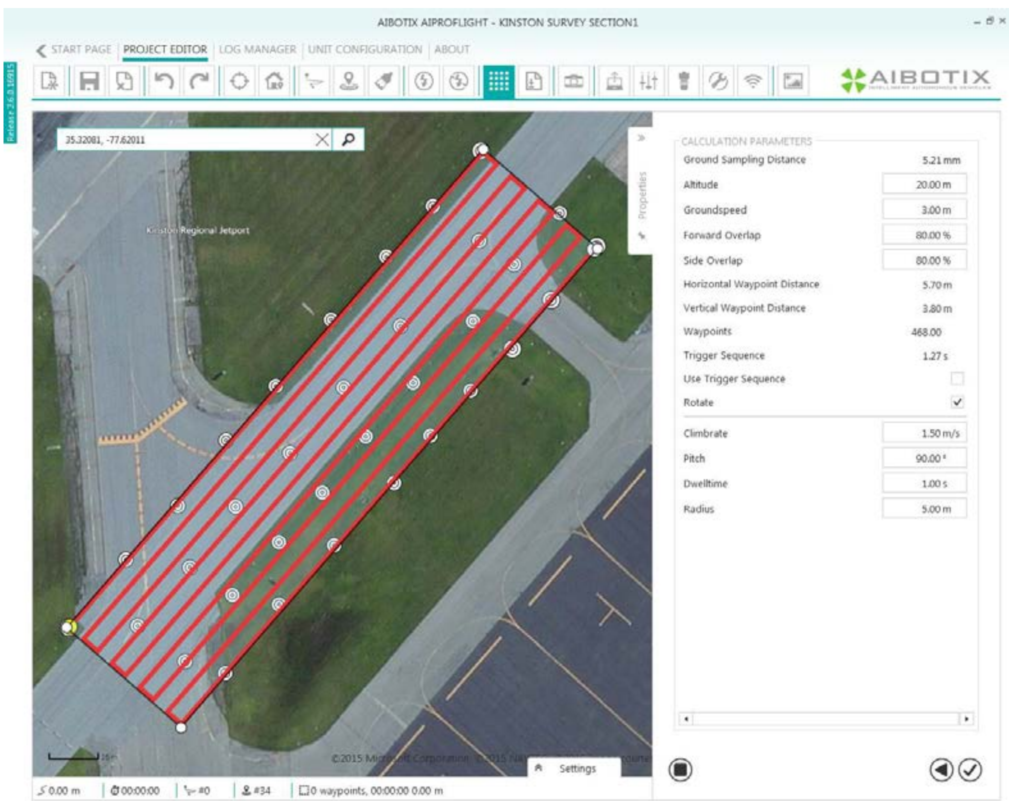

Figure 15: Kinston Area 1 FP Elevation: 20m (Planned)

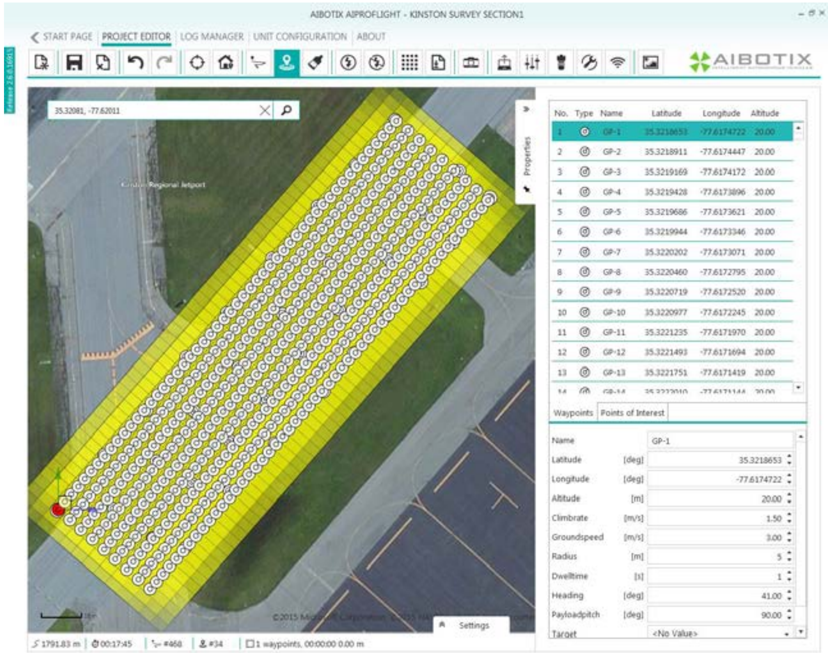

Figure 16: Kinston Area 1 FP Coverage (Planned) (80% Overlap)

4.4.3 Waynesville Construction Project (R-4047)

<u>Test Mission</u>- R-4047 Construction Project Survey

The Waynesville construction project was to be flown with the Aibotix X6 in the fall of 2015. Original flight planning for the X6 showed that the aircraft flight path would fly over major active roads, private property, commercial buildings, and a school. In order to minimize traffic interruptions and overflying private property, the project area was divided into two areas (see Figure 17, Figure 18, and Figure 19). These flights were not flown before the X6 was lost in the accident at Lake Wheeler. NGAT is now able to revisit this kind of project under the Blanket COA and use a different small UAS solution, such as the Trimble ZX5.

Figure 17: R-4047 FP Waynesville Site Boundaries

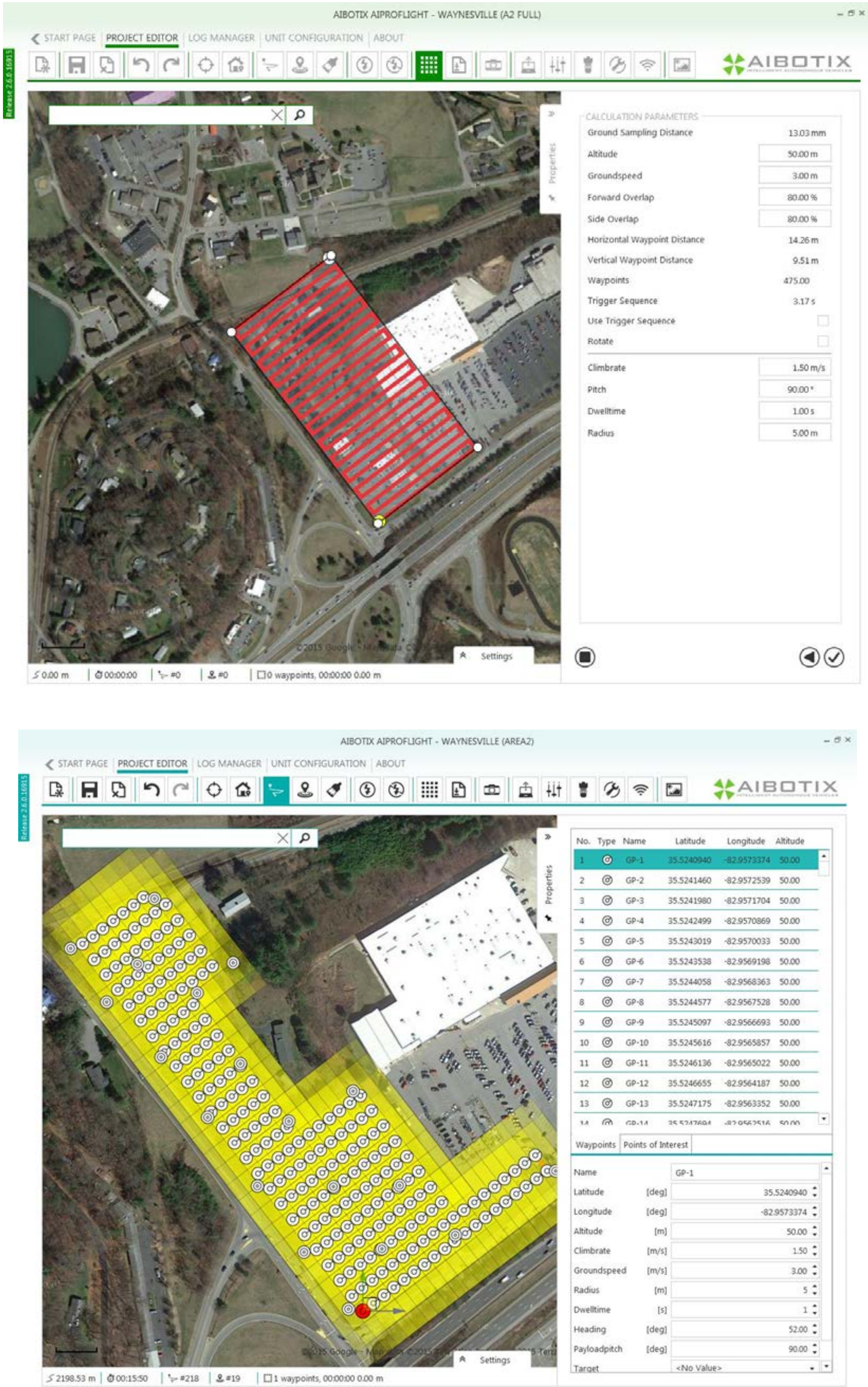

Figure 18: R-4047 FP Area 1 (80% Overlap)

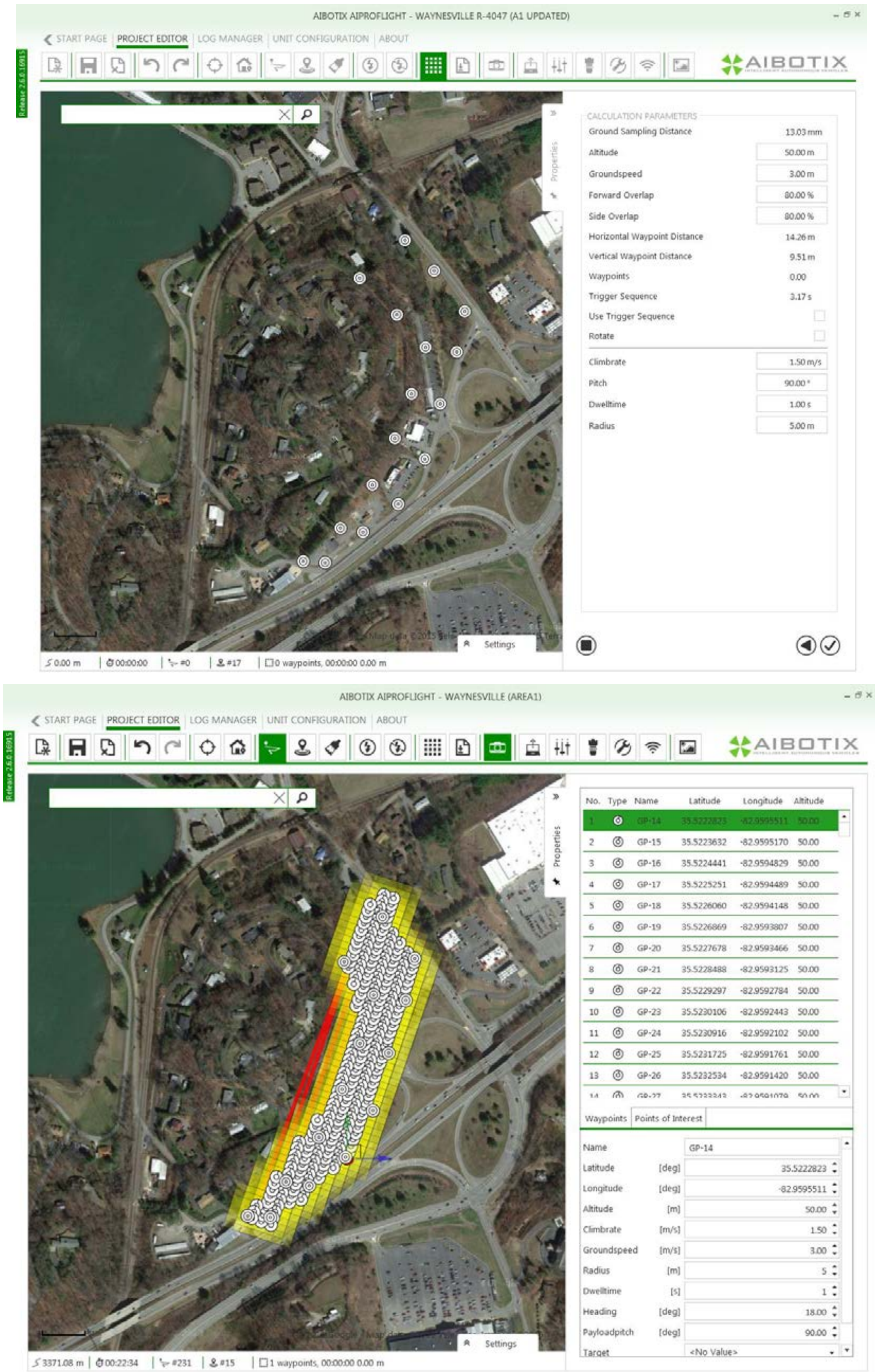

Figure 19: R-4047 FP Area 2 (80% Overlap)

4.4.4 I-40 at MP 6 in Haywood County (I-5508)

Test Mission: Geotechnical Monitoring

The Geotechnical Monitoring Site was located at I-40 MP6 (Figure 20). Winds, terrain, and traffic would have complicated flights at this location. The flights were planned to be completed in less than 10 minutes so that UAS operations would correspond with the construction schedule to minimize the time that a portion of I-40 would have to be closed to traffic. In order to survey the landslide terrain and meet the time restrictions, the aircraft flight altitude was raised to 60.96 m [200 ft] with the sensors pointed perpendicular to the slope of the terrain (45 degrees). The flight plans are shown (Figure 21) for the X6 using the AI-ProFlight planning software and proposed ground control points. These flights were canceled because the blasting was completed before the COA was approved by the FAA.

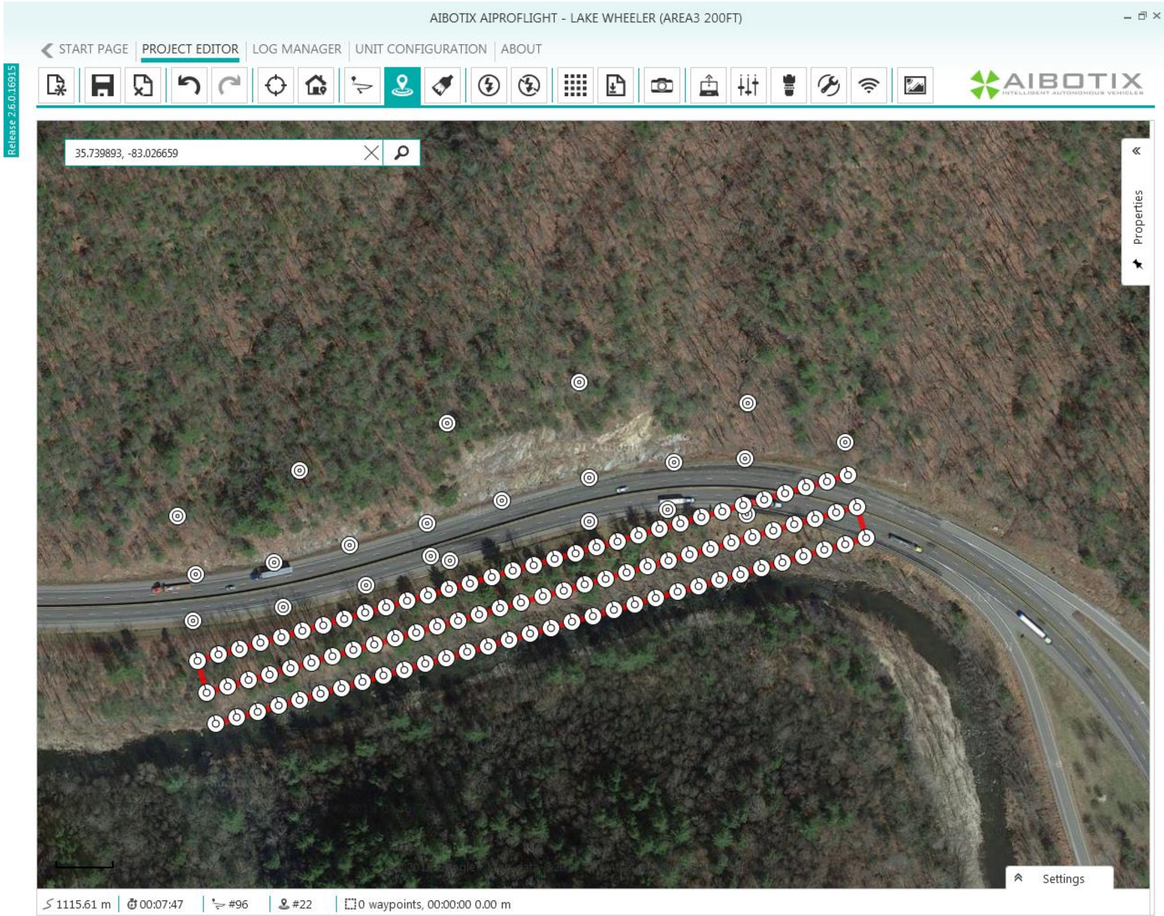

Figure 20: Haywood County Ground Control Points and Flight Plans (Proposed Locations)

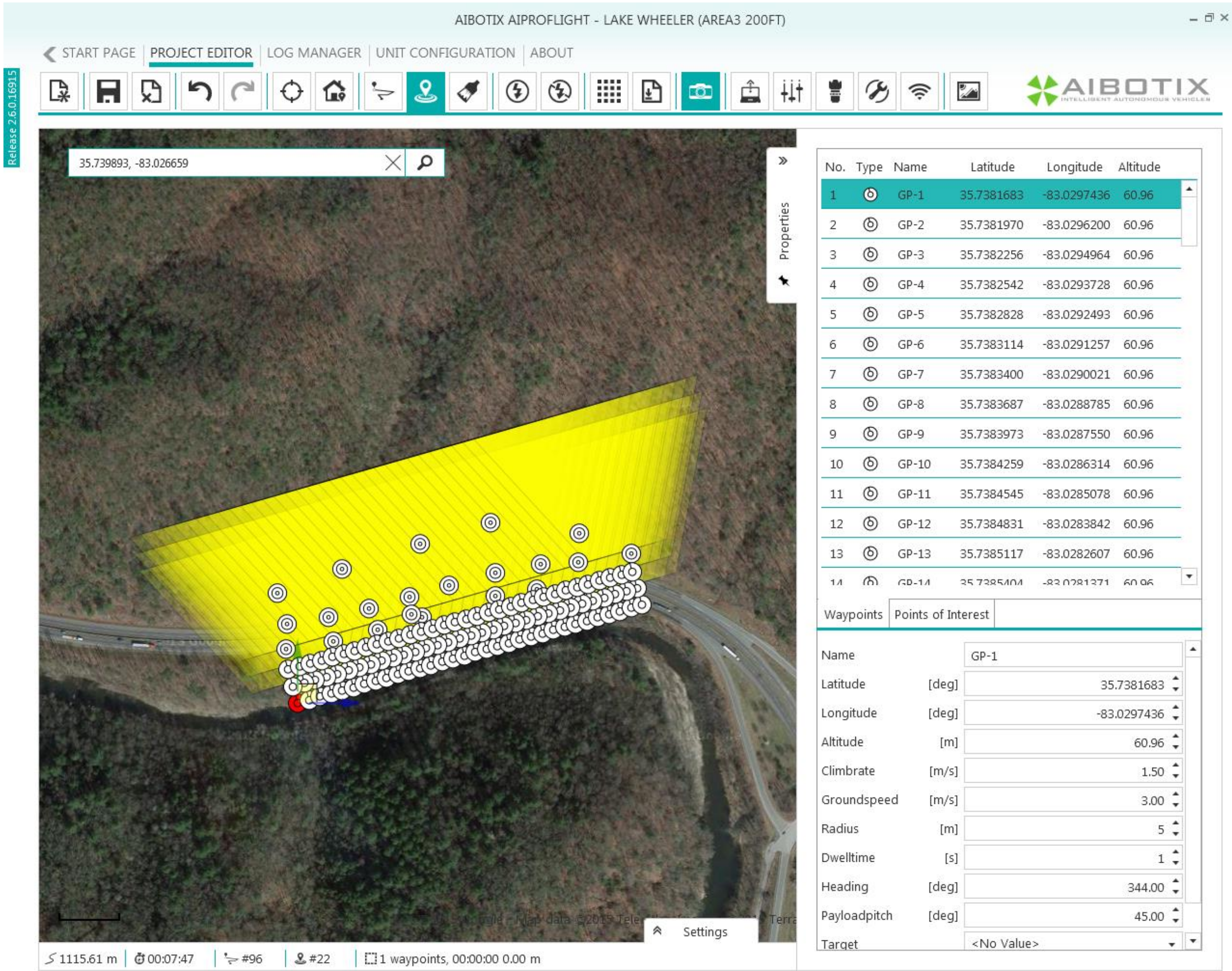

Figure 21: Haywood County Exposure Positions 60.96 m [200ft] AGL (Proposed Locations) (80% Overlap, Sensor Heading 344 Degrees, Pitch 45 Degrees, Aircraft Heading 74 Degrees)

4.4.5 Diverging Diamond Interchange I-40 at Union Cross Road, Kernersville, NC.

<u>Test Mission-</u> Traffic Monitoring

A number of sites were evaluated for monitoring traffic with UAS. None of the five original locations were used because of their proximity to airports (the Concord site) or the lack of suitable launch and recovery areas. Eventually the Diverging Diamond Interchange at I-40 at Union Cross Road at Kernersville, NC (Figure 22) was used for the traffic monitoring test location. The DJI Inspire was selected for the traffic monitoring mission because of the confidence in aircraft performance and the quality of the 4K video product. This mission was flown in May 2016 (Figure 23).

Figure 22: Diverging Diamond Interchange in Kernersville from Google Earth

Figure 23: Diverging Diamond Interchange Image from UAS Video

4.4.6 Gallants Channel Bridge

Test Mission- Bridge Inspection

As with the traffic monitoring sites, safety concerns and aviation regulations restricted the possible locations that could be utilized for bridge inspection testing, including the Henderson County site. The Gallants Channel Bridge (Figure 24) was selected for the testing because it was over water which is considered a major benefit for using a UAS for bridge inspections. Although this bridge is extremely close to an airport, the Duke University flight team had previously secured permission to fly at this location under their 333 Exemption. The NGAT Flight Team worked with the DUML Flight Team to obtain permission and access to the bridge during construction in June of 2016. These flights were very successful with everything operating as expected.

Figure 24: Gallants Channel Bridge with Data Analysis Overlay on Google Earth

4.5 Data Processing

With over 100 flights on the Aibotix X6 aircraft in support of this research project, the majority of the data sets processed and lessons learned during the flight operations are using the Nikon D5200 camera data from X6 flights and Agisoft to process the data. Most of those flights were at the Lake Wheeler SECREF facility using NCDOT installed GCPs and multiple flight plans to evaluate system performance. The research team used data quality, data accuracy, and overlap comparison as the evaluation criteria for assessing UAS performance for capturing aerial imagery.

Figure 25 captures the lifecycle of the UAS imagery from capture on the aircraft through data processing, analysis, and storage (management). NGAT uses this process for most UAS mission data analysis. NCDOT was a participant in each of these processes for this project with field teams supporting the flight operations, data analysts processing the data sets, and the research teams collaborating on results analysis.

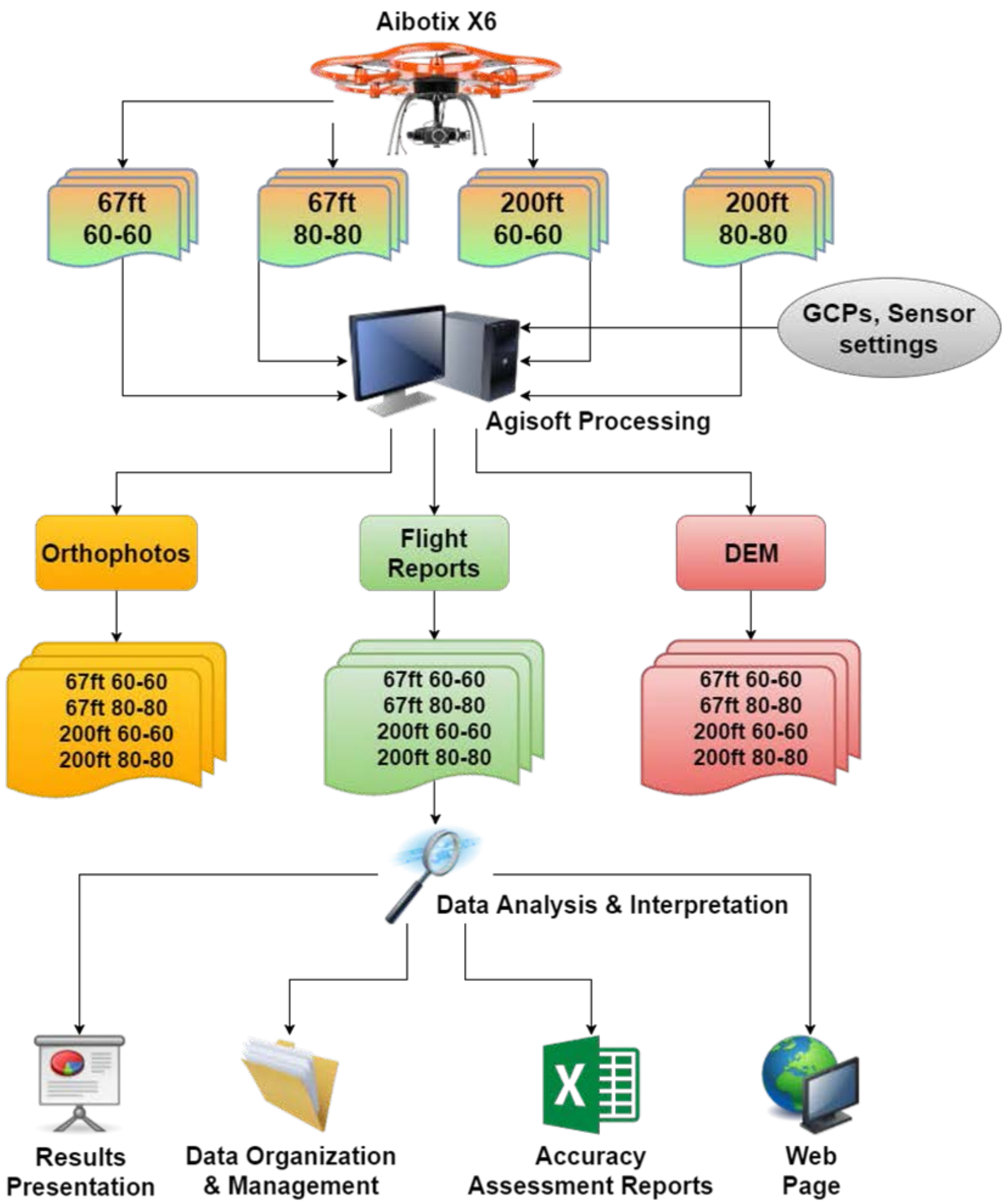

Figure 25: UAS Data Management Lifecycle

4.5.1 Data Quality

Image quality plays an important role when generating orthophotos because it is important to generate high quality final results. Some factors that may affect image quality are the camera, the flight, and GCP pattern, material, and size.

Camera

Camera calibration is the first and most important step to obtain high quality images. The camera's settings are determined based on the flight mission (location, weather, height, and lighting.). These settings consist of ISO settings, the aperture, auto-focus, shutter speed, white balance, image stabilization, image capture time. The main objective is to capture a sharp image with minimum noise.

Flight

Along with flight altitude and the camera model, image blur plays an important role in obtaining high image quality. Image blur is caused by the forward motion of the UAS which can degrade the quality of data. Multicopters can stop to hover as the image is taken eliminating this effect, but this adds time to the flight plan and increases battery drain. Turns and turbulences can also degrade image quality. The blurred images should not be processed using automatic image processing software (Agisoft PhotoScan) because the software can fail to identify control targets or tie points. Manual processing therefore becomes necessary, which is time consuming and prone to error (Sieberth, 2013).

Ground Control Points

After evaluating several different types of GCP markers, we selected a black and white circular target (Figure 26) design that is recommended by Trimble for their UAS and processing software. The markers were printed on a durable glossy paper that was glued to metal or wood panels before distribution (Figure 28).

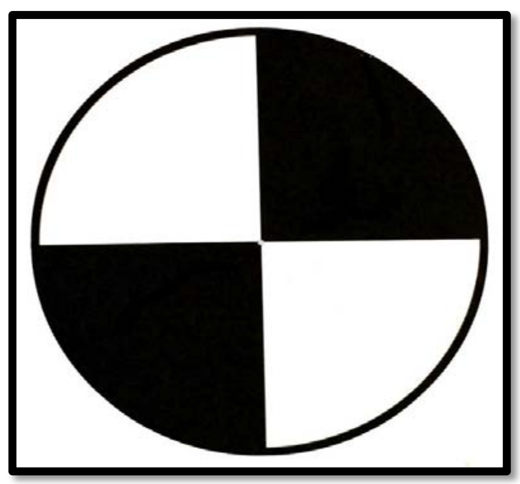

Figure 26: Example of the ground control point used in the project

Figure 27: Example Ground Control Points

Figure 28: GCP from 67 feet flight with GSD 0.589 cm/pixel

The image data quality can be assessed in the Agisoft PhotoScan software after the initial data transfer process. Images with a quality score of less than 0.6 should not be included in the processing. Poor image quality usually occurs at each turn-about and at the end of each leg. Most of the images usually score a quality value between 0.7 and 0.9. Many other factors can affect image quality, some of which come from the environment. Images with poor quality must be removed to eliminate the risk of incorrect alignments and poor orthophoto quality.

Sample project image quality results from the research flights are in the following tables (note: scores higher than 0.7 are the goal) (Figure 29 and Figure 30):

Photos

Label	Size	Aligned	Quality	Date & time
DSC_4130.J...	6000x4000	✓	0.604178	2015:12:06 11:03...
DSC_4131.J...	6000x4000	✓	0.621361	2015:12:06 11:03...
DSC_4132.J...	6000x4000	✓	0.641991	2015:12:06 11:03...
DSC_4133.J...	6000x4000	✓	0.637199	2015:12:06 11:03...
DSC_4134.J...	6000x4000	✓	0.634778	2015:12:06 11:03...
DSC_4135.J...	6000x4000	✓	0.703816	2015:12:06 11:03...
DSC_4136.J...	6000x4000	✓	0.709905	2015:12:06 11:03...
DSC_4137.J...	6000x4000	✓	0.567779	2015:12:06 11:04...
DSC_4138.J...	6000x4000	✓	0.579118	2015:12:06 11:04...
DSC_4139.J...	6000x4000	✓	0.548666	2015:12:06 11:04...
DSC_4140.J...	6000x4000	✓	0.555404	2015:12:06 11:04...
DSC_4141.J...	6000x4000	✓	0.514738	2015:12:06 11:04...
DSC_4142.J...	6000x4000	✓	0.677844	2015:12:06 11:04...
DSC_4143.J...	6000x4000	✓	0.752931	2015:12:06 11:04...

Figure 29: Image quality results for 67 feet flight, 60-60 overlap

Photos

Label	Size	Aligned	Quality	Date & time
01_01-DSC_...	6000x4000	✓	0.618748	2015:12:08 12:18...
01_02-DSC_...	6000x4000	✓	0.63345	2015:12:08 12:18...
01_03-DSC_...	6000x4000	✓	0.609561	2015:12:08 12:18...
01_04-DSC_...	6000x4000	✓	0.598487	2015:12:08 12:18...
01_05-DSC_...	6000x4000	✓	0.577227	2015:12:08 12:18...
01_06-DSC_...	6000x4000	✓	0.634174	2015:12:08 12:19...
01_07-DSC_...	6000x4000	✓	0.598173	2015:12:08 12:19...
01_08-DSC_...	6000x4000	✓	0.586579	2015:12:08 12:19...
01_09-DSC_...	6000x4000	✓	0.564015	2015:12:08 12:19...
01_10-DSC_...	6000x4000	✓	0.575118	2015:12:08 12:19...
01_11-DSC_...	6000x4000	✓	0.546493	2015:12:08 12:19...
01_12-DSC_...	6000x4000	✓	0.611096	2015:12:08 12:19...
01_13-DSC_...	6000x4000	✓	0.716018	2015:12:08 12:19...
01_14-DSC_...	6000x4000	✓	0.786883	2015:12:08 12:19...
01_15-DSC_...	6000x4000	✓	0.719638	2015:12:08 12:19...
01_16-DSC_...	6000x4000	✓	0.657712	2015:12:08 12:20...
02_01-DSC_...	6000x4000	✓	0.623939	2015:12:08 12:22...
02_02-DSC_...	6000x4000	✓	0.629458	2015:12:08 12:22...
02_03-DSC_...	6000x4000	✓	0.57131	2015:12:08 12:22...

Figure 30: Image quality results for 200 feet flight, 60-60 overlap

4.5.2 Data Accuracy

The NGAT team used two aircraft at the Lake Wheeler facility for testing data accuracy for high resolution surveying and mapping applications. The X6 UAS was flown over the Lake Wheeler area of interest (AOI) with an 80% front – 80% side overlap and 60% front-60% side overlap, using 33 ground markers as GCPs. The ground markers were specifically positioned to assess accuracy objectives (Figure 31).

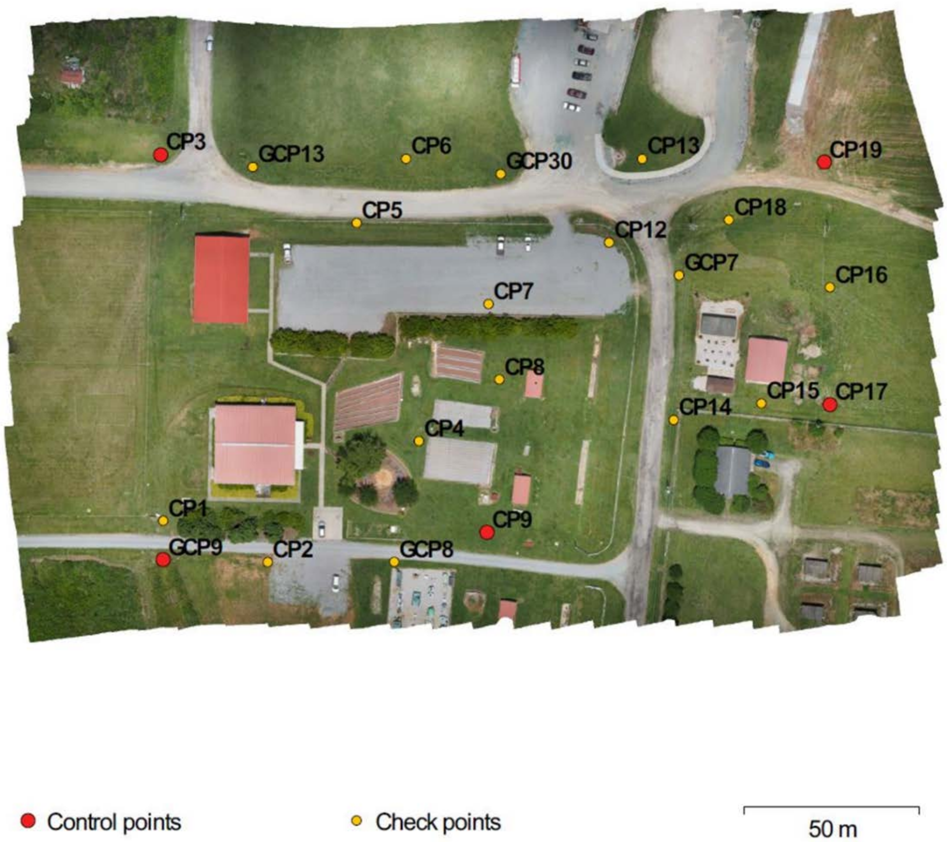

Figure 31: GCP Positions for Accuracy Analysis

The X6 data analysis did not meet NCDOT expectations for aerial imaging accuracy. The NGAT team then gained access to the Trimble ZX5 multirotor system for evaluation at Lake Wheeler. Although the data set for comparison is smaller, the data accuracy is much higher and closer to what NCDOT considers acceptable.

The following table (Table 5) provides an analysis of a ZX5 data set for evaluating data accuracy across multiple criteria, including Root Mean Square Error (RMSE) and number of GCPs used for assessing confidence. Based on this analysis and the flight operations experience with the ZX5, further analysis and testing is recommended for developing UAS surveying requirements.

Table 5: ZX5 Data Accuracy Analysis

5 Control Points							
Control Point Statistics		X error (ft)	Y error (ft)	Z error (ft)	Error (ft)	Projections	Error (pix)
No. Points =		5	5	5	5	5	5
Min (ft) =		-0.16	-0.06	-0.22	0.00	0.00	0.00
Max (ft) =		0.00	0.02	0.14	0.27	24.00	0.15
Mean (ft) =		-0.02	0.00	0.00	0.04	2.96	0.02
Std Dev (ft) =		0.05	0.02	0.06	0.07	6.48	0.05
RMSE (ft) =		0.05	0.02	0.06	0.08	7.00	0.05
FVA (ft) =				0.12			
RMSE R (ft) =	0.05						
Case 1 95% CE(ft) =	0.09						
Case 2 ~ CE(ft) =	0.08						

17 Check Points							
Control Point Statistics		X error (ft)	Y error (ft)	Z error (ft)	Error (ft)	Projections	Error (pix)
No. Points =		17	17	17	17	17	17
Min (ft) =		-0.13	-0.10	-0.16	0.00	0.00	0.00
Max (ft) =		0.05	0.03	0.14	0.18	14.00	0.37
Mean (ft) =		-0.06	-0.02	0.00	0.09	7.75	0.11
Std Dev (ft) =		0.05	0.03	0.07	0.07	5.38	0.10
RMSE (ft) =		0.08	0.04	0.07	0.11	9.37	0.15
FVA (ft) =				0.14			
RMSE R (ft) =	0.09						
Case 1 95% CE(ft) =	0.15						
Case 2 ~ CE(ft) =	0.14						

4.6 Results

The research team collected a large number of data sets for evaluating UAS as a DOT tool with over 100 flights using multiple aircraft across a wide range of applications. These data sets include orthophotos, DEMs, videos, and flight logs. This data has been shared with NCDOT and will remain in the NGAT data repository. In general, the Leica X6 system did not meet expectations for data products, flight operations performance, or reliability. Other systems tested produced better data sets, performed with higher operational confidence, and demonstrate a continued maturation of the technology.

4.6.1 Orthophotos and DEMs

Orthophotos are photographic images constructed from vertical or near-vertical aerial imagery. The processes used to generate orthophotos remove the effects of terrain relief displacement and tilt of the aircraft. When properly generated, the digital images have a predictable constant positional accuracy throughout the entire image.

Design parameters for an orthophoto are generally defined by the expected final imagery accuracy requirements. Suitable imagery and ground control points are the basic elements that determine the final orthophoto reliability. This reliability is determined by the accuracy distances and areas within the final orthophoto as well as the relative accuracy of features with respect to their true location on the earth. Distance and area accuracy are based on the pixel size.

In this project, generating accurate orthophotos was crucial for NCDOT because they are used for transportation facility planning and design. The data analysis team generated eight orthophotos (examples include Figure 32 and Figure 33) from the X6 test data sets, with and without GCPs using Agisoft PhotoScan, to evaluate if more GCPs would improve the overall accuracy of the orthophoto. **The conclusion is that more GCPs were not necessary.**

Figure 32: Orthophoto at Lake Wheeler at 67', 60-60 Overlap

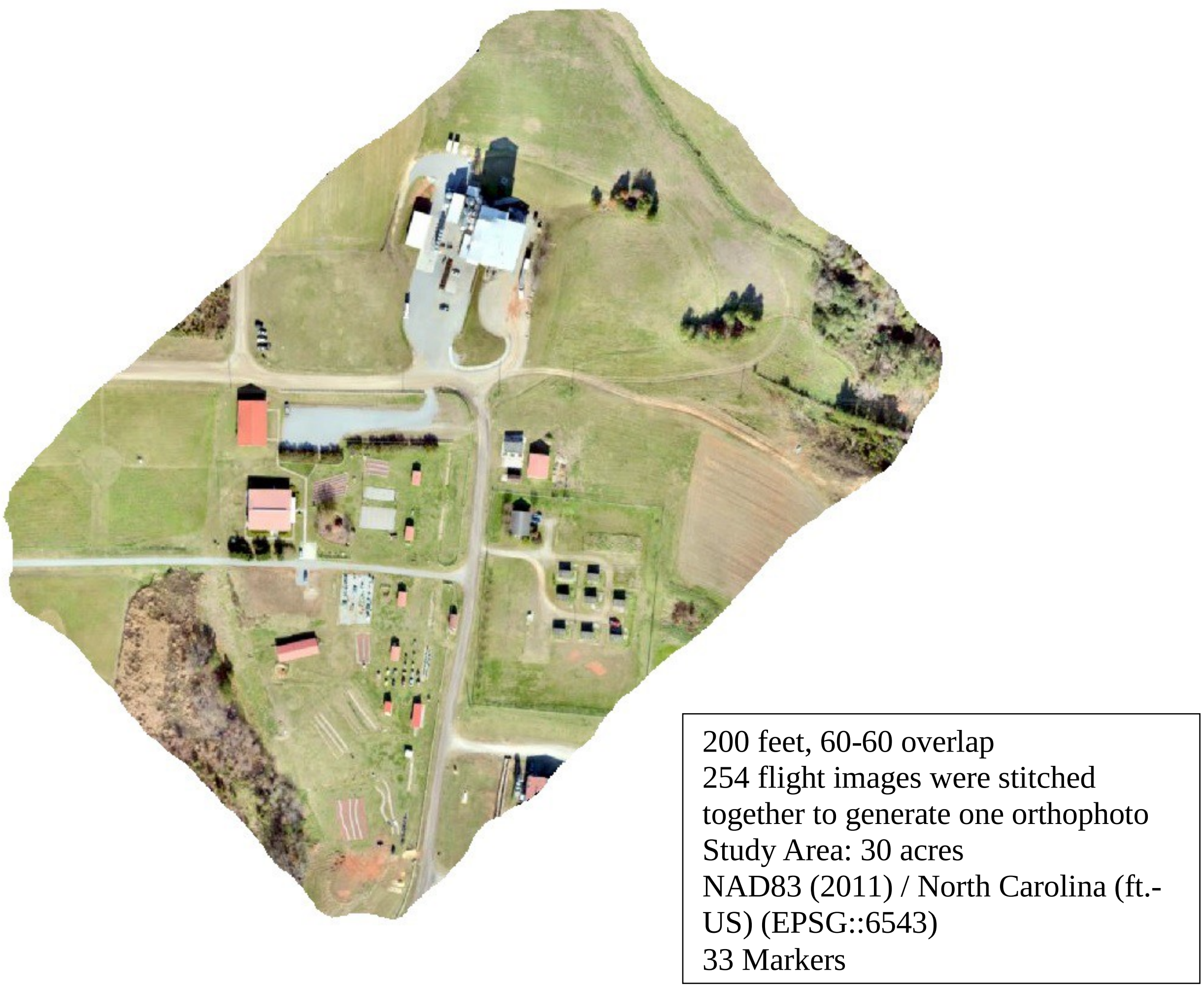

Figure 33: Orthophoto at Lake Wheeler at 200', 60-60 Overlap

Digital Elevation Models (DEM) are continuous 3D representations of a terrain surface area that has been geometrically corrected, so it can be used to measure distances and heights. DEMs are widely used for topographic maps and are based on a grid file that derives topographic contours, in addition to calculating slope and aspect. The two types of DEMs are:

- Digital Surface Model (DSM): 3D representation of all elements in the area.
- Digital Terrain Model (DTM): 3D representation of the terrain base surface without vegetation and artificial objects.

Agisoft PhotoScan and Trimble Business Center generate DSM from the still imagery collected by a UAS. The advantage of using a UAS to create a DSM is that it is quicker than traditional ground based methods; this is particularly true as areas get larger than 10 acres. A DTM will require more processing time to remove vegetation and other artifacts. Spatial resolution and accuracy are approximately twice the resolution of the images used to create the DSM. Figure 34 and Figure 35 demonstrate the DEM resolution from the typical X6 flight altitudes at Lake Wheeler.

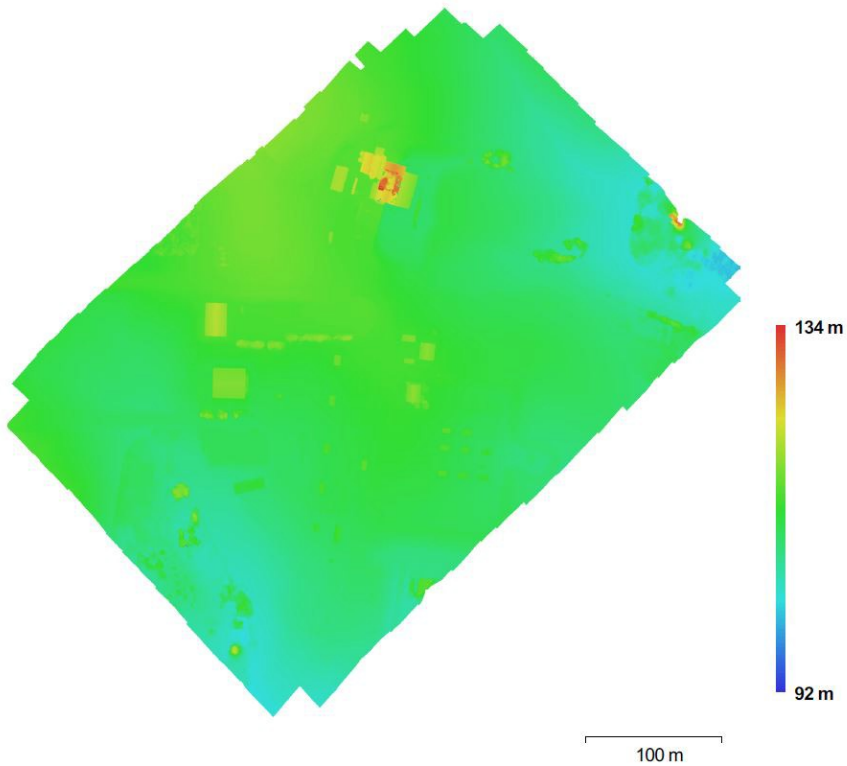

Figure 34: DEM from 200’ flight, 60-60 overlap

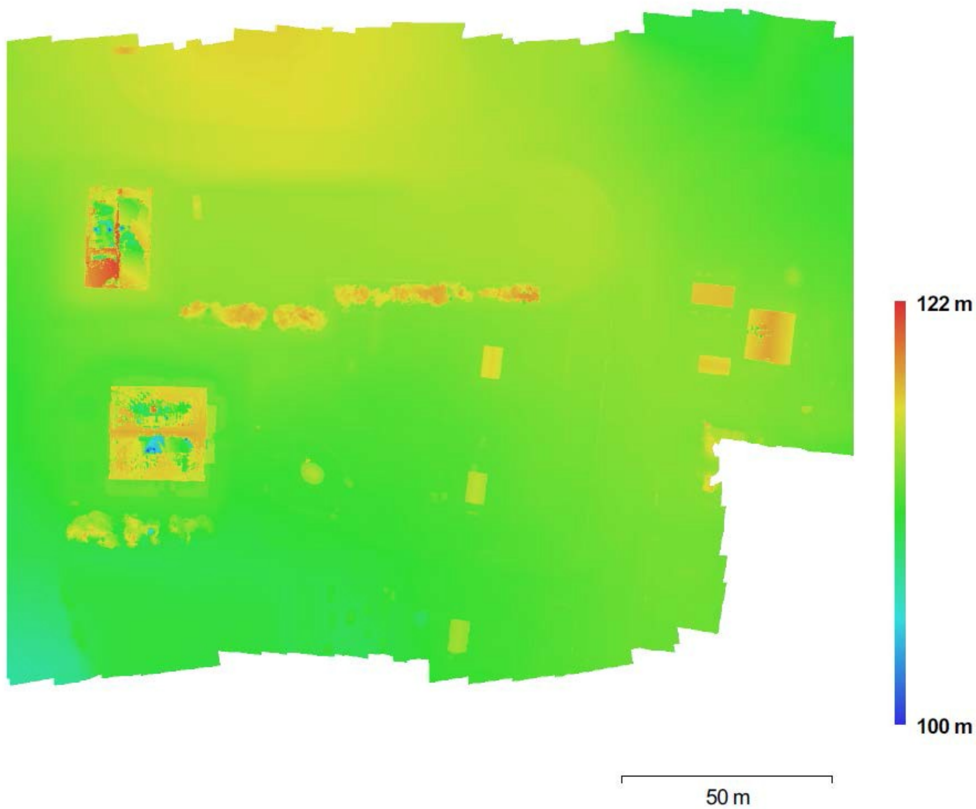

Figure 35: DEM from 67' flight, 60-60 Overlap

The imagery collected from the X6 UAS was not as accurate as imagery collected with traditional airborne sensors. The lack of a stabilizing camera mount, the "confusion" of the onboard GPS when flying low and slow for high resolution, overlapping images, and the very short battery life on the X6 results in the conclusion that the product is a non-viable option for frame imaging and photogrammetric processing of typical NCDOT small survey areas. The orthophotos and the DEMs produced with the X6 data do not meet NCDOT Photogrammetry requirements. The imagery could be used to supplement traditional surveys for applications that do not require the highest degree of accuracy, such as earthworks projects and volumetric analyzes.

The Trimble ZX5 platform produced much more reliable results and met flight operations expectations, thereby providing confidence in the potential value for UAS integration.

Figure 36: Lake Wheeler Ortho From ZX5

Figure 37: ZX5 Image Detail of 167' Tall Building (Camera Shutter at 1/1000)

The ZX5 comparison data was captured in 238 images flown in 9 flight lines using the same GCPs used for the X6 data capture (Figure 38).

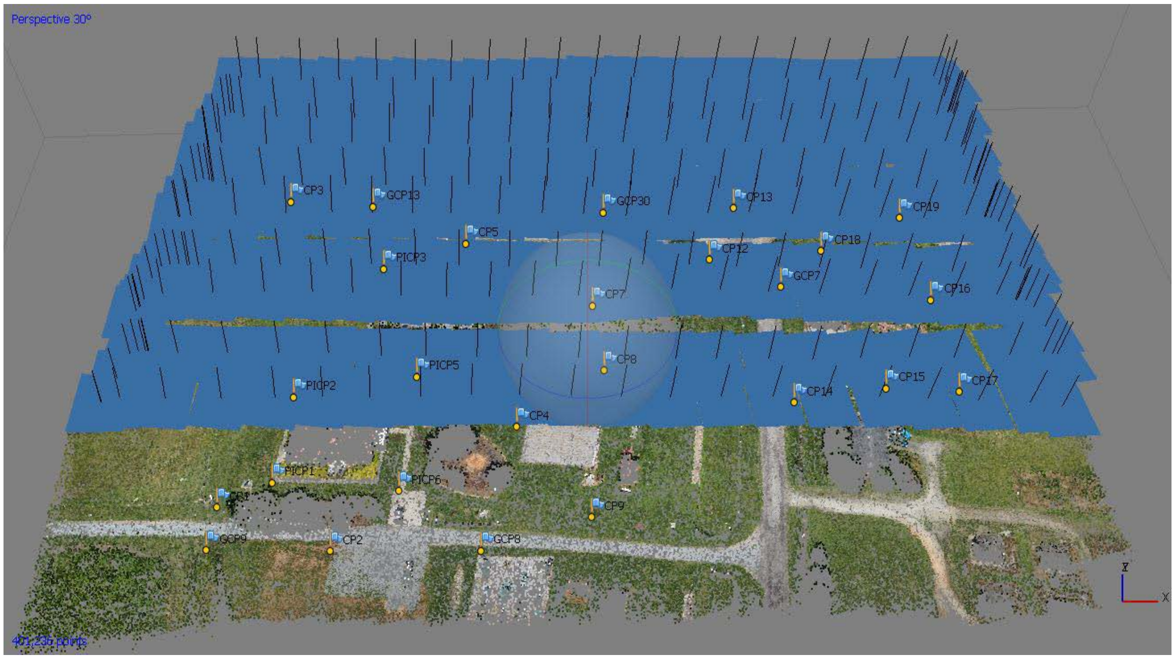

Figure 38: ZX5 Data Capture

The Agisoft algorithm to automatically identify markers did not consistently locate the GCP markers. The GCP markers were identified manually which increased processing time. The image estimation quality score application in Photoscan allowed the research team to statistically understand the value of the acquired data and if it would produce high resolution stitched images. Although the compiled image resolution was not consistent across data sets, using Agisoft provided a common tool for comparing data sets between NCDOT and the NGAT research team.

4.6.2 Video Imagery

Video imagery was collected for the traffic monitoring and bridge inspection applications. Typically, video imagery can be viewed in real time though the GCS; both the X6 and Inspire have the capability to transmit the video on another display. The video can also be saved for later viewing. The 4K video imagery collected was found to be suitable for each application however, the large files can create data management issue. A 10 minute 4K video is approximately 4.5GB.

Bridge Inspection

Unmanned aircraft have demonstrated benefits to bridge inspectors assessing the condition of bridges, in particularly hard to reach locations such as the underside of the bridge decks or overwater structures. While much of the mandated testing required by the National Bridge Inspection Standards (NBIS) requires hands-on inspections, UAS can be used in situations that do not require hands-on test or for initial situational scans to help inspectors prioritize. Both the Minnesota and Florida Department of Transportation have conducted studies that conclude that UAS can aid bridge inspections.

The research team looked at two areas that UAS technology would aid NCDOT bridge inspections: thermal imagery scans and long, overwater structures. A Michigan Technological University study shows thermal imagery can be used to detect delamination in areas that are not visible to RGB (visible) imagery. The thermal camera is able to detect delamination because of the differential heating that existed on the bridge deck. To test this, we went to two bridges that NCDOT identified as having bridge deck delamination. A hand-held FLIR E4 and a FLIR Tau 640X480 sensor mounted on a UAS was used for data collection. For this test, the UAS was mounted on a 20' pole to simulate flight, because the bridge locations were over a highway that prohibited standard flight operations. First, we tested the FLIR E4 which has a thermal detector and a RGB camera to make sure the thermal image would detect bridge delamination (Figure 39).

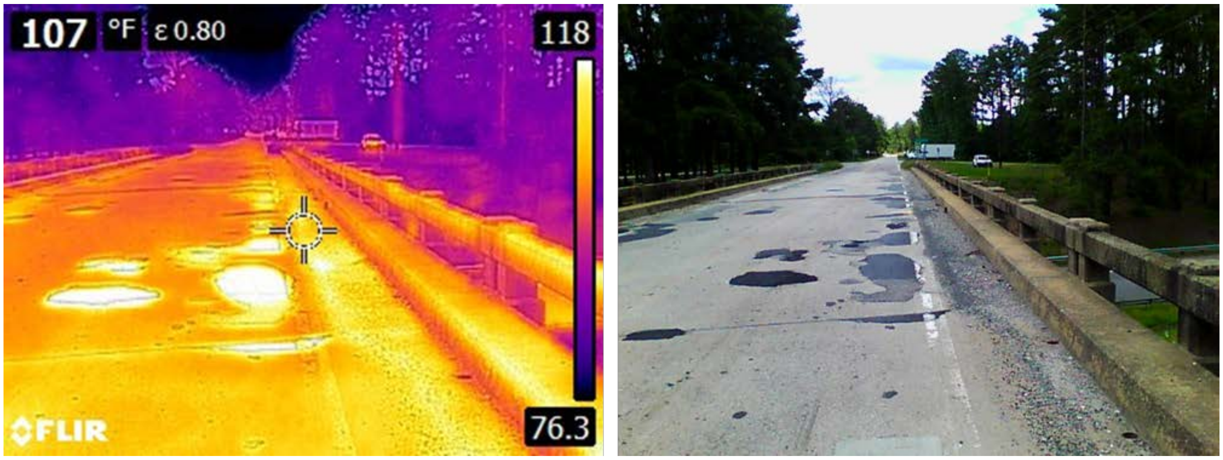

Figure 39: Example 1 of Known Damage, Left E4 thermal, Right E4 RGB image.

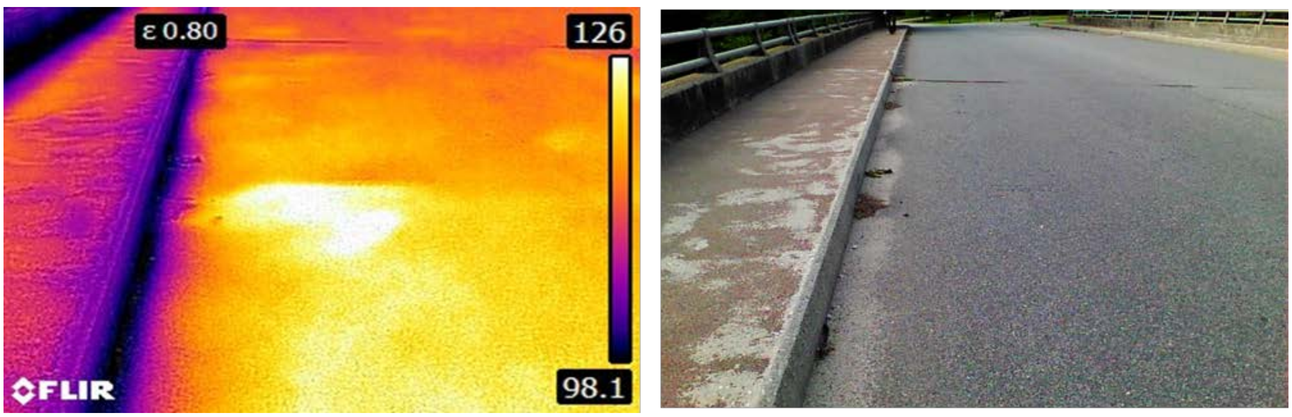

Figure 40: Example 2 of Unknown Damage, Left E4 Thermal and Right E4 RGB Image

The tests indicated that the thermal imagery could detect areas of bridge delamination that were not visible in the RGB imagery, as seen in Figure 40. Next we used the UAS surrogate to determine whether or not we could produce the same result with a low flying UAS, (Figure 41).

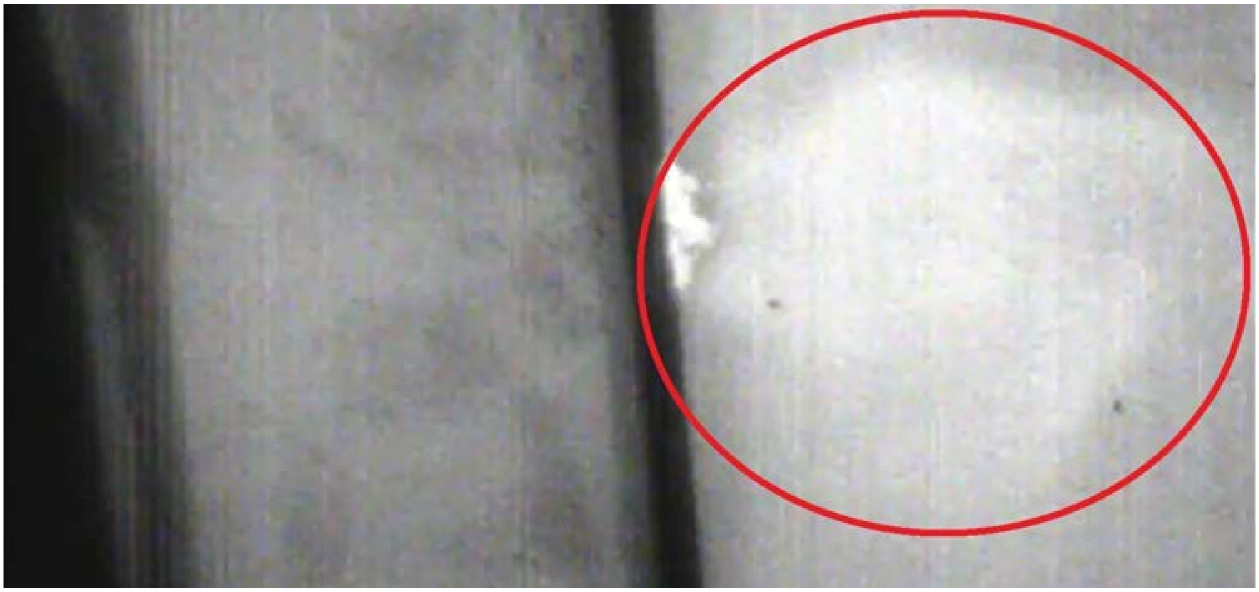

Figure 41: Vireo thermal image of possible delamination on Melbourne Rd.

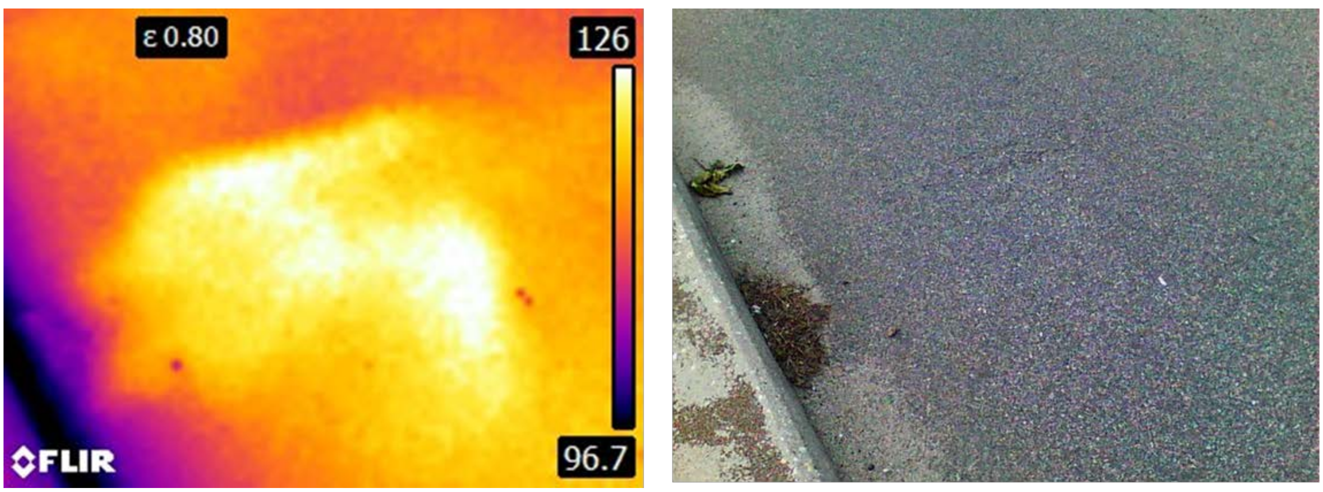

Figure 42: Left E4 thermal, Right E4 visible of the same location on Melbourne Rd.

- Thermal imagery is able to identify spots in which there was preexisting damage to the road in both the thermal and visual images (Figure 42).
- Additionally, hot spots that appeared visually undamaged but were extremely noticeable on the thermal imager were identified in several locations.

Thermal cameras are relatively expensive. For example, the handheld FLIR E4 and the UAS FLIR each costs nearly $10,000. Considering the cost of a UAS in addition to the sensor, the handheld FLIR could be more practical because permission to fly a UAS in congested areas over non-participants could be difficult to obtain or may not meet the department's flight safety risk analysis during mission planning.

Bridge Inspection – Overwater

North Carolina has many long over water bridges which create safety and logistic issues for bridge inspectors. The current practices of a bridge inspector using a lift, which requires lane closures, or boats to inspect under the bridges are costly in terms of time, manpower, safety, and disruption to the traffic flow. The Gallants Channel Bridge which is under construction near Beaufort, NC was chosen to test the ability of UAS to safely operate around a bridge in a marine environment.

To complete the bridge inspection mission, three different multicopters were selected: the Cinestar (for oblique data), Mikrocopter Hex (for nadir imagery), and the DJI Inspire (for FLIR and underflights). While the bridge structure did create turbulence, the UAS autopilots were able to maintain flight stability. The research team found the UAS would lose GPS signal about a third of the way as it passed under the large structure (Figure 43). This loss of GPS required the pilot to take manual command of the UAS for navigation. It is recommended that any UAS operations around bridges be performed by a trained pilot with proven manual control experience.

Figure 43: Underside of the Bridge Deck

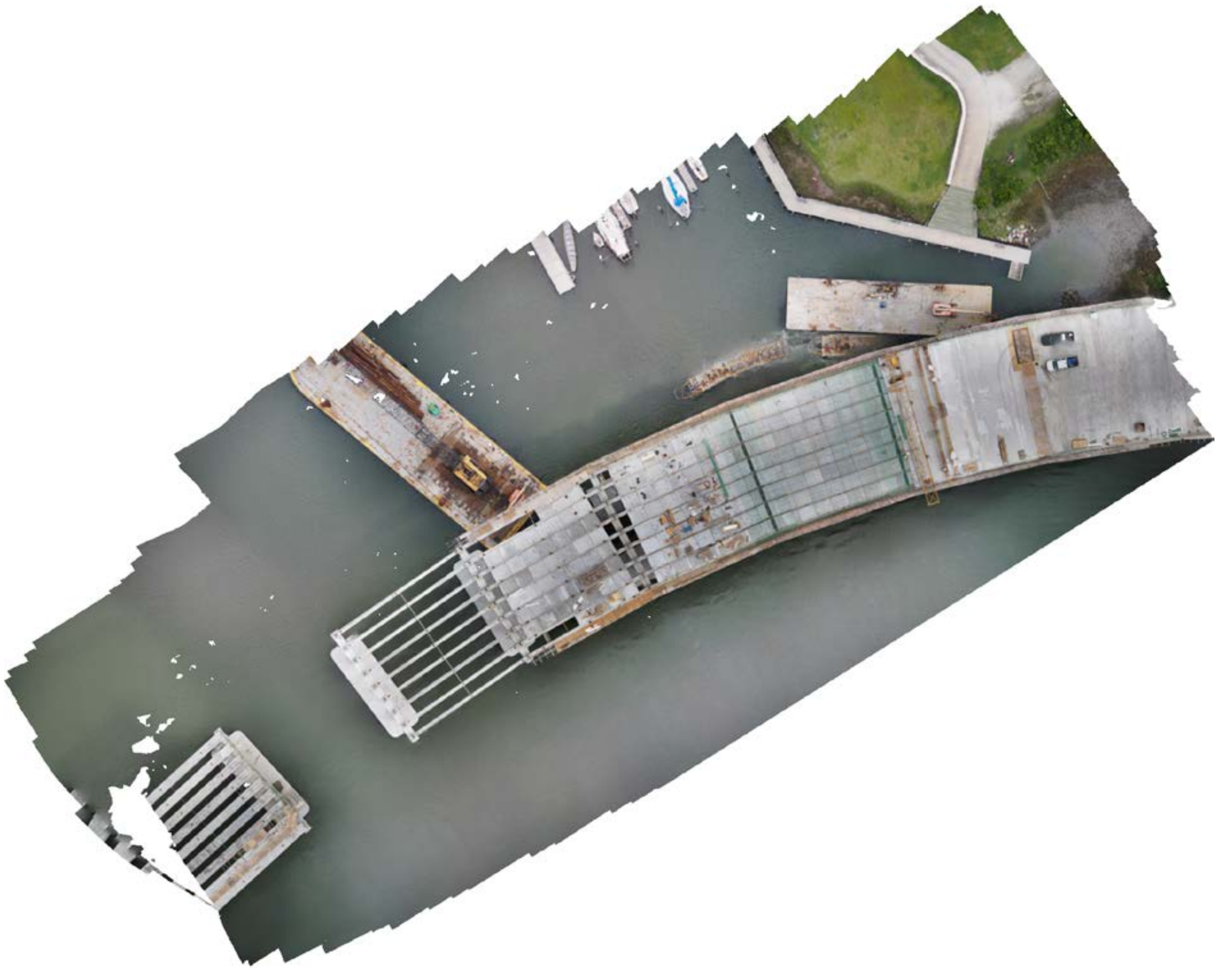

Figure 44: Orthomosaic of the Gallants Channel Bridge

3D Modeling

UAS imagery can be used to create 3D models of structures because the position and orientation of the camera are known. This technology could prove useful for 3D rendering of objects such bridges, and other earthwork projects using a UAS. 3D models of these objects would allow the extractions of mass, volume, and weight and can be used for public meetings or engineer collaborations. Using the imagery from the Gallants Channel Bridge, the North Carolina State University Center for Geospatial Analytics attempted to reconstruct a partial model of the bridge (Figure 44). The results show that creating 3D models of bridges is possible, but a lot of post-processing is necessary before the model is acceptable (Figure 45 and Figure 46).

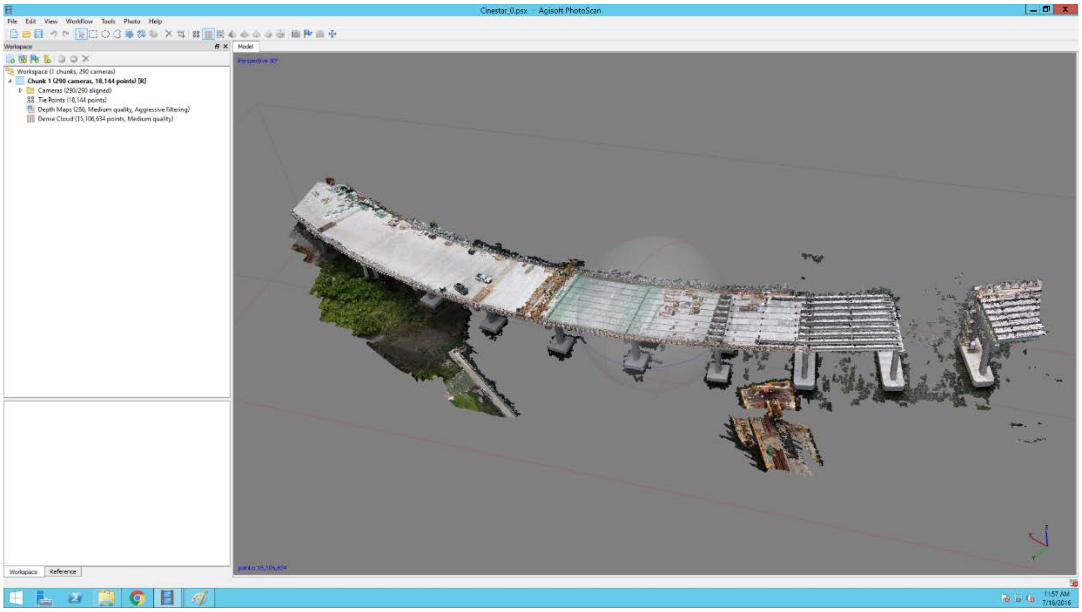

Figure 45: Gallants Channel 3D model 1

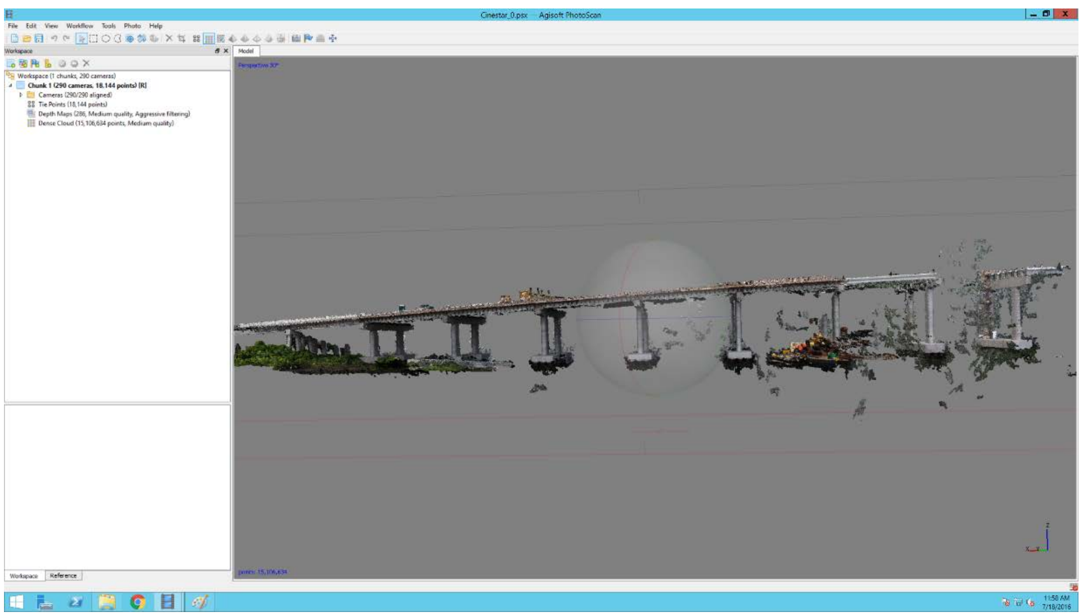

Figure 46: Gallants Channel 3D model 2

Small UAS can be useful tools for bridge inspection processes that do not require the inspector to use hands-on inspection techniques by providing digital imagery data that can be repeated as needed. Imagery can be used to alert and focus an inspector's attention or provide a historical reference for condition monitoring. A UAS used for bridge inspections should have a camera that has an unobstructed upward view for inspecting the underside of the bridge. A separate view screen for the bridge inspectors to view the data in real time is also recommended for routine inspection.

Traffic Monitoring

A final test case was designed to investigate the feasibility of using video obtained from UAS to monitor traffic behavior in regions of interest. This case evaluated whether a portable and accurate monitoring system could allow analysts to selectively monitor specific areas without creating permanent recording installations.

Aerial footage was obtained by flying a DJI Inspire 1 equipped with a 4K video camera. The initial test flights were made near Lake Wheeler Road in Raleigh and were authorized and covered by an FAA Section 333 Exemption. In an attempt to mimic settings similar to those at the diverging diamond at the intersection of I-40 and Union Cross, the flights were made at an altitude of 200 feet and approximately 400 feet horizontally from the road.

This test case was analyzed using live vehicle detection, tracking, and counting using algorithms based on OpenCV. This process can run on a live video feed and theoretically produce live results. However, most of these programs were open source and primarily intended to use on Linux operating systems with little-to-no graphical user interface or professional level development. To move these open source programs to a deployable state would require a significant amount of development. While Traffic Vision does have a commercial software package that could provide live and accurate results with the correct UAS video downlink equipment, the detection settings cannot be modified by the end user and must be done by the Traffic Vision team. Traffic Vision currently does not support video taken from UAS, but they are working to provide this service in the future.

With a focus on post processing aerial footage, OpenCV was developed to the point of compiling and running SimpleVehicleCounter. This program was able to detect vehicles and track them with moderate accuracy, but there was no way to obtain data from the program such as travel time, free flow speed, queue counts, and stop counts. Since this is the type of data needed, other approaches were explored. ITRE's Highways Systems Group uses Autoscope developed by Image Sensing Systems to process video taken from both deployable and stationary traffic cameras. Due to the high resolution of the raw video (4096x2160) and the low resolution required by

Autoscope (720x480), the wide angle image was cropped to optimize the view for processing. Furthermore, this software requires a composite analog video feed, so the cropped videos were burnt to DVD-r's and played with a standard DVD player to the processing units. This process is redundant as it requires converting from digital to analog and then back again (Figure 47), so it is necessary to develop a more streamlined workflow. A possible solution is to use something similar to a VGA to Composite Converter which would allow the video to be played directly from the computer to the processing unit. However, as found by ITRE's Highways Safety Group, the analog output from these devices has been proven to lack the quality needed by Autoscope, so a more robust system would be required.

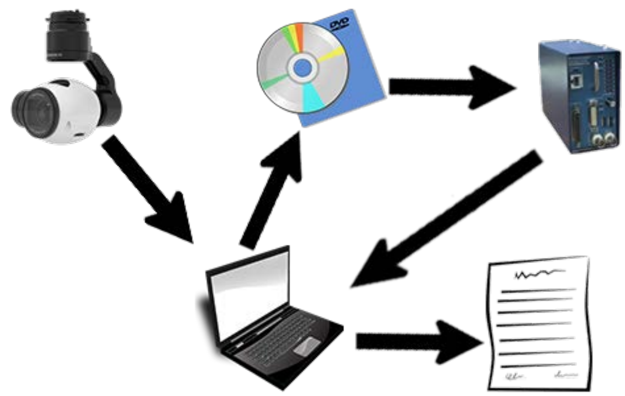

Figure 47: Video Capture Workflow Process

A nine-minute segment of video was analyzed for thru traffic and turns (Figure 48). ITRE staff used Autoscope to place detectors that counted the number of right moving and left moving vehicles, as well as vehicles turning onto Inwood Road (Figure 49). The number of cars in each category was manually counted for comparison. These results are summarized in Table 6. For thru traffic, the left moving and right moving vehicles undercounted by 2.87% and 6.00% respectively. Unfortunately, only one vehicle turned onto Inwood from either direction of Lake Wheeler during the recording, but each was counted and there were no false positives.

Figure 48: Frame from original video showing Lake Wheeler Rd and Inwood Rd

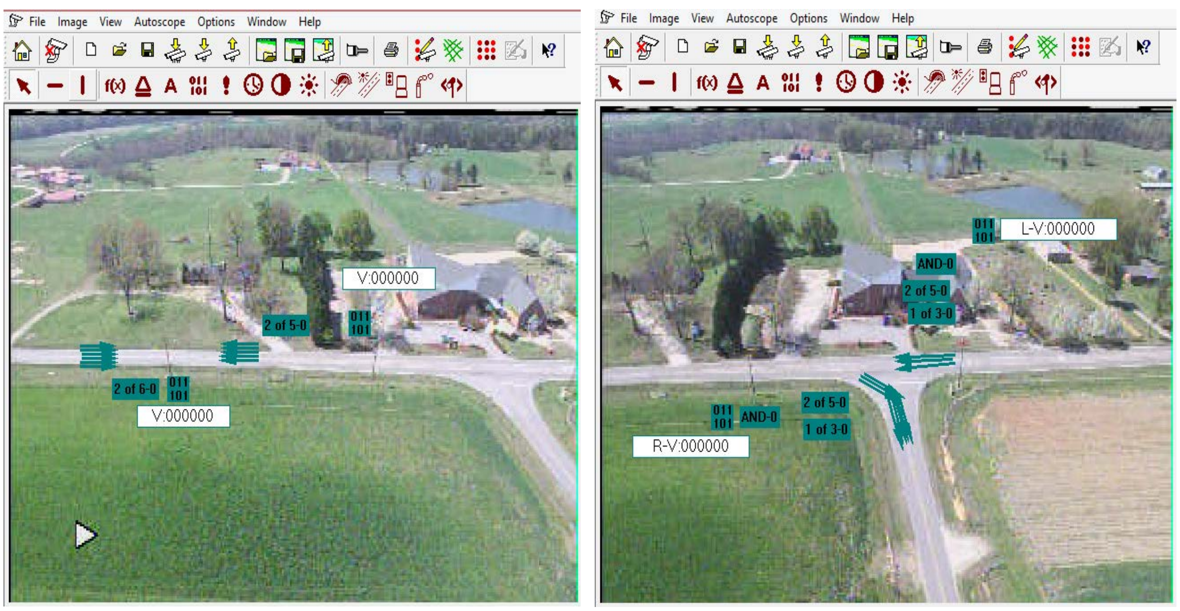

Figure 49: AutoScope thru (left) and turning (right) detectors

Table 6: Summary of Traffic Monitoring Results from Flight at Lake Wheeler

Date:	4/20/16
Manual count:	
Thru Traffic on Lake Wheeler	
Left	58
Right	50
Turns onto Inwood	
Off Right	1
Off Left	1

AutoScope Results:

Direction:	**Average:**	**% Difference:**
Left	56.33	-2.87%
Right	47	-6.00%

Turns onto Inwood:	**Average:**	**% Difference:**
Off Right	1	0.00%
Off Left	1	0.00%

Overall these results are promising, but it would be necessary to repeat this experiment on a larger scale for more conclusive results. A limiting factor of scaling this test is the flight times of multirotors. The DJI Inspire 1 has an average flight time of 20 minutes, so it is impossible to monitor an area of interest for multiple hours uninterrupted. Multiple UAS could be used in succession, but there would be overlaps or gaps in the coverage. The accuracy and lack of false positives from the results is a good sign and shows the robustness of the Autoscope program which was not designed for use with aerial footage. However, Autoscope does not track the vehicles themselves and only works through detectors. As such, it is possible that a vision tracking software such Traffic Vision has more potential for accurate results, but there is currently nothing developed for use with UAS specifically. For now, Autoscope appears to be the best commercially available solution for analyzing aerial traffic footage.

5 FINDINGS AND LESSONS LEARNED

Initially, the scope of the project was to test if UAS can be used as a tool for situational assessments and decision-making for smaller and difficult to reach areas. In addition, the research was designed to determine if the collected UAS imagery met DOT data standards. Given the project scope and authorizations process, the research goal was to obtain multiple data sets of actual DOT project activities to evaluate against current capabilities. The cost of UAS tested ranged from \$3,500 – \$70,000. Comparing these systems against each other is not completely an apples to apples comparison, because a myriad of options can impact system costs including sensors, gimbals, support equipment, and maintenance programs. However, to meet the objectives of this research project, comparing data sets from a wide range of aircraft used in an even wider range of flight environments to test a large number of applications, accomplished the goal of determining whether or not UAS would be useful for an NCDOT field engineer. The research team discovered that some applications are more conducive to UAS integration; some aircraft are more dependable and suited for transportation scenarios; and data expectations need to be determined ahead of flight plans.

The following is an additional list of findings that were discovered, experienced, or produced during the research for this project. After the Findings are a list of Lessons Learned related to flight operations, sensor integration, GCP usage, and data processing.

Findings

- UAS can support NCDOT missions by being a part of the tool kit that provides repeatable, high-resolution (spatial and temporal) datasets for some, but not all, applications. Imagery requirements should be specified ahead of time as part of mission planning and expectation management.
- The requirement to obtain a COA, which included knowing the specific aircraft and location of the flight months in advance, was cumbersome and led to mission opportunities being missed because the location specific COA was not in place before the project that was selected for imaging was completed. Blanket COAs and Part 107 Licenses eliminated this obstacle at the end of the project.

- The 14 CFR Part 107 Small UAS regulation has created a structure for UAS to safely, routinely, and efficiently support DOT missions.
- Proper training is essential to efficient, effective operations.
- System cost does not equate to improved operational performance, i.e. more expensive products do not necessarily produce better results.
- Weather, wind, and precipitation limit the utility of UAS.
- Batteries are a limiting factor for electric UAS. Successful operations require enough batteries to complete the mission without recharging in the field.
- Batteries degrade over time. They can also be expensive- $180-$520 for small UAS class batteries. Some systems require more than one battery per flight. Batteries are the most significant maintenance cost once a system is procured.
- The commercial software used for this project performed as expected and produced satisfactory results. However the system that is running the software needs to have a powerful computational processing capability to analyze the data sets in a timely and effective schedule. The point clouds created from the UAS imagery are very large data sets!
- The UAS used in this study had some technical issues but UAS technology is rapidly maturing and these issues will be addressed as technology improves.

Lessons Learned

1. When possible, use a sensor that is already fully integrated with the selected UAS. For applications that require high spatial accuracy, the sensors must interface with the UAS onboard GPS and Internal Measurement Unit (IMU) to create geotagged imagery. Geotagged images typically allow imagery processing software for best results. Mirrorless SLR cameras outperform full- size DSLR cameras and are lighter and less expensive.

2. Standard Operating Procedures should be established before beginning flight operations and strictly followed. NGAT has developed a number of SOPs and

Best Practices based in part from the experiences gained from this project. These Best Practices have been shared with the NCDOT Division of Aviation UAS Program Office.

3. The GCP markers tended to be washed out in the imagery, particularly on sunny days, even in imagery that was correctly exposed. The research team concluded that was due to the contrast between white and black marker surrounded by darker terrain. The application of a clear matte paint corrected this issue. The 24" marker provided the best accuracy for determining the exact georeferenced coordinate.

4. The mission planning software for most of the UAS allow for flight plans to be developed for planning purposes. Exact flight times are dependent upon wind and exact launch and recovery locations. These locations also affect the UAS flight path to and from the camera exposure locations. The Aibotix planning software AiProFlight also allows the user to calculate camera exposure points.

5. Waterbody challenges learned from Gallants Channel Bridge data analysis:
    - If the water is unclear and not transparent enough, the imagery results will not be usable for further analysis.
    - If the water is very clear and transparent, there is a chance of reconstructing the water bed, but with the distortions related to the refraction.
    - The camera cannot be calibrated when the image capture is only water since it is very hard to find keypoints on the water surfaces. If keypoints are found by chance, it is still difficult since water ripples.
    - Keep minimum 30% of land surfaces in images captured.
    - Water surfaces have almost no visual content due to large uniform areas. Sun reflection on the water and waves cannot be used for visual matching. Oceans are impossible to reconstruct. Other water surfaces such as rivers or lakes need to have land features in each image to

reconstruct digitally. Flying higher may help to include more land features.

6 FUTURE SCOPE

The maturation of FAA regulations, UAS technology and NGAT services over the last two years is promising. Regulations now enable routine operations without burdensome approvals. Technology has developed to meet the needs of the civilian commercial user. NGAT is now able to provide UAS services as a daily rate function with usually less than one month needed to schedule. The following concepts provide opportunities for future research and development to support UAS adoption, exploitation, and integration into the NAS.

- This project looked at multiple missions. Future projects should focus on a single mission and build upon the fundamental lessons that were accumulated in RP2015-16.
- The utility of traffic monitoring will be enhanced with the addition of new traffic monitoring software and longer endurance UAS.
- The new FAA regulations and exemptions open up the possibly of using fixed wing UAS to image larger areas.
- As computing power progresses, using UAS to capture data for 3D modeling will be more practical.

NGAT has continued supporting NCDOT UAS integration by using UAS for data capture on two other research projects in the Fall of 2016.

- **The Effects of Late Lane Merges on Travel Times.** The objective of the project is to determine if zipper merges and wide dotted lines impact where drivers merge or diverge determine if driver behavior improves safety and operations on these facilities. UAS are assisting by providing an optimal vantage point for collecting data along ¼ to ½ mile sections of roadway. In addition, they provide supplemental before and after video of the sites which can be used for marketing purposes within NCDOT.

- **Planning Level Evaluation of the Effects of Ramp metering on NC Freeways**. The objective of this project is to provide a platform for future analysis efforts of ramp meters. Without the before dataset, future operational analysis is almost impossible. In addition, the research panel wanted to put in place a repeatable method that future contractors could employ to evaluate future ramp metering installations. UAS provide

1) data capture capabilities along the mainline arterial and freeways at four interchanges in North Raleigh along I-540. Four UAS flying in succession provide a method for analyzing the entire facility. NCDOT may also want to use this video for marketing purposes.

7 CONCLUSION

UAS imagery cannot replace manned aircraft imagery, but it has the potential to be an additional tool for DOT surveying and inspection projects. There are many factors that can affect the performance of a UAS. These factors consist of weather, sensor capabilities, flight planning, software processing, and GCP design and placement. This research experienced, tested, and documented all of these factors. Just as in every other aviation operation, proper mission planning and expectation management is essential to accomplishing success and correctly, safely using the tool of small UAS. As the technology improves, the usefulness of UAS as a tool for transportation applications will expand.

8 WORKS CITED

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9 APPENDICES

- 9.1 Part 107 Summary
- 9.2 Aircraft Descriptions
- 9.3 Image Processing with Agisoft

9.1 Part 107 Summary

FAA News

Federal Aviation Administration, Washington, DC 20591

June 21, 2016
SUMMARY OF SMALL UNMANNED AIRCRAFT RULE (PART 107)

Operational Limitations	• Unmanned aircraft must weigh less than 55 lbs. (25 kg). • Visual line-of-sight (VLOS) only; the unmanned aircraft must remain within VLOS of the remote pilot in command and the person manipulating the flight controls of the small UAS. Alternatively, the unmanned aircraft must remain within VLOS of the visual observer. • At all times the small unmanned aircraft must remain close enough to the remote pilot in command and the person manipulating the flight controls of the small UAS for those people to be capable of seeing the aircraft with vision unaided by any device other than corrective lenses. • Small unmanned aircraft may not operate over any persons not directly participating in the operation, not under a covered structure, and not inside a covered stationary vehicle. • Daylight-only operations, or civil twilight (30 minutes before official sunrise to 30 minutes after official sunset, local time) with appropriate anti-collision lighting. • Must yield right of way to other aircraft. • May use visual observer (VO) but not required. • First-person view camera cannot satisfy “see-and-avoid” requirement but can be used as long as requirement is satisfied in other ways. • Maximum groundspeed of 100 mph (87 knots). • Maximum altitude of 400 feet above ground level (AGL) or, if higher than 400 feet AGL, remain within 400 feet of a structure. • Minimum weather visibility of 3 miles from control station. • Operations in Class B, C, D and E airspace are allowed with the required ATC permission. • Operations in Class G airspace are allowed without ATC permission. • No person may act as a remote pilot in command or VO for more than one unmanned aircraft operation at one time. • No operations from a moving aircraft. • No operations from a moving vehicle unless the operation is over a sparsely populated area. • No careless or reckless operations. • No carriage of hazardous materials.

	• Requires preflight inspection by the remote pilot in command. • A person may not operate a small unmanned aircraft if he or she knows or has reason to know of any physical or mental condition that would interfere with the safe operation of a small UAS. • Foreign-registered small unmanned aircraft are allowed to operate under part 107 if they satisfy the requirements of part 375. • External load operations are allowed if the object being carried by the unmanned aircraft is securely attached and does not adversely affect the flight characteristics or controllability of the aircraft. • Transportation of property for compensation or hire allowed provided that- o The aircraft, including its attached systems, payload and cargo weigh less than 55 pounds total; o The flight is conducted within visual line of sight and not from a moving vehicle or aircraft; and o The flight occurs wholly within the bounds of a State and does not involve transport between (1) Hawaii and another place in Hawaii through airspace outside Hawaii; (2) the District of Columbia and another place in the District of Columbia; or (3) a territory or possession of the United States and another place in the same territory or possession. • Most of the restrictions discussed above are waivable if the applicant demonstrates that his or her operation can safely be conducted under the terms of a certificate of waiver.
Remote Pilot in Command Certification and Responsibilities	• Establishes a remote pilot in command position. • A person operating a small UAS must either hold a remote pilot airman certificate with a small UAS rating or be under the direct supervision of a person who does hold a remote pilot certificate (remote pilot in command). • To qualify for a remote pilot certificate, a person must: o Demonstrate aeronautical knowledge by either: ▪ Passing an initial aeronautical knowledge test at an FAA-approved knowledge testing center; or ▪ Hold a part 61 pilot certificate other than student pilot, complete a flight review within the previous 24 months, and complete a small UAS online training course provided by the FAA. o Be vetted by the Transportation Security Administration. O Be at least 16 years old. • Part 61 pilot certificate holders may obtain a temporary remote pilot certificate immediately upon submission of their application for a permanent certificate. Other applicants will obtain a temporary remote pilot certificate upon successful completion of TSA security vetting. The FAA anticipates that it will be able to issue a temporary remote pilot certificate within 10 business days after receiving a completed remote pilot certificate application. • Until international standards are developed, foreign-certificated UAS pilots will be required to obtain an FAA-issued remote pilot certificate with a small UAS rating.

	A remote pilot in command must: • Make available to the FAA, upon request, the small UAS for inspection or testing, and any associated documents/records required to be kept under the rule. • Report to the FAA within 10 days of any operation that results in at least serious injury, loss of consciousness, or property damage of at least $500. • Conduct a preflight inspection, to include specific aircraft and control station systems checks, to ensure the small UAS is in a condition for safe operation. • Ensure that the small unmanned aircraft complies with the existing registration requirements specified in § 91.203(a)(2). A remote pilot in command may deviate from the requirements of this rule in response to an in-flight emergency.
Aircraft Requirements	• FAA airworthiness certification is not required. However, the remote pilot in command must conduct a preflight check of the small UAS to ensure that it is in a condition for safe operation.
Model Aircraft	• Part 107 does not apply to model aircraft that satisfy all of the criteria specified in section 336 of Public Law 112-95. • The rule codifies the FAA's enforcement authority in part 101 by prohibiting model aircraft operators from endangering the safety of the NAS.

9.2 Aircraft Descriptions

9.2.1 Aibotix X6

The Aibotix, X6 is a lightweight, six bladed multi-rotor, vertical takeoff and landing (VTOL) Unmanned Aerial System (UAS). The basic copter is delivered with a bottom mounted roll and pitch stabilized gimbal mount that can accommodate a wide variety of sensors including still and video cameras, gas detectors, and laser ranging devices. In addition, a top mounted, stabilized gimbal was purchased that can be attached to the system for performing inspection of the underside of structures. The aircraft is powered by two, five cell Lithium Polymer batteries which provide up to a maximum of 15 minutes of flight time. The Aibot can be manually controlled or preprogrammed to fly to a series of waypoints. The system can perform both automatic takeoffs and landings. The system cost for the Aibot was $70,000 with included several options including an extra flight controller, top mount gimbal, and real-time video downlink kit.

Aircraft Performance Analysis – The Aibot X6 did not collect constantly clear dataset. Multiple cameras and lens combination were evaluated but we still had issues with the data quality. The issue was isolated to the camera mount or gimbal servos. The aircraft was involved in a crash that rendered the aircraft unusable before this issue was isolated.

Reliability – We had several issues with the Aibot, the first was an inflight failure of the GPS card. The second issue was that the aircraft did not achieve the advertised flight endurance of 30 minutes with two batteries. The Nikon d5200 as flown was approximately 2.5 lb, yet our operational flight were about 11 – 14 minutes. The Aibot also had issues in windy conditions that affected flight endurance and data quality. Finally, the flight team experienced a catastrophic crash that was the result of a nonstandard launch that could not be aborted by the flight controller and the system did not have failsafe mechanisms to prevent the disastrous series of events.

After we concluded that the Aibotix X6 did not meet the requirements for this project and it crashed into an unrepairable state, three other platforms for performing the NCDOT desired missions and capturing survey / inspection imagery were tested.

9.2.2 DJI Inspire

This small lightweight (6.4 lbs.) quadcopter has retractable landing gear that allow for an unobstructed view. Sensor options include, 16MP video and still cameras with interchangeable lenses, or thermal cameras. The fight endurance from a single 4500 mAh battery gives it an endurance of 18 minutes. The GCS consists of an R/C Transmitter that is supplemented by the DJI GO Application run on a cell phone or tablet computer. A DJI Inspire Pro with two controllers- one for the pilot and one is optional for a camera operator, is $3,400. In the summer of 2016 NGAT bought a $10,000 Zenmuse XT thermal camera that was used for bridge inspection testing at the Gallants Bridge during construction (Figure 50).

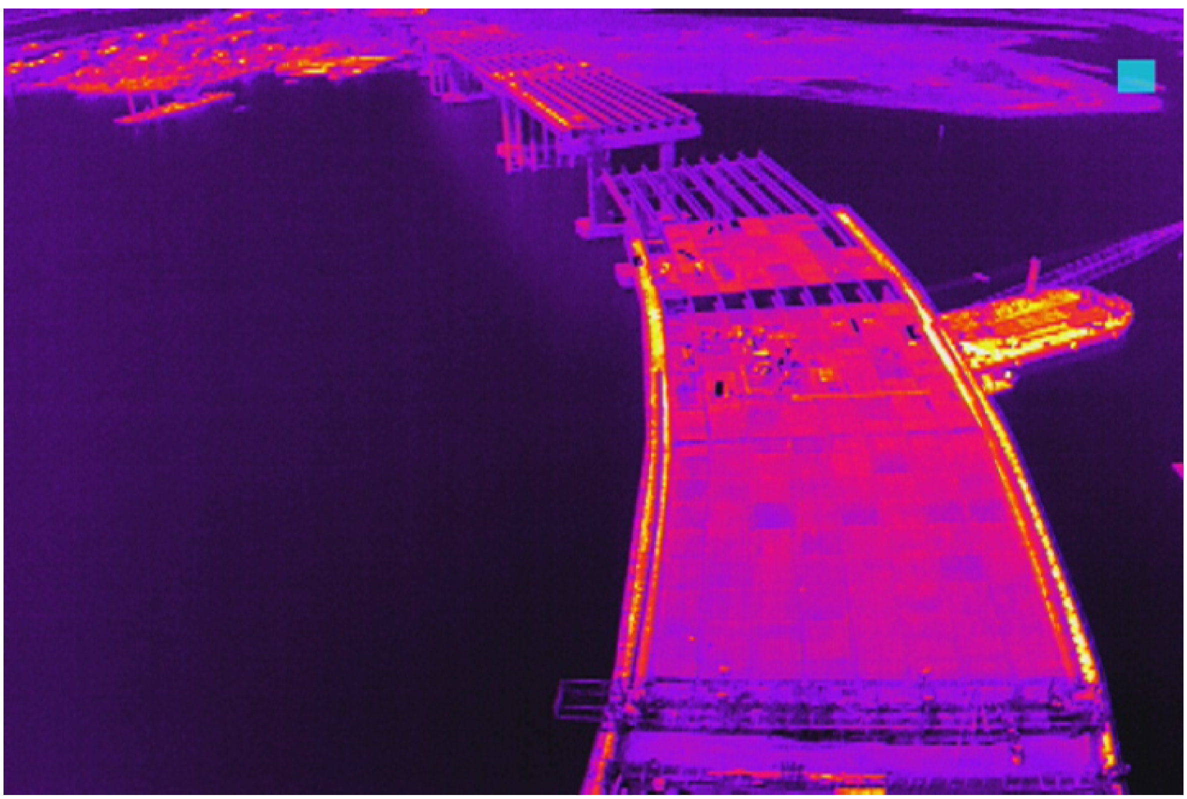


Figure 50: Thermal Imagery of Gallants Bridge from NGAT Inspire UAS

The Inspire has been used extensively for other projects in addition to RP2015-06.

The research team has not encountered any issues with the system other than the Apple cell phones used as ground control displays overheat in the sun.

9.2.3 Trimble ZX5

The ZX5 hexacopter weighs 11 lbs. with a payload capacity of 5.1 lbs. The sensor is a 16MP Olympus mirrorless 14 mm lens. The GCS allows the system to be controlled manually but for most operations the flight is preprogramed into the GCS and the fight is executed autonomously. It requires two 6600 mAh batteries that gives it an endurance of 20 minutes.

This UAS and sensor combination did provide acceptable quality imagery that produced reliable results for the DOT small survey application.

9.2.4 Duke University Marine Laboratory Freefly Cinestar 6 and Mikrokopter Hexa XL

DUML flew two UAS over the Gallants Channel Bridge, each was a Ready to Fly (RTF) kit instead of an integrated UAS product from a major manufacturer. The Mikrokopter Hexa XL and Freely Cinestar 6 are carbon frame aircraft with a lifting capacity 3.3 and 5.8 lbs respectively. Both use Mikrokopter control electronics that allow for autonomous flight by pre-programmed Points of Interest (POI), GPS and

Altitude hold and safety features such as automatic return to home/ Autoland. These systems cost far less than the purpose-built commercial systems: $5,000 for the Hexakoper XL and $8,000 for the Cinestar 6.

9.3 Image Processing with Agisoft

Data Management

Data Management can be handled using data repositories. These are central locations made up of one or more databases which make it ideal for storage and management. Data repositories serve as long-term storage, preservation, or backup systems. The best way to maintain data is by following specific guidelines. The DOT provided a specific naming scheme, formats, versioning, and keywords to use. Each specific attribute had its own meaning in order to distinguish itself from other schemes. Data management can get complicated as data processing takes place and more files are generated. Each folder should have metadata file, excel file, and imagery. The file content may vary depending on the files and the collected data.

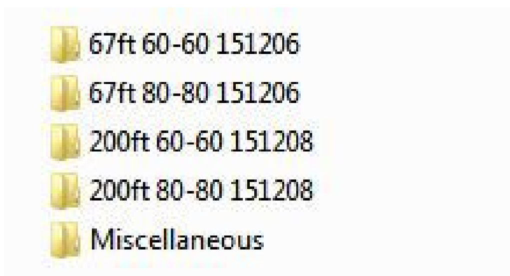


Figure 51: Flights

Naming Convention

The naming conventions varied depending on the file type. This project had digital mosaics (TIF), aerial imagery (JPG), comma separated value tabular data files (CSV-Excel), and digital elevation models. The TIF and JPG files' had a similar naming scheme of "tip#_ph_m_tile@_DOP.tif". The tip # specifies the flight, ph specifies it as a photo, "m" means mosaic or multiple images and "tile@" relates to the area captured. The excel files had a different naming scheme which was "flightName_ph_fxew.xls". The flight name will be the same as it is used for the images. "Ph" means it is part of a group of photos, and "fxew" states it is an excel file.

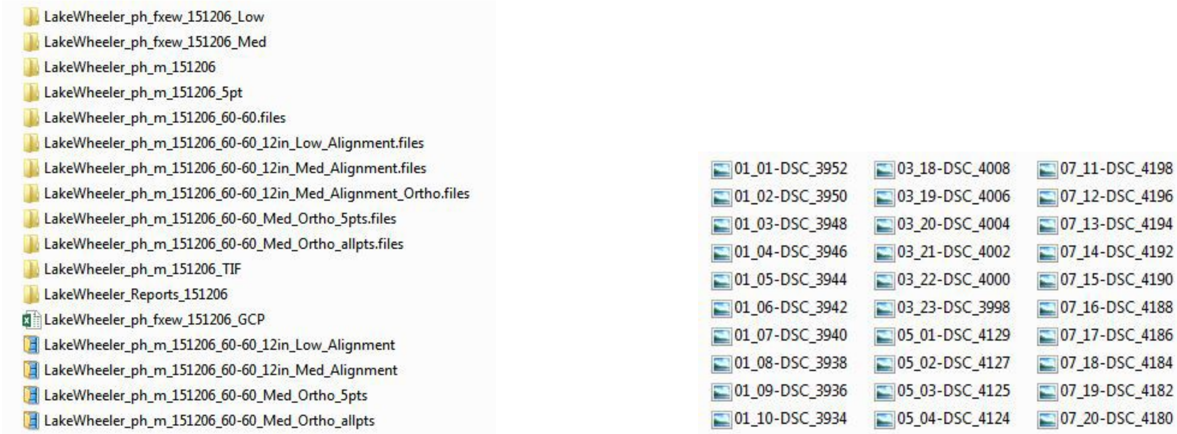


Figure 52: Naming conventions for images, documents and folders

Archiving

Archiving is used for long-term storage of historical data which are not needed for immediate access. Generally, archived files are created in a platform and software independent formats for stable programs. These files are created to be kept indefinitely and be saved in a basic format for compatibility. Archives are labeled, catalogued, and stored in a controlled and protected environment. This allows for the DOT to protect and access historical record and information at any time. In order to specify the archived folder, the folder should have the conventional flight name and the date it was archived. An archived excel file is documented with this file name "tip#_mission#_adjusted_GPS-IMU_EO_grid.xls". If the file contains metric data, "_metric" will need to be added to the end of the file. This will easily distinguish metric versus non-metric files.

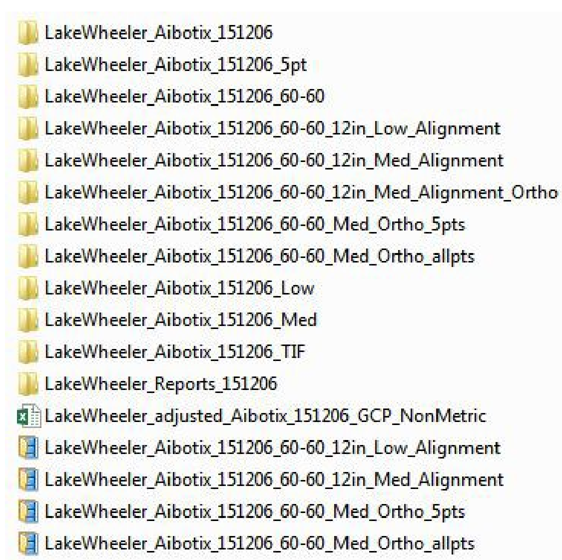
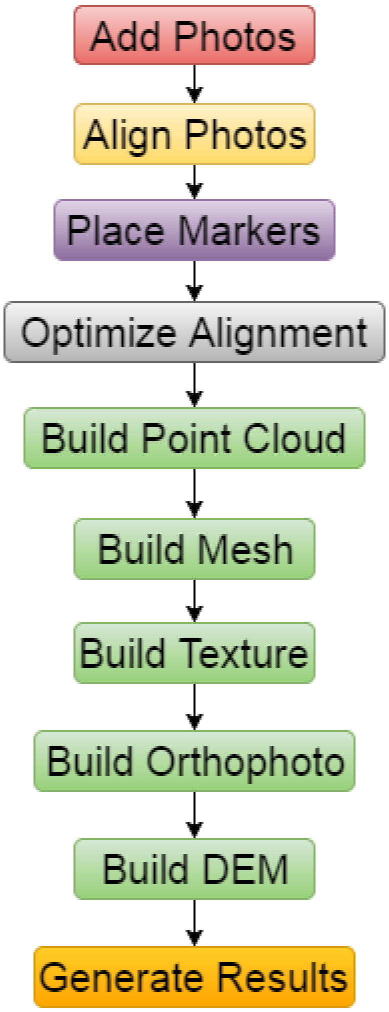


Figure 53: Archive naming convention

Agisoft PhotoScan Processing

Processing Workflow



Add Photos or **Add Folder** - The first step is to load all of the raw images into the software's interface.

Align Photos - The first processing step compares the pixels in the photos to find matches and estimate camera locations, and 3D geometry within them.

Place Markers – In this step the ground control points are added then optimized for alignment.

Build Dense Cloud - Once the alignment is complete, the sparse point cloud is processed into a dense cloud in which each corresponding pixel will get its own X, Y, Z location in 3D space

Build Mesh - This step connects each set of three adjacent points into a triangular face. This combines to produce a continuous mesh over the surface model

Build Texture - In the final step, the original images are combined into a texture map and wrapped around the mesh, resulting in a photorealistic model of your original object.

Build Orthophoto – The Orthophoto is built from the dense cloud and mesh.

Export Orthophoto & Flight Report – The final step is to export the data processed and generate a project report.

This project was completed in Agisoft PhotoScan. The following sections will provide greater detail of the workflow.

Open Project

To open and start a new project, click on File -> Open or click the Open icon on the toolbar. Then, locate the project file folder and click Open. Agisoft allows the user to upload the project folder file or by selecting each photos. The project will be loaded with photos and corresponding GPS positions of the cameras. Select Create Multispectral Camera from Files as Came to complete the process. The camera positions represented by blue dots in the main Model window.

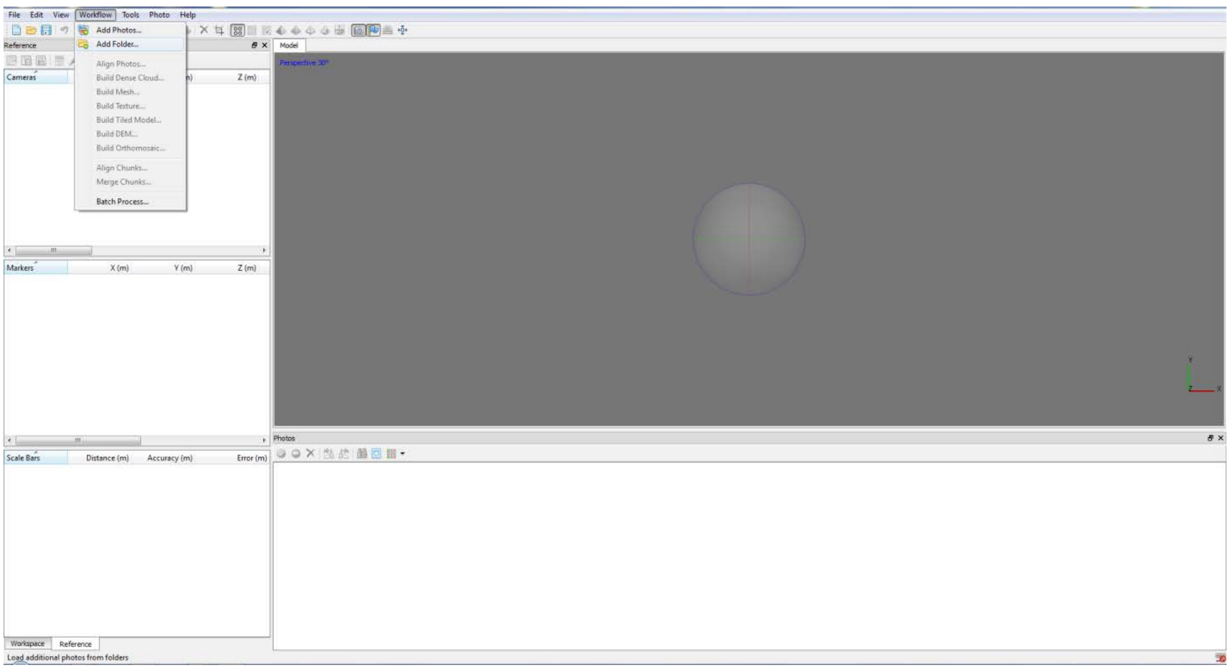


Figure 54: Add Photos interface in Agisoft PhotoScan

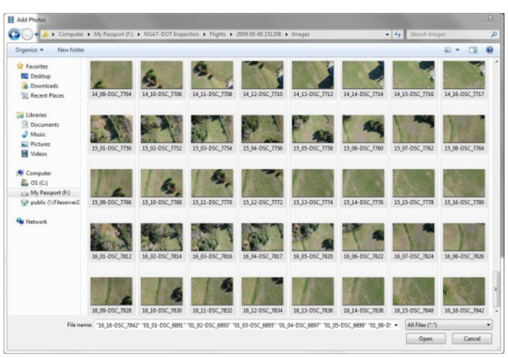


Figure 55: Add individual photos

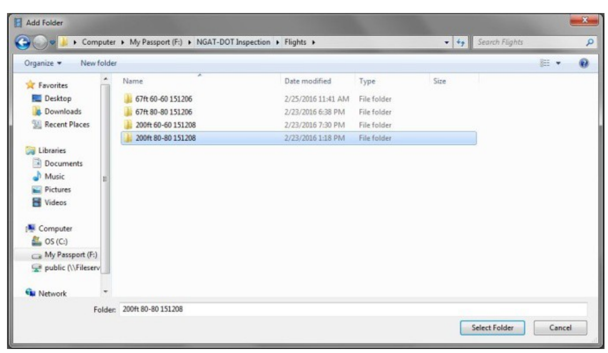


Figure 56: Add project folder

Select a photo by left-clicking it in the image list in the workspace Overview pane. The selected image will be highlighted in the main model window. The photo can be opened in a tab in the Model window by double-clicking. The different window panes can be toggled on and off from the View menu and maneuvered around the window to customize the user interface. Save the project after this step is completed.

Align Photos

To begin aligning photos, go to Workflow and select Align Photos. The window will ask for the type of accuracy. Select Low accuracy for rapid processing or High accuracy for precise alignment. High accuracy will take longer to process. Click OK and save the alignment once it is completed.

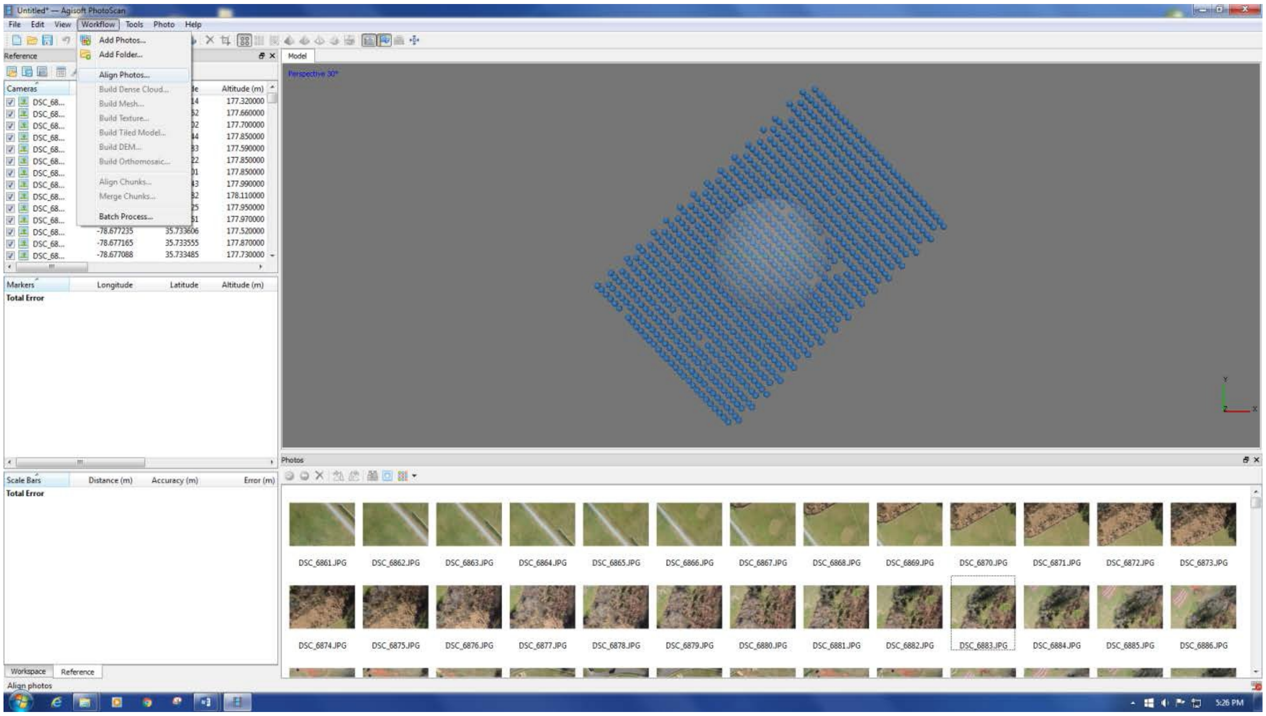


Figure 57: Align Photos Interface in Agisoft PhotoScan

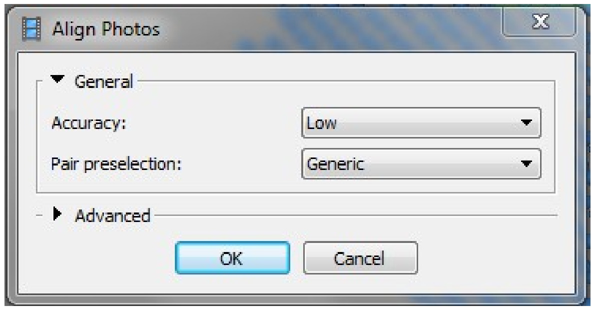


Figure 58: Setting the accuracy for Photo Alignment

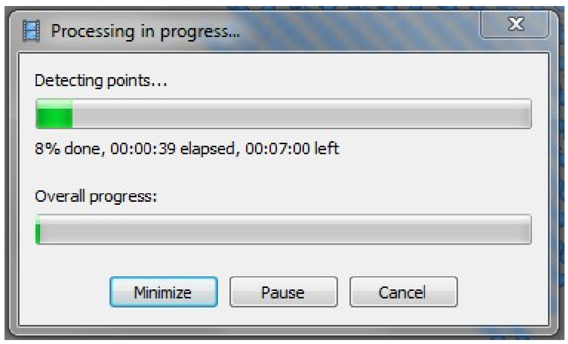


Figure 59: Agisoft PhotoScan processing window

The main model window should display a sparse 3D point cloud. A successful alignment displays blue dots across the surface. These blue dots represent the initial positions.

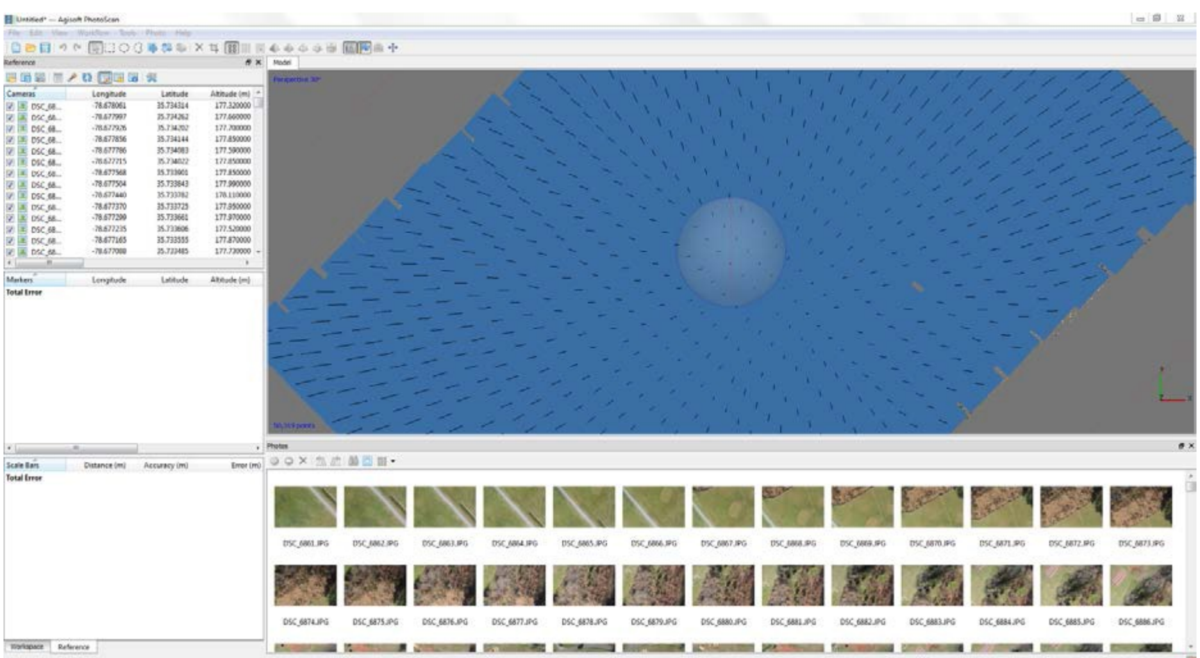


Figure 60: Results of the Photo Alignment

Calculating Image Quality

After the photos are aligned, it is necessary to clean up the images to improve the overall quality. It is recommended that images with quality value of less than 0.5 units should be disabled or deleted from the pane. This can be done using the Disabled button . To estimate image quality, switch to the detailed view in the Photos pane using Details command from the change menu on the Photos pane toolbar. Select all photos in the pane. Right-click the selected photos and choose Estimate Image Quality command from the context menu. Once the procedure is over, the estimated values will populate the image quality field. Save the project after this step is completed.

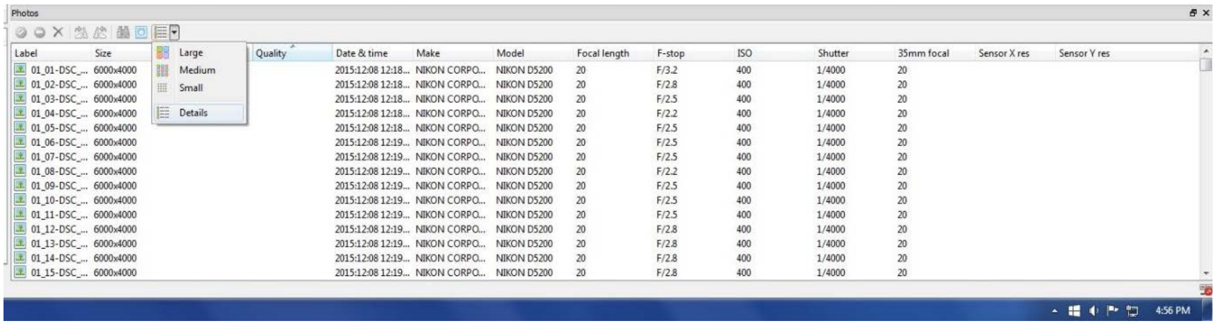


Figure 61: Calculating Image Quality window

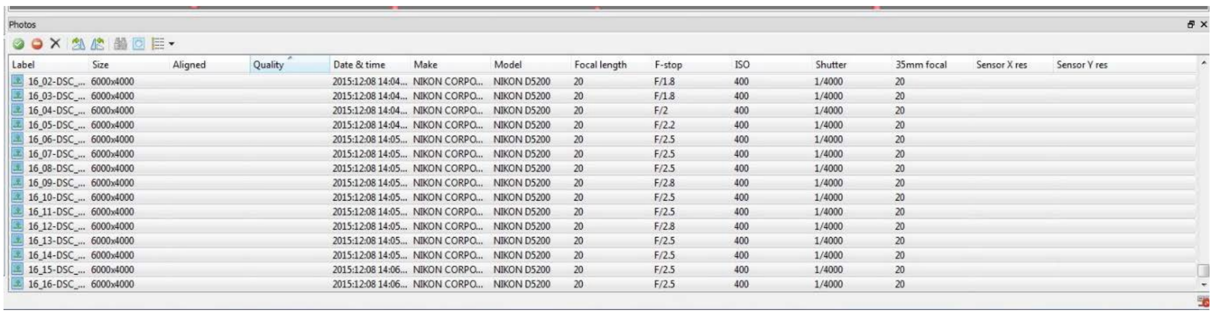


Figure 62: Calculating Image Quality, photo selection

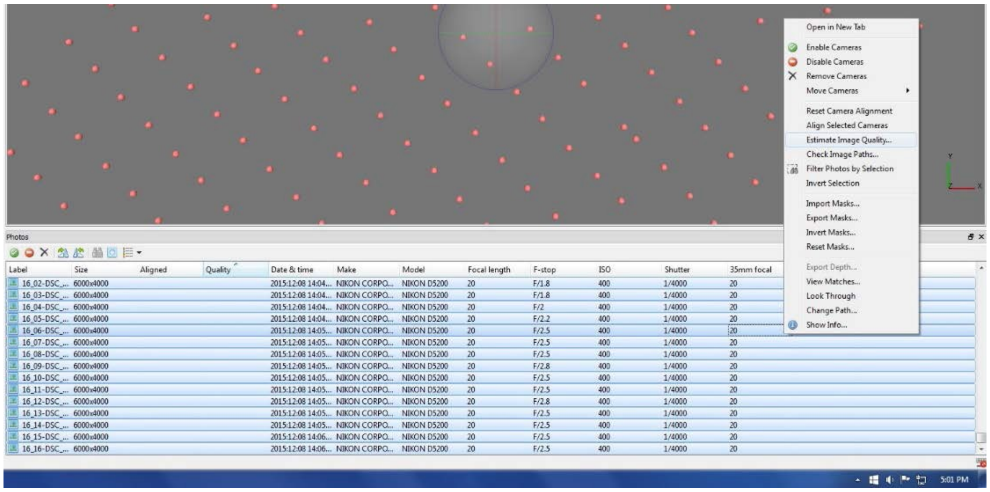


Figure 63: Estimate Image Quality

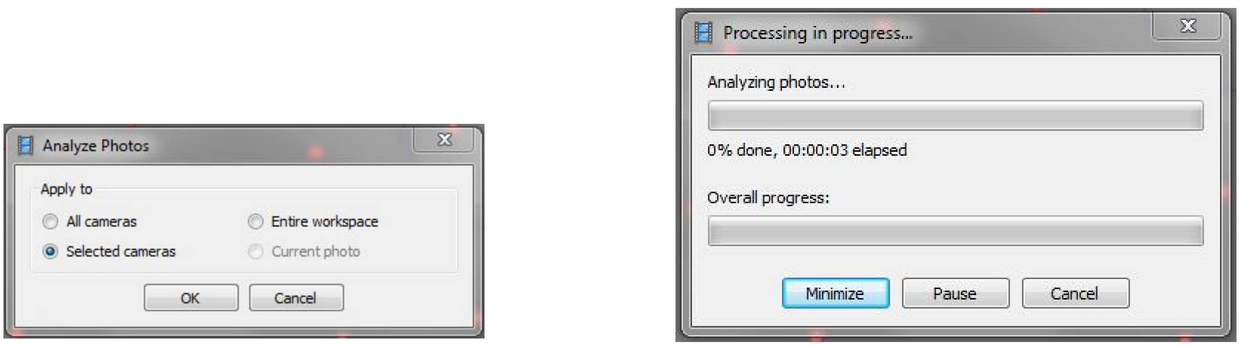


Figure 64: Image Quality window

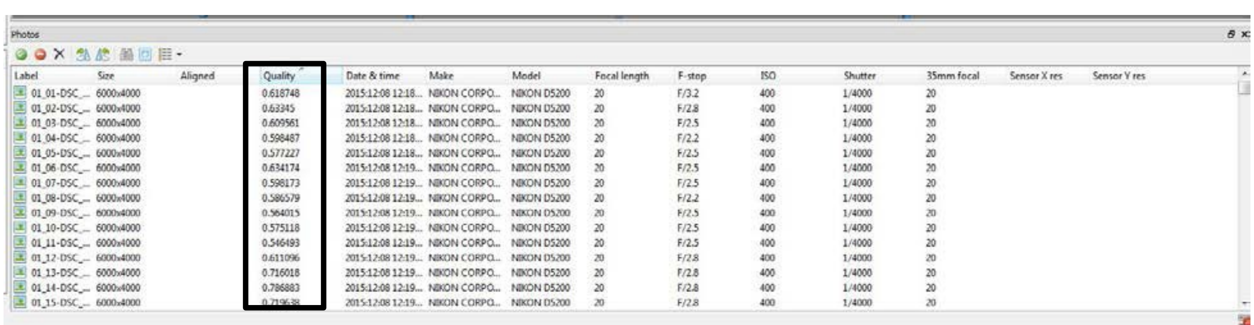


Figure 65: Image Quality Results

Indicate GCPs

Skip this step if ground control points are not being used to process the orthophoto.

Select a GCP in the pane, then select a photo and click Filter by markers  to see the images that correspond to the GCP. Double-click on the image to open into another tab. The GCP will appear as a grey icon. The markers will be identified with  until the markers are repositioned. The markers can be corrected by clicking on and dragging the point. The corrected marker will appear as a green flag. Continue the process with other corresponding images and markers. Find the lowest error for that image. Save the project after this step is completed.

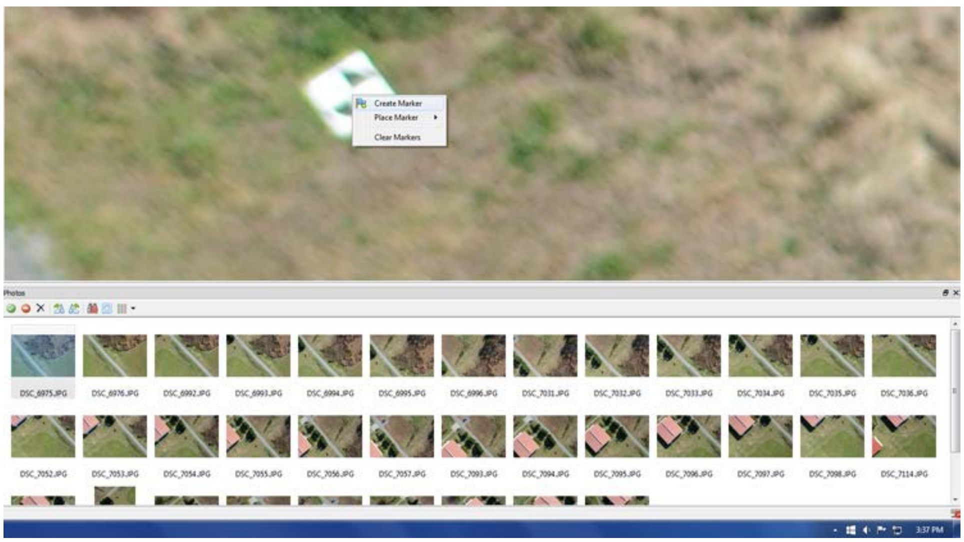


Figure 66: Creating a Place Marker in Agisoft PhotoScan

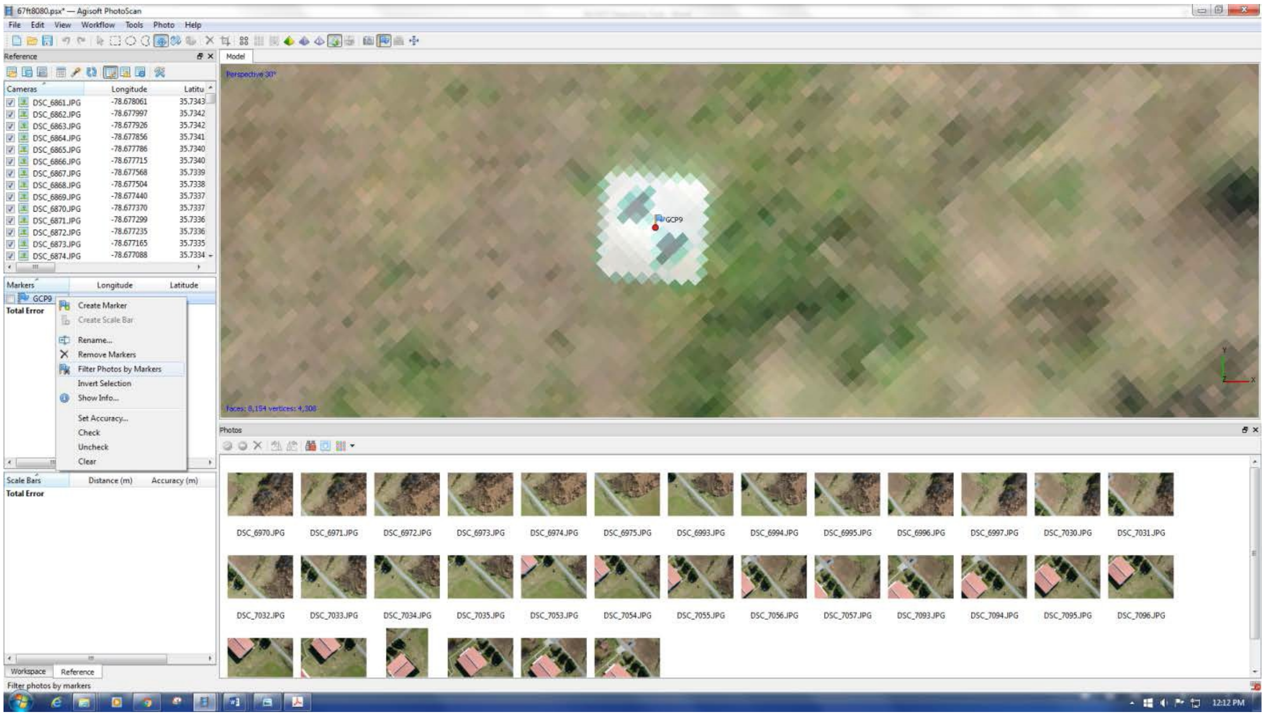


Figure 67: Align photos by place marker

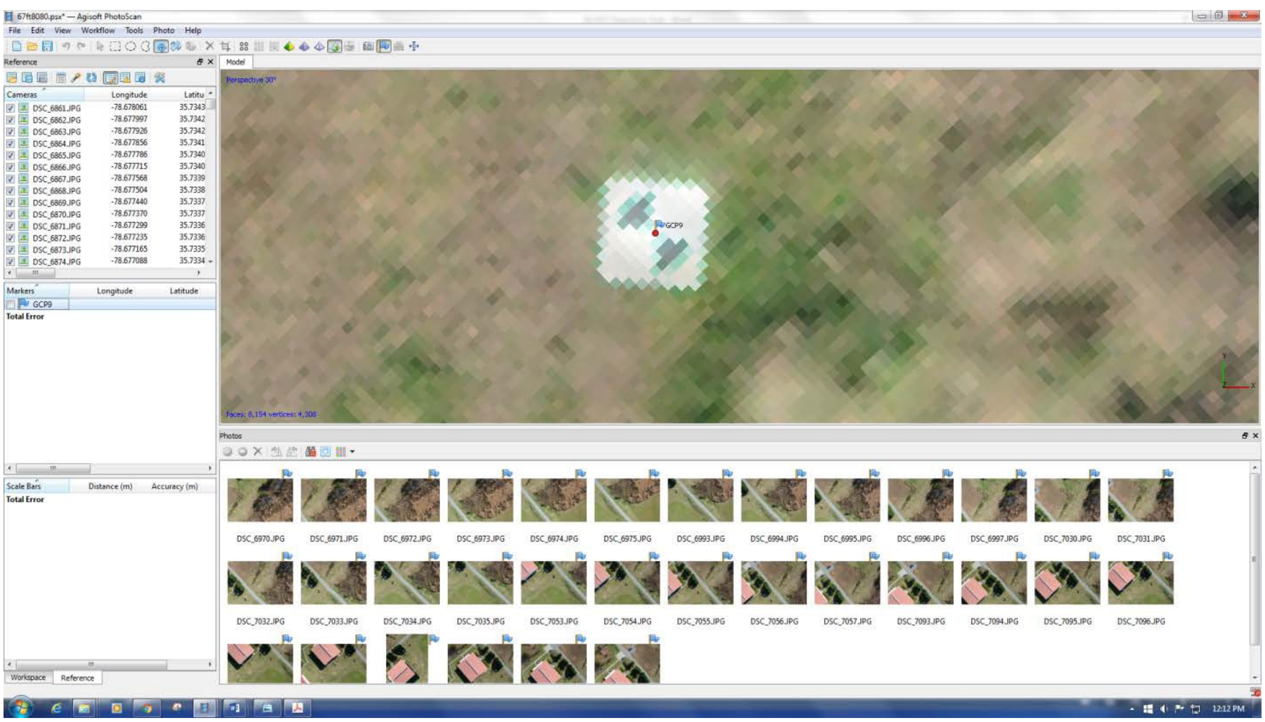


Figure 68: Correcting the pixel error

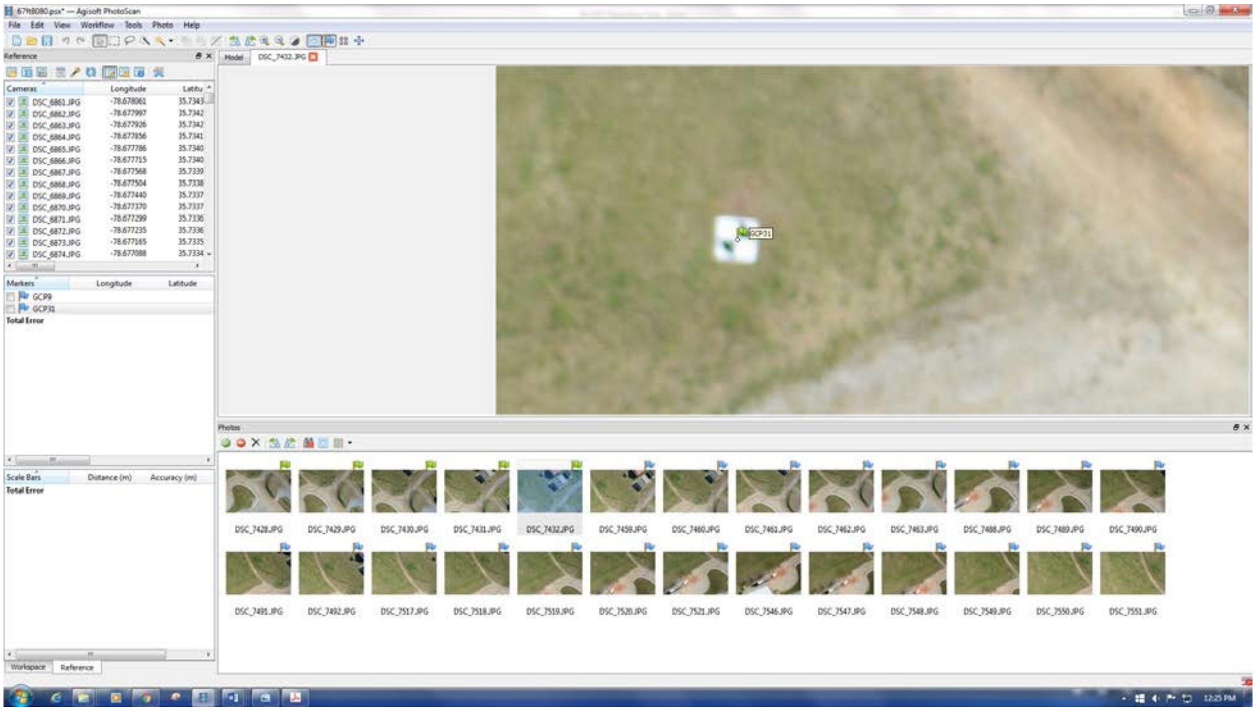


Figure 69: Place marker with fixed (green) and unfixed (blue) markers

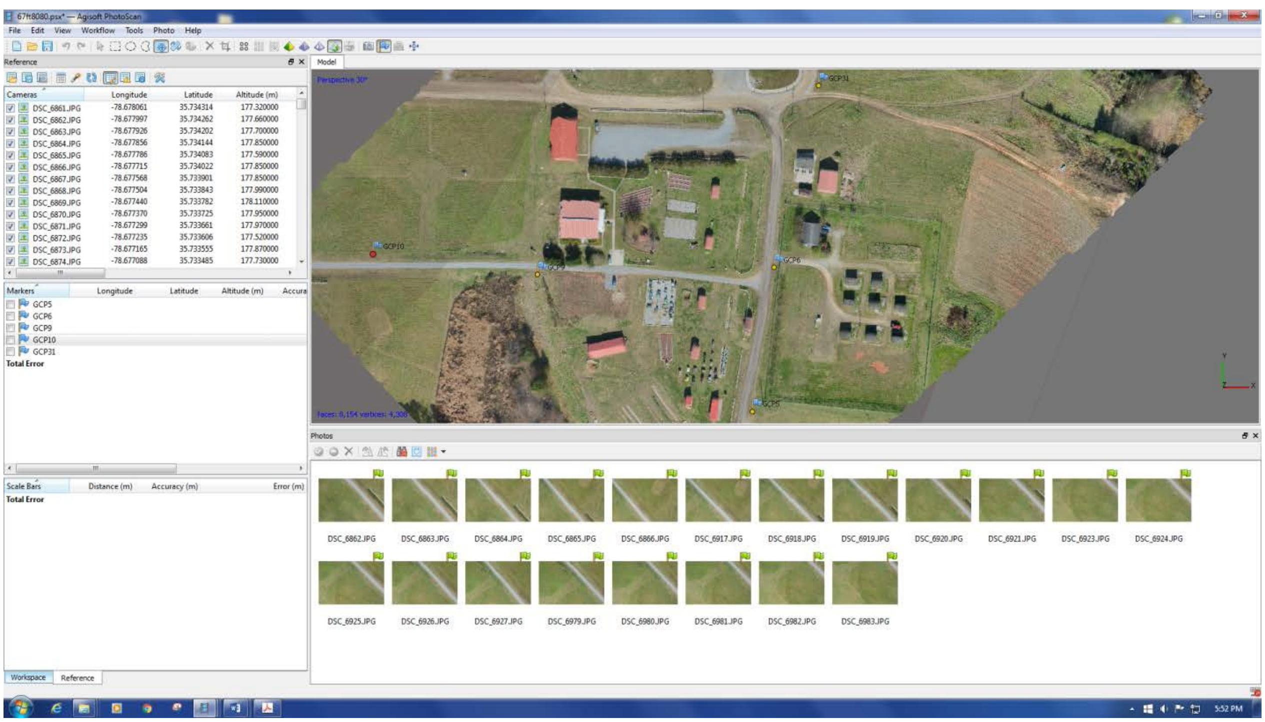


Figure 70: Output of five corrected GCPs

Importing GCPs

Ground Control Points (GCPs) can be imported by the coordinate file. First, the camera coordinates need to be converted to the datum and coordinate system of the GCPs.

Then, select all photos and click Convert  in the Ground Control pane toolbar. Set the datum and coordinate system according to the project. Click More to select the system, filter by EPSG code or load the projection file (.prj). Save the project after this step is completed.

Next, click Import  on the Ground Control pane toolbar and search for the GCP file in any CSV format with .txt extension and click OPEN. Specify the desired delimiter and the order of the columns. It is important the metadata of the imported file is deleted and it starts at row 0. Check “Yes to all” to create all the selected GCP markers. The selected markers will show in the image acquisition center in the 3D Model pane. This is below the image pane. Save the project after this step is completed.

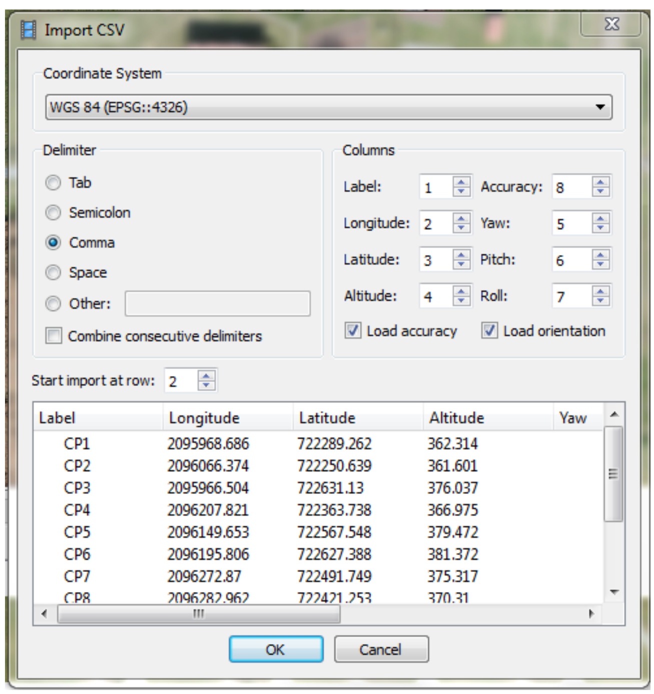


Figure 71: Import a file with the original GCP points

Optimize Alignment

Clean up the outlier points using the freehand tool and click Delete to finalize the selection. Then, uncheck all of the GCPs for optimization. Click the Optimize in the Ground Control toolbar and leave all options at the default value. Click OK and Save.

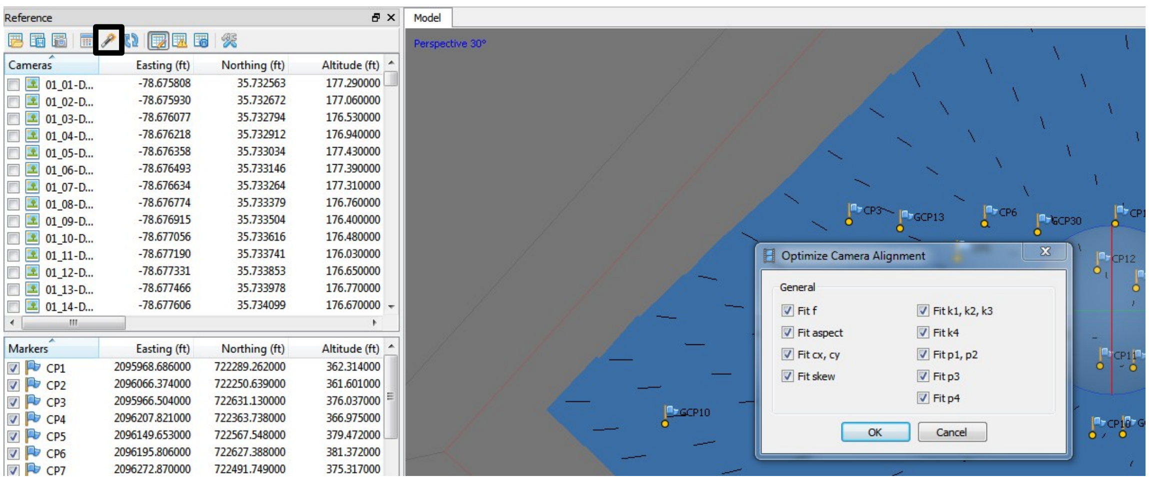


Figure 72: Photo Optimization

Build Dense Cloud

Dense clouds are produced from camera positions and the corresponding points generated from aligning photos. To build a dense point cloud, adjust the bounding box to resize region and rotate region to display the image properly. In the Workflow window, select Build Dense Cloud and keep all of the parameters consistent or default. A progress box will show during the processing stage. Save the project after this step is completed.

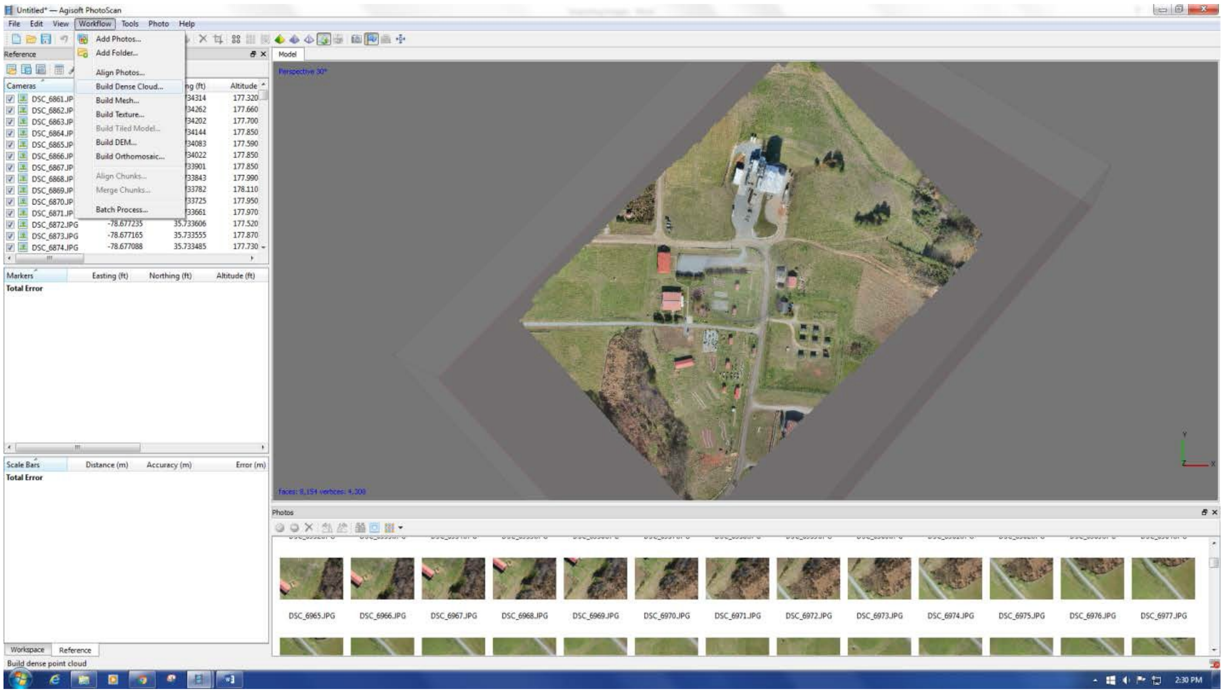


Figure 73: Build Dense Cloud interface in Agisoft PhotoScan

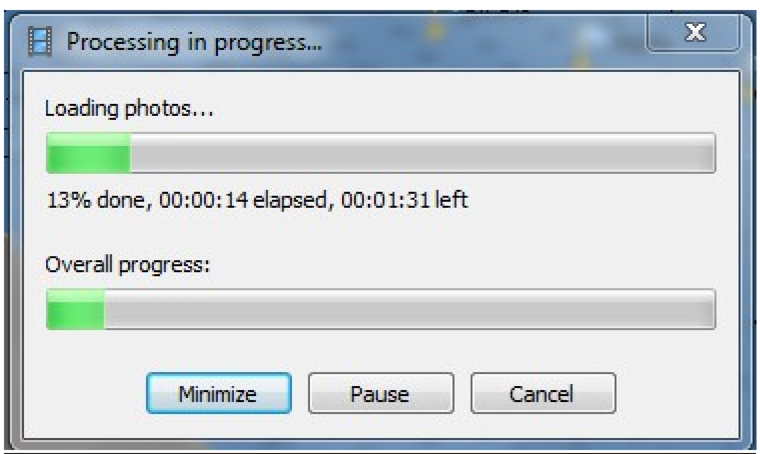


Figure 74: Dense Cloud processing window

Build Mesh

Markers are used to optimize camera position and orientation which produces better accuracy. Depending on the size of the area, select five or more ground control points (GCPs) evenly distributed around the area of interest. Keep all of the processing settings the same and consistent. Save the project after this step is completed.

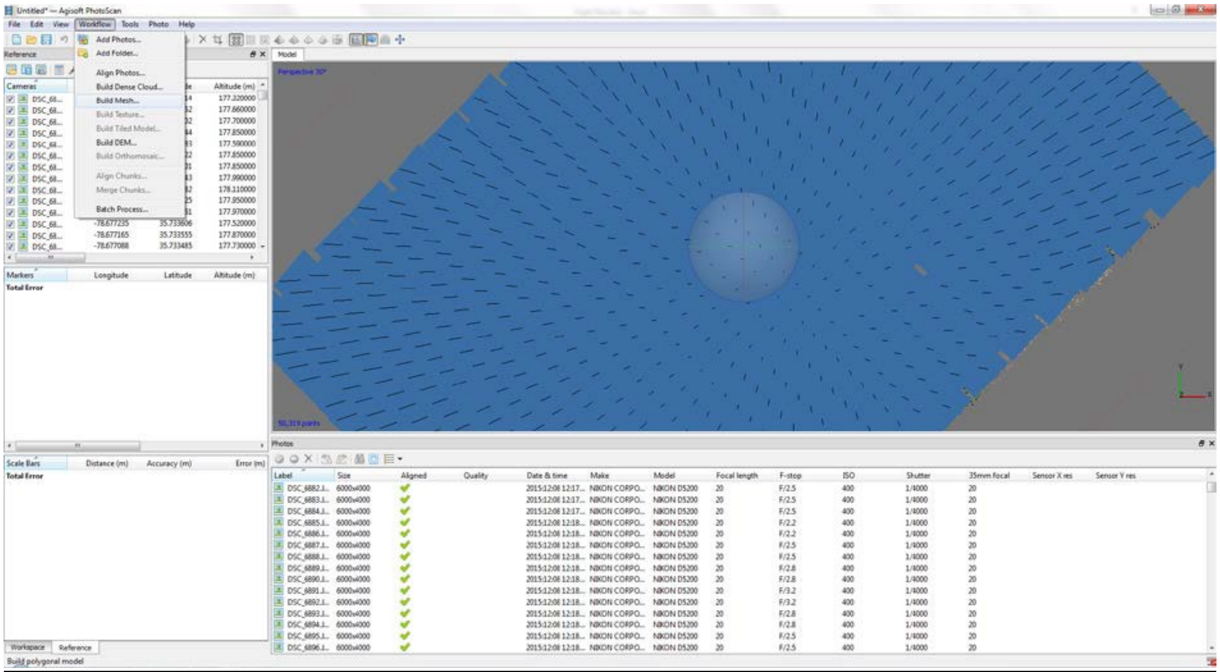


Figure 75: Build Mesh Cloud interface in Agisoft PhotoScan

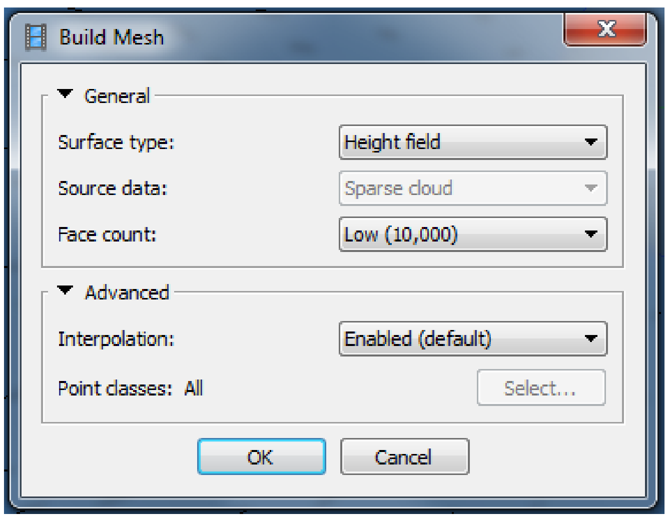


Figure 76: Build Mesh settings interface

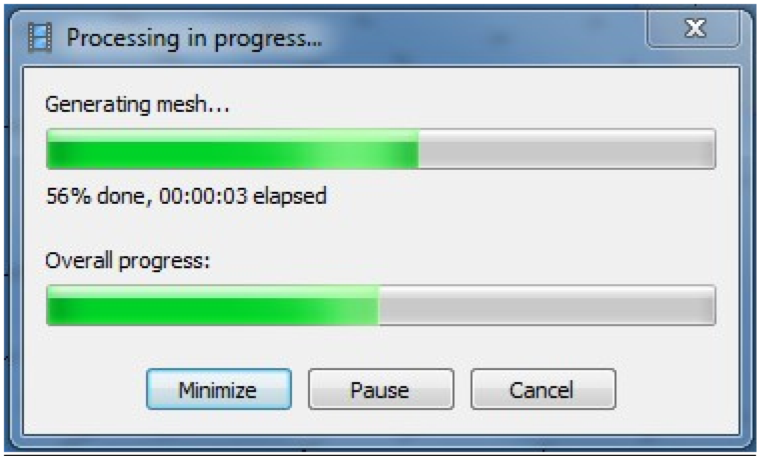


Figure 77: Build Mesh processing window

Build Texture

Select the Workflow window and choose the Build Texture option. Make sure the mapping mode is set to Orthophoto and the blending mode is set to Mosaic. Keep all of the default settings. The processing should be fairly quick for this step.

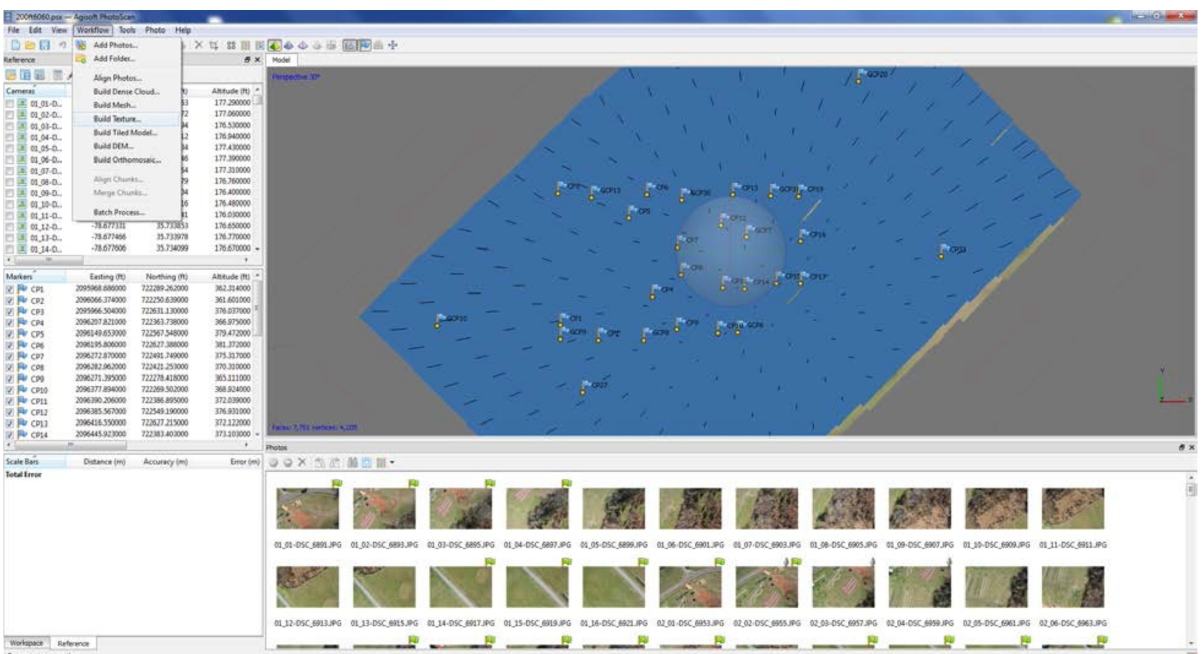


Figure 78: Build Texture interface

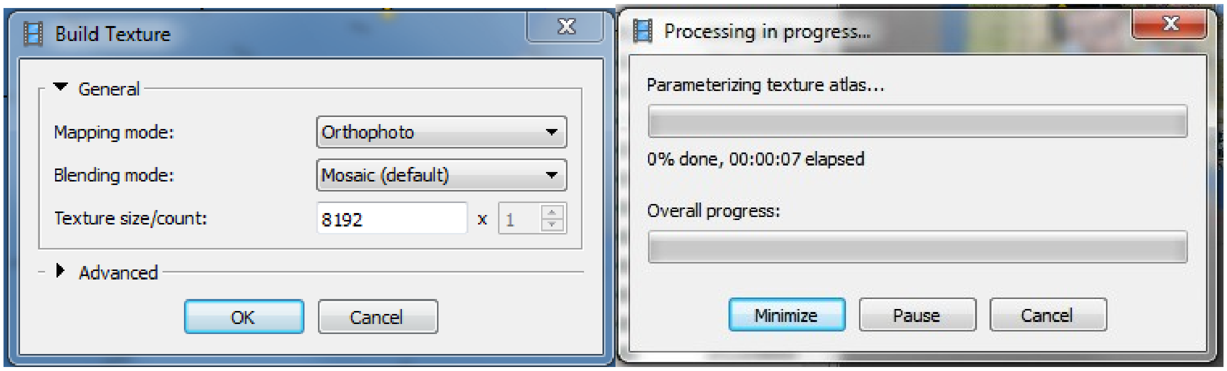


Figure 79: Build Texture settings and processing

Build DEM

To build a DEM, open the Workflow window and choose Build DEM. Set the coordinated system based on the project but it is usually selected based on the photos' metadata. Change the resolution, source data and some other settings for project specifications, otherwise leave it as default.

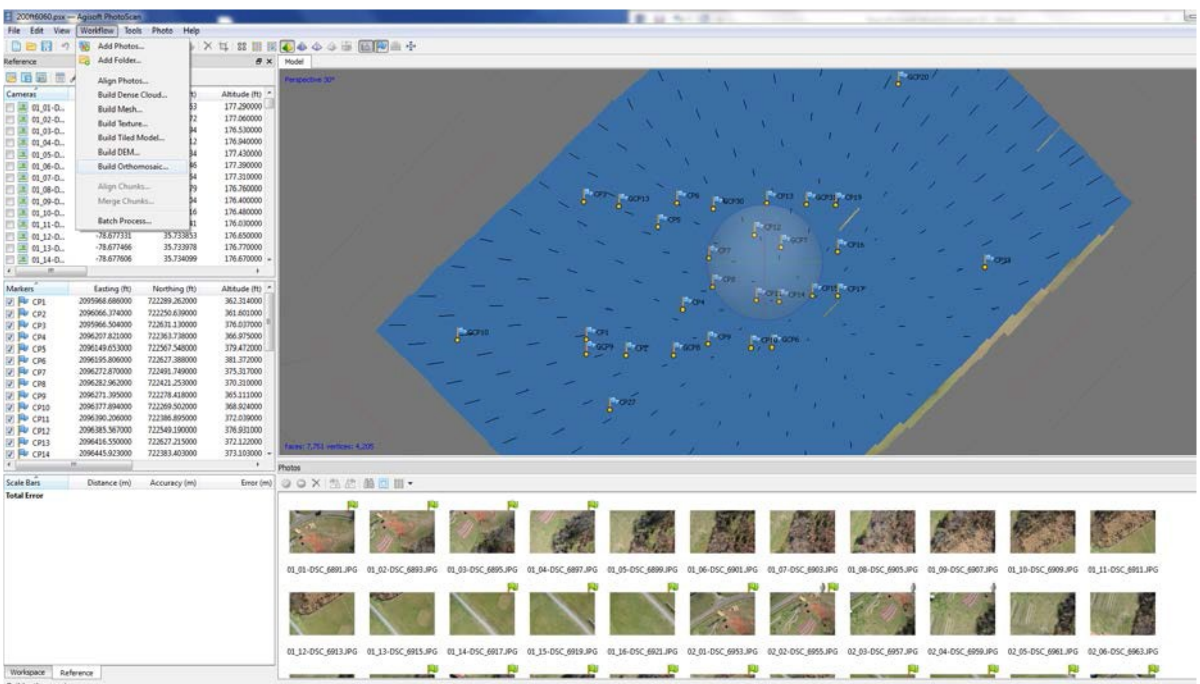


Figure 80: Build DEM interface

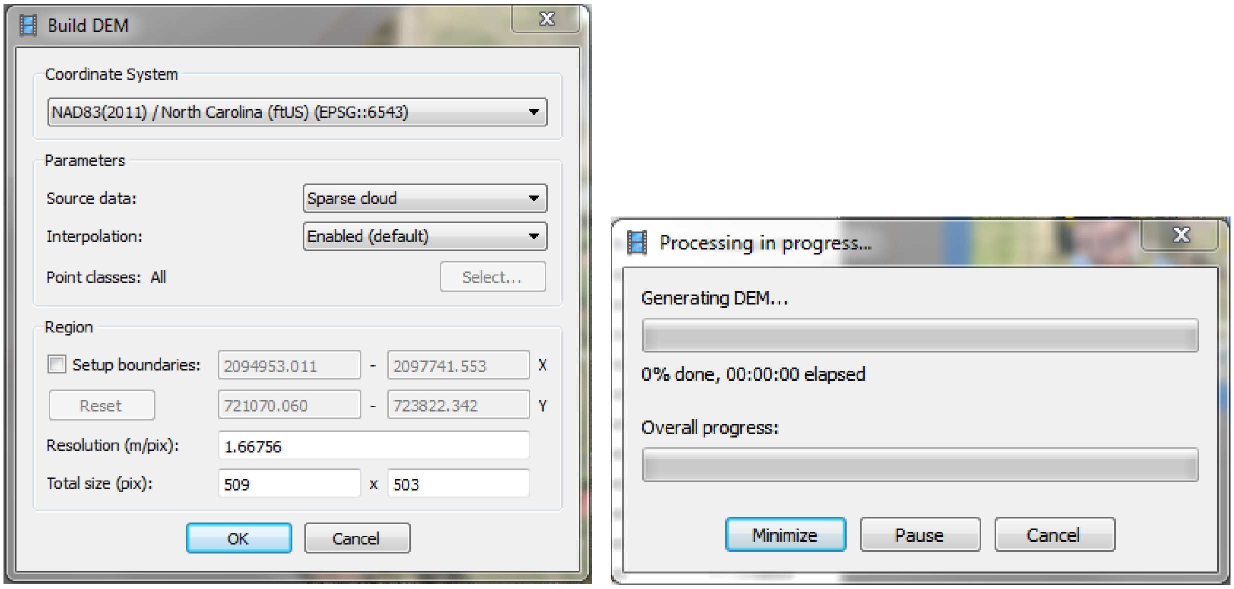


Figure 81: Build DEM settings window

Build Orthomosaic

Select the projection, select DEM from the Surface parameter, leave the Blending mode and pixel size as default. For additional use, if the Orthophoto is going to be opened on the Google Earth, make sure the image's resolution is not too high.

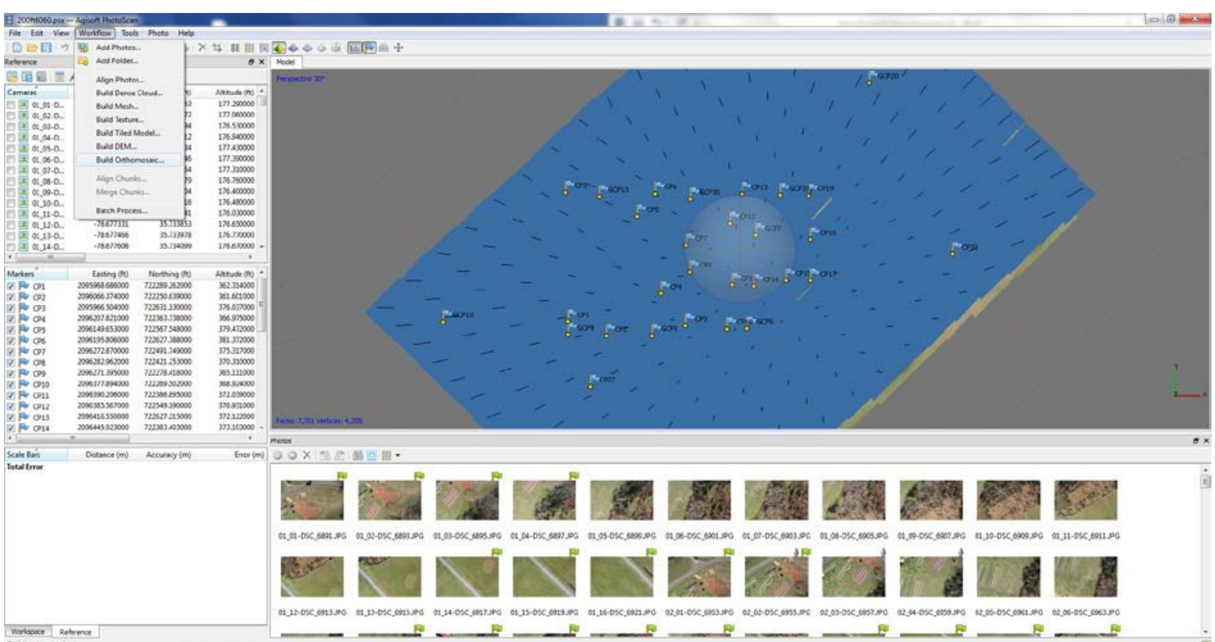


Figure 82: Build Orthomosaic interface

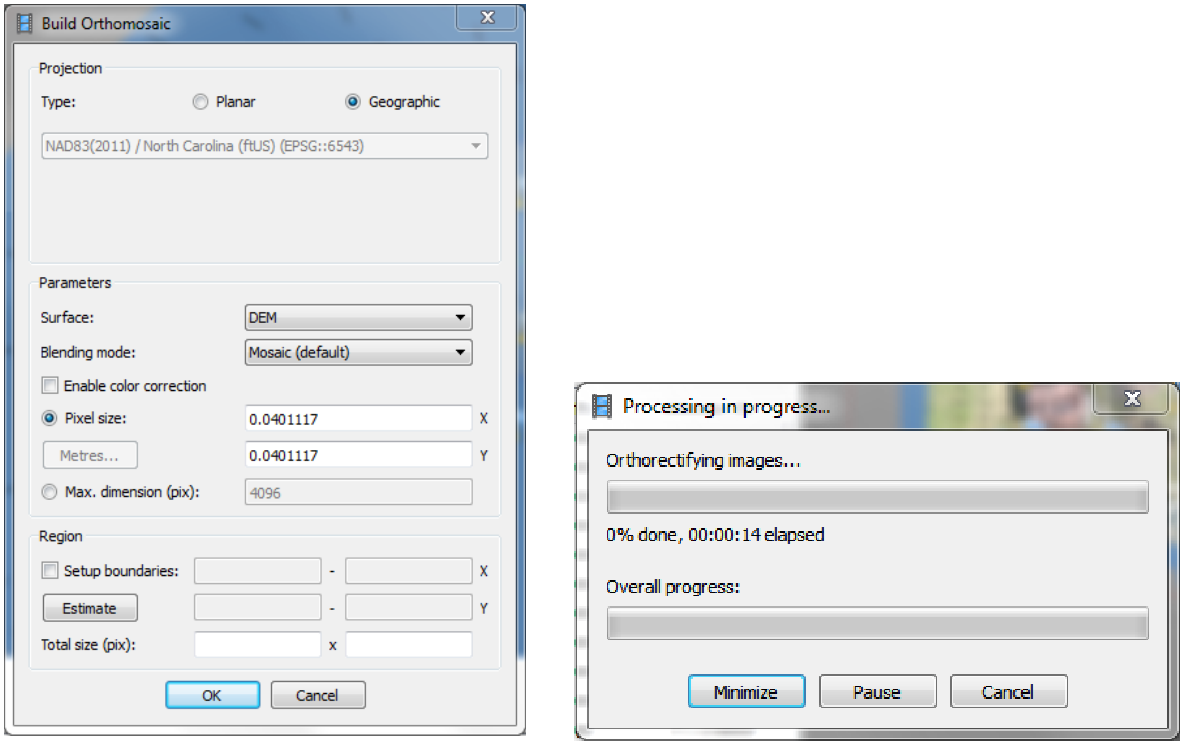
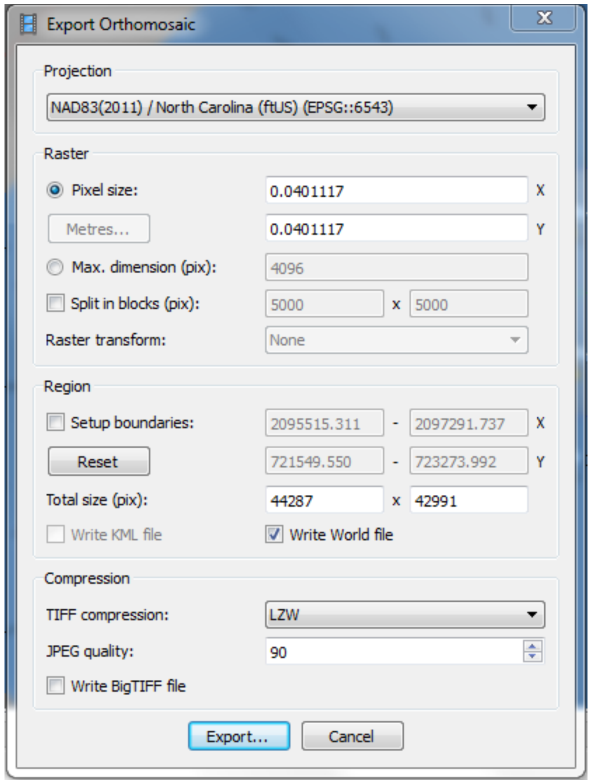


Figure 83: Build Orthomosaic settings window

Export Orthomosaic & DEM

To export an orthomosaic, select File -> Export Orthophoto -> Export JPEG/TIFF/PNG. A process window will display as the orthomosaic is being exported. Keep all the default settings unless told otherwise. These settings include projection type, file format, blending mode, pixel size, etc.

To export a DEM, select File -> Export DEM -> Export JPEG/TIFF/PNG. A progress window will display on the graphical user interface. Keep all the default settings unless told otherwise. These settings include projection type, file format, blending mode, pixel size, etc. Save all the default files.



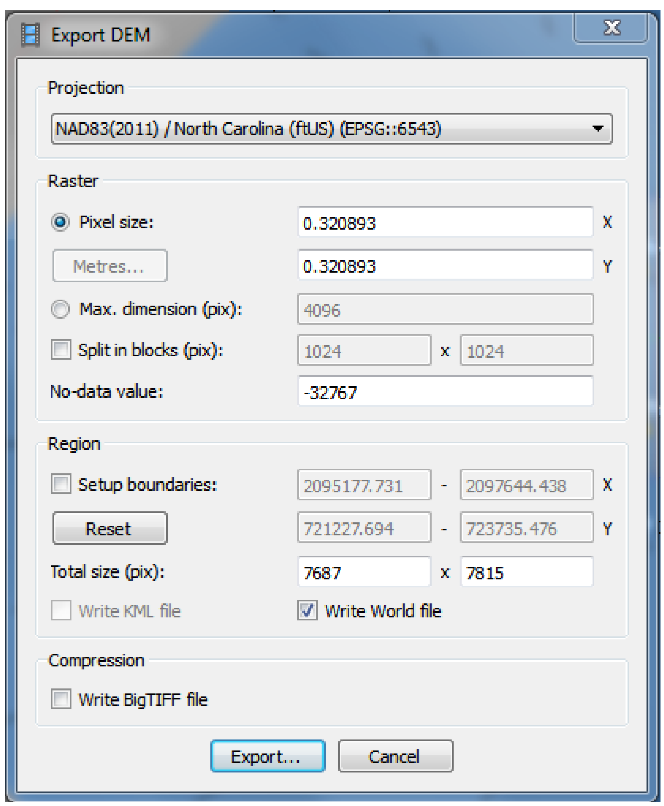
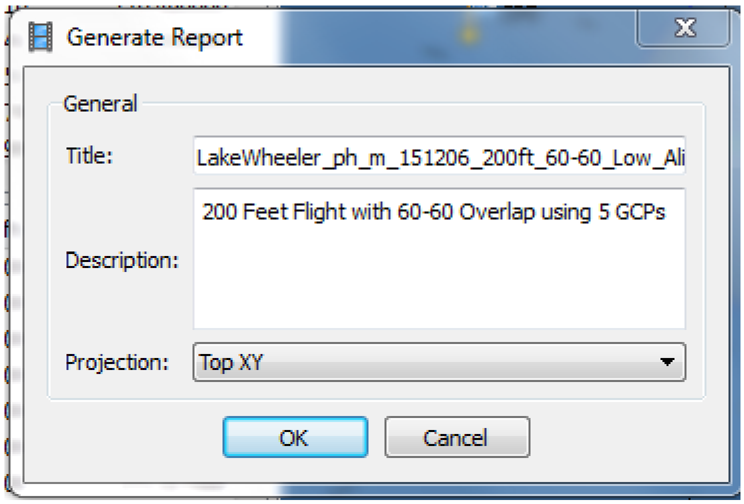


Figure 84: Export DEM settings

Generate Report

To generate a processing report, select File -> Generate Report, and specify a file name and location. A processing report is automatically generated at the end of every project. The report includes a thumbnail of the orthomosaic, DEM, statistics, number of 3D points, projection errors, etc. Be sure to open the file and make sure the information is correct. Save the project after this step is completed.



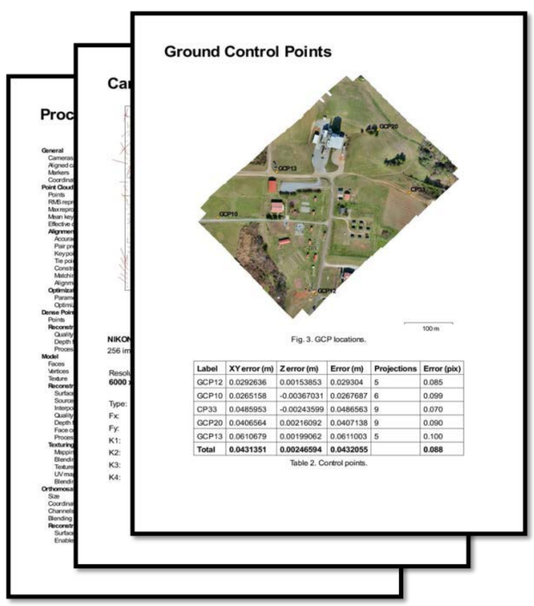


Figure 85: Example of a generated processing report

Memory Requirements

Memory storage plays a major role in a project. The following sections will highlight key requirements depending on the size of the project. The fewer images and settings requires less memory versus its counterparts.

Aligning Photos

The memory consumption is influenced by the number of images aligned and the accuracy setting being used. The image resolution is not a factor while the photos are being stitched together. Figure 10 provides a general idea of the memory requirements for the size of the project.

Photos	100	200	500	1000	2000	5000	10000
Memory consumption	500 MB	1 GB	2.5 GB	5 GB	10 GB	25 GB	50 GB

Figure 86: Information provided by P, Alexey

Building Model

Memory consumption in height-field mode depends on the number of photos, the resolution, the selected quality, and overlap. There is a linear correlation between the number of photos and the resolution.

The following table approximates memory consumption for 24.1 megapixel photo resolution.

Photos	100	200	500	1000	2000	5000	10000
Lowest quality	25 MB	50 MB	125 MB	250 MB	500 MB	1.25 GB	2.5 GB
Low quality	100 MB	200 MB	500 MB	1 GB	2 GB	5 GB	10 GB
Medium quality	400 MB	800 MB	2 GB	4 GB	8 GB	20 GB	40 GB
High quality	1.6 GB	3.2 GB	8 GB	16 GB	32 GB	80 GB	160 GB
Ultra-high quality	6.4 GB	12.8 GB	32 GB	64 GB	128 GB	320 GB	640 GB

Figure 87: Information provided by P, Alexey

Building Model (Arbitrary Processing)

Arbitrary processing mode is designed for compact objects, mainly captured from the ground level. It can be used to process data sets containing up to several hundreds of photos. Memory consumption in arbitrary mode depends on the number of photos, the resolution, the overlap, the selected quality level, the shape of the object.

The following table approximates memory consumption for 24.1 megapixel photo resolution. Please note that memory consumption depends significantly on the kind of object being processed.

Photos	20 - 50	100	200	500
Lowest quality	100 MB - 300 MB	150 MB - 450 MB	300 MB - 1 GB	1 GB - 3 GB
Low quality	500 MB - 1.5 GB	750 MB - 2.2 GB	1.5 GB - 4.5 GB	4 GB - 12 GB
Medium quality	2 GB - 6 GB	3 GB - 9 GB	6 GB - 18 GB	15 GB - 45 GB
High quality	8 GB - 24 GB	12 GB - 36 GB	24 GB - 72 GB	60 GB - 180 GB
Ultra-high quality	32 GB - 96 GB	48 GB - 144 GB	96 GB - 288 GB	240 GB - 720 GB

Figure 88: Information provided by P, Alexey

Decimating Model

The memory requirement for model decimation depends on the initial polygon count. In other words, memory consumption cannot be saved if the target faces are broken up into smaller sets.

Faces (millions)	1	5	10	20	50	100	200	500
Memory consumption	128 MB	640 MB	1.3 GB	2.5 GB	6.2 GB	12.5 GB	25 GB	63 GB

Figure 89: Information provided by P, Alexey

Agisoft Recommended Hardware

In addition to memory, hardware platform selection is important when operating Agisoft PhotoScan. The size of the project is limited by the amount of RAM available in the hardware. Therefore, it is important to select a hardware platform that flexible to installing additional RAM.

Please check Memory Requirements section above for estimated RAM requirements for the kind of projects you are going to process. This information is provided by Agisoft in the Memory Requirements section of the user guide.

1. Basic configuration (up to 32 GB RAM)
   CPU: Quad-core Intel Core i7 CPU, Socket LGA 1155 (Sandy Bridge or Ivy Bridge) Motherboard: Any LGA 1155 model with 4 DDR3 slots and at least 1 PCI Express x16 slot
   RAM: DDR3-1600, 4 x 4 GB (16 GB total) or 4 x 8 GB (32 GB total) GPU: Nvidia GeForce GTX 580 or GeForce GTX 680 (optional)
2. Advanced configuration (up to 64 GB RAM)
   CPU: Six-core Intel Core i7 CPU, Socket LGA 2011 (Sandy Bridge-E) Motherboard: Any LGA 2011 model with 8 DDR3 slots and at least 1 PCI Express x16 slot
   RAM: DDR3-1600, 8 x 4 GB (32 GB total) or 8 x 8 GB (64 GB total) GPU: NVidia GeForce GTX 580 / GeForce GTX 680 / GeForce GTX 780 / GeForce GTX TITAN
3. Extreme configuration (more than 64 GB RAM)

For processing