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Multicopter-Based Small Format Aerial Photography using Free and Open Source Photogrammetry

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MULTICOPTER-BASED SMALL FORMAT AERIAL PHOTOGRAPHY USING FREE AND OPEN SOURCE PHOTOGRAMMETRY

A thesis submitted to
the Graduate College of
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In partial fulfillment of
the requirements for the degree of
Master of Science
in
Physical and Applied Science: Geobiophysical Modeling
by
Robert Matthew Davis
Approved by
Dr. Ralph Oberly, Committee Chairperson
Dr. Anne Axel
James Wolfe, M.S.E.

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ABSTRACT

A process is described to convert aerial photographs from flat images to 3D point clouds and then convert into height maps to be used as pseudo digital elevation models for surface modeling. All software used in the process is either free or open source. The process uses a DJI Phanton multicoper and two Canon point and shoot digital cameras. One camera is unaltered, and a second camera is modified to produce infrared images. A DJI Phantom FC-40 multicopter is used as the aerial platform to carry the cameras. Multiple paths are described to convert from still images (or video to still images) to N-view matches, followed by sparse point clouds then dense point clouds. Point clouds are distinct 3D points charted in an XYZ coordinate system. The dense point clouds can be converted into 3D models for viewing and analysis. A height map is extracted from the point cloud and surface images (in raster format) are created and then used in QGIS or ArcMap as pseudo digital elevation models for surface modeling. Finally, the digital elevation models are evaluated in comparison to similar LIDAR images.

Keywords: Passive Remote Sensing; LIDAR; Spatial Resolution.

CHAPTER 1

INTRODUCTION

Background

Aerial photography is almost as old as photography; since the invention of the camera photographers have wanted to capture images of interesting subject matter in new and innovative ways. Technological innovations have improved photography, better glass led to better lenses, innovations in chemistry led to better film, engineering and physics led to photo resistors for digital sensors, and computer science led to ways to store large image files on solid state storage. What some people may not understand is that innovations in photography have also led to technological innovations in other fields. The invention of the airplane to the first commercial jet flying passengers happened in a span of less than 50 years. These innovations were heavily pushed due to the advent of aerial photography. Telecommunications as we know them today might not exist if it were not for the first spy satellites developed during the cold war. The need for airplanes that can fly for extended periods of time across very large distances without the need for constant human control led to the development of modern military drones to take pictures and video of targets. It could be argued that their development has had a trickledown effect and created a civilian market with a demand for low cost flying platforms to capture videos for entertainment and research. Just as technology pushes innovations in aerial photography, aerial photography has pushed innovations in technology.

History and Development of Aerial Photography

Aerial Photography can trace its roots back to the first half of the 19th century in France. With the invention of the heliograph by Nicephore Niepiece and subsequently Louis Daguerre and Niepiece's invention of photography in 1839 the groundwork was created for aerial photography (Schenk, 2005). It was only a few years later when "French pioneer photographer Nadar (Felix Tournachon), affixed a camera to the basket of a balloon and took the first successful aerial photographs near Paris in the spring of 1856" (Smith, 1985). By 1859 his aerial photos had garnered such attention that the French Minister of War asked him to use his expertise in aerial photography to experiment in battlefield intelligence, but he refused (Smith, 1985). A year later, on the other side of the Atlantic, J.W. Black received notoriety for his aerial photographs of Boston. This led to General McLellan of the Union Army to use a photographer in a tethered balloon to take photos, then return to the ground and create two identical grids of the city of Richmond. The general used a photographer in a balloon to telegraph back enemy locations using the grid diagrams, during the siege of Richmond (Smith, 1985). This strategy worked and set into motion a series of technological innovations that have led to modern aerial photography and remote sensing.

After inventing the airplane with his brother, Wilbur Wright travelled around Europe to demonstrate their invention. He flew outside the city of Centocelle, near Rome, accompanied by a photographer who took photographs from Wilbur's simple airplane (Taylor et. al, 1978). At about the same time, just a few miles away, the first true aerial photos were being taken. "The first successful still photographs taken from an aeroplane were by M. Meurisse, in December 1909, and showed the flying-fields at Mourmelon and Chalons (France)" (Taylor et al., 1978). By 1915 Lieutenant Moore-Barbazon of the Royal Flying Corps led a small airplane-based aerial photography unit which mapped the trenches during World War I. Sir Douglas Haig was able to use this intelligence in the attack at Neuve Chapelle and immediately afterwards there was a demand for aerial photographic reconnaissance (Taylor, et. al, 1978). Prior to this, airplanes had been small and very lightweight machines made of wood and canvas and fitted with small engines, unable to carry much in the way of weaponry. Afterward, there was an arms race between England/France and the Germans. Improvements in airframes, engines, cameras, guns, and technologies to effectively shoot guns from airplanes followed. The rapid developments in photographic equipment, processing, and analysis pushed by the war continued in the form of civil aerial photography during the period between World War I and World War II. Based on the intelligence derived from aerial photography during World War I, General von Fritsch, the Commander-in-Chief of the German army, made the statement that he believed the side with the best photographic reconnaissance would win the next war. He died in 1939 before seeing his prediction come to fruition (Smith, 1985).

Now jump ahead to 1960. By this time aerial photography was the basis for most USGS mapping. It was so normal there was even a specific format size for most aerial images. The images were large format, 23x23 centimeters, for most resource management programs (Meyer, 1997). For a reference, a standard 35mm camera has an aspect ratio of 2:3 and yields prints in 4x6 inches (Datta, 2006). That meant the standard format of an aerial photograph was about three times the size of a regular 35mm photograph. Taking large format aerial photos required expensive cameras, highly skilled photographers, pilots, special processing equipment and labs that could process these images. Even in recent years, hiring a contractor to collect aerial images can be cost prohibitive, costing as much as $24,000 to $43,000 for an area of 150km^2 (Mumby et al., 1999). The expense of producing aerial photographs proved to be a serious limitation, and resulted in low temporal resolution of coverage. “Most of this large format coverage was, because of cost, obtained at 8 - 10 year intervals, and employed B&W photography” (Meyer, 1997).

In the 1960s if a student or independent researcher wanted an aerial photograph of a location they would have to order it from the United States Geological Survey (USGS) or private contractor, and they were limited to the stock inventory, unless they had the funds to hire a contractor to photograph an area of interest. The solution came from a relatively common source, and mirrored the initial developments of aerial photography. At this time 35mm film for consumer cameras could be purchased in not only black and white, but also color, and color infrared, and it could be processed with the same chemicals used for most true color film (Meyer, 1997). A new style of small format aerial photography was created. Researchers found that they could use balloons, kites, and even rockets to get their cameras into the air to take photos of their areas of interest. For the most part, small format aerial photography was limited to students and researchers. “Initially, technique development in the U.S. began with individual investigators working with very modest equipment and even more modest funding - often out of their own pockets. Since many of their findings were of interest, more organized groups such as public land management agencies and a few academic institutions took notice and began serious work in development” (Meyer, 1997). Small format aerial photography was not widely adopted in America, Canada was a completely different story.

Canadian Small Format Aerial Photography as a Cost Effective Solution

Canada is much further north of the equator than the contiguous United States and the weather, even during the short summers, can be unpredictable. Large format aerial photography was not always possible for all areas of interest, and it was not uncommon to have to cut missions short due to changes in weather. “In 1958, (Canada) launched a comprehensive program of systematic forest inventory based on aerial photography” (Zsilinszky, 1997). The Canadian Forest Service (Forest Research Inventory or “FRI”) was given the task of photographing 170,000 sq. miles at a scale of 1:15,840 and the seasons, terrain, and weather were not on their side (Zsilinszky,1997). They needed a solution that could be used in places that were inaccessible to ground studies, a solution that could fill in gaps caused by unsafe weather conditions, and above all else it had to be cost effective. Once again, off-the-shelf consumer cameras came into use for research. In 1967 engineers mounted a Nikon F Camera with a 250 exposure motorized back, an intervalometer, a battery pack and a 55mm Auto-Micro Nikkor Lens on a shock absorber mounted on a circular piece of plexiglass that could be mounted on an aircraft’s cargo hold (Zsilinszky, 1997). The project was a success filling in the gaps and supplementing large format aerial photographs. This consumer camera assembly opened up the possibility of turning any plane into an image collection platform. Despite the success, the field of remote sensing took a different turn, one that steered away from aerial photography. In 1972 the United States launched Landsat 1. With the proliferation of computers and advancements in digital image processing and the availability of large datasets from the USGS, small format aerial photography’s role gradually diminished. The advent of consumer digital cameras in the early 1990s brought small format aerial photography back into general use.

Modern Small Format Aerial Photography for Photogrammetry

In 1994 Ron Graham and Jon Mills of the University of New Castle in the United Kingdom experimented with a Kodak DCS digital camera mounted on an ultralight aircraft to produce digital aerial photographs of St. Neots, Cambridgeshire. Over the next three years they and other remote sensing researchers had different degrees of success. The American Society for Photogrammetry and Remote Sensing (ASPRS) took notice and in 1997 held a symposium they billed as “The First North American Symposium on Small Format Aerial Photography.” By 1997 Graham and Mills had pushed beyond just flat images and conversion of aerial photographs into orthophotos, and were about to embark on a different form of photographic analysis and into the realm of photogrammetry.

The development of photogrammetry followed the development of photography and the two were often intertwined. Photogrammetry is the science of obtaining reliable information about the properties of surfaces and objects without physical contact with the objects, and of measuring and interpreting this information (Schenk, 2005). It is defined by ASPRS as “The art, science, and technology of obtaining reliable information about physical objects, and the environment, through processes of recording, measuring, and interpreting images and patterns of electromagnetic radiant energy and other phenomena” (ASPRS, 1980). In photogrammetry, photos are taken with a calibrated camera (or stereo cameras) of items, objects, or geographical features. These photos are then processed so that measurements can be calculated with results in real world physical measurements of length, width, and height based on information extracted from the photographs. It is based on the work of German Physicist Carl Pulfrich who discovered stereo-photogrammetry in 1901 (Schenk, 2005). He discovered that the human brain will perceive depth while viewing two separate images (one viewed with each eye) of the same scene slightly shifted but with significant overlap. By taking images in pairs that are separated by approximately the same distance as the human eyes and then viewed in the same orientation, a user can perceive depth in the photos. This led to the first stereoplotter constructed by Orel in 1908 (Schenk, 2005). Through World War I and World War II significant improvements were made in stereoplotters and topographic maps. At that time there was not much in the way of computation. A famous researcher by the name of von Gruber was quoted as saying "photogrammetry is the art of avoiding computation" (Schenk, 2005). At this stage analogue photogrammetry needed a human operator to run a stereoplotter it was all done by human hand. By 1950 Helmut Schmid had access to computers and began using matrix algebra to analyze photos. "For the first time a serious attempt was made to employ adjustment theory to photogrammetric measurement" (Schenk, 2005). By the 1960s Duane Brown had "developed the first block adjustment program based on bundles" (Schenk, 2005). After this development many industries began using photogrammetry as a means of producing accurate measurements of real world objects. At this stage of development digital photogrammetry was not being used by researchers using small format aerial photography. It was not until 1997 that Ron Graham and Jon Mills, of the University of New Castle in the United Kingdom, began using their stereo imagery collected during their small format aerial photography research along with a software package designed to work with commercial large format aerial photographs. With the use of VirtuoZo they were successful in creating digital elevation models with a 250mm cell size (Graham et al., 1997).

Statement of the Problem

Small format aerial photography based surface modeling can be a cost effective, scalable, high spatial resolution, high temporal resolution solution for creating GIS compatible data representations of real world surface features. There is a demand for user-created digital surface models and currently there are only a few options. Users must employ terrestrial based laser scanners such as Leica Geosystems Scanstation P20, an aerial platform such as an airplane carrying a LIDAR scanning system, or satellite based systems such as ASTER.

Laser scanning systems such as the terrestrial based Leica Geosystems Scanstation P20 has a maximum scan resolution between 55 millimeters (with scan times of 20 minutes) and 0.8 millimeters (with longer scan times upwards of 54 minutes) (Leica, 2014). The systems are designed to have a high level of accuracy and precision, but with that comes a price. The Scanstation P20 retails for $123,915.00 and does not include any accessories (other than a tripod and a plastic carrying case), or training, and it also does not include the software to process the information it gathers. The software for processing this data requires a license with a price tag that starts at $22,575.00 (Leica, 2014). This system is also limited to a range of 120 meters.

Satellite systems such as ASTER create digital elevation models with a ground cell size of 30 meters by 30 meters with elevation measured in one meter increments (Fujisada, et al, 2012). This means that in any given area with a ground cell size of 900 square meters ASTER will give a single elevation value as a digital number. For each cell in an ASTER digital elevation model (DEM) the digital number (DN) values are determined by an algorithm which calculates the median value for all points collected in the cell and produces a single DN value (Fujisada et al, 2012). For many applications such as mapping watersheds, city planning, or large scale agriculture this is a high resolution but if you wanted to model a small park, neighborhood, rock outcropping, sandbank, or coal stack, the spatial resolution is just too low. The temporal frequency at which ASTER collects global Digital Elevation Models is unpredictable. As of 11/1/2014 there was only one dataset available from USGS Earth Explorer for Barboursville, West Virginia collected 10/17/2011, approximately three years ago.

Aerial LIDAR scans completed using airplanes scanning the earth's surface in swaths are available free to the public from USGS's Earth Explorer for this study area (but are not freely available for many regions). They were created by federally funded contractors, and in the case of this project's area of interest that contractor was Woolpert Inc. of Dayton, Ohio. The data that are available have a date of acquisition of 3/18/2009. These scans have a higher spatial resolution, 0.8 meter by 0.8 meter pixels, with an elevation interval in meters. The area of interest was completely encompassed in 2 frames, but each frame was almost unusable due to large artifacts which ran the entire length of the frames.

The final option for surface modeling is via topographic maps created from stereo photos collected by the USGS. These are free to download; users do not need to know anything about stereo photos, interpolation, or 3D modeling to use them. The topographic maps can be accessed for free via the USGS Store website (http://store.usgs.gov/b2c_usgs/b2c/start/(xcm=r3standardpitrex_prd)/.do) accessed 11/4/2014. ArcGIS and QGIS both have the ability to georeference these and extract the elevation via recognition of topographic lines. In ArcGIS the topo to raster tool creates digital elevation models based on the topographic lines. In QGIS there are multiple options including Inverse Distance Weighting, Raster Interpolation, and external plugins. Both of these pipelines will create a digital elevation model, but they are limited to the topographic scale of the USGS maps. ArcGIS and QGIS are limited to creating a raster based on a topographic map based on the real world stereo images. The end result is a generic interpolation of the earth’s surface at the area of interest.

In 2012, Anthony Turley (2012) reviewed the suitability of off the shelf aerial platforms for aerial photography and discovered that radio controlled airplanes can be used for small format aerial photography. After attempting to use two different airplane models he found there were limitations inherent in their designs. Turley found that radio controlled airplanes need wide areas for take-off and landing. Airplanes have to keep moving so camera settings have to be adjusted accordingly. He encountered a problem where it was difficult to keep the aircraft at a constant altitude due to the effects of wind. The changes in altitude, caused by wind, affect the scale of the photographs. When an intervalometer is set on a camera it takes photos at a set frequency of time regardless of plane altitude. Changes in photo scale can introduce errors when mosaicing the resulting images. These images will have a different scale and the resulting inconsistency will affect the ground resolution. In the resulting images, some areas will appear very clear, but others may appear blurry. In addition to the changes in altitude, wind can cause the radio controlled airplane to change pitch, roll, and yaw. This can introduce distortion. These images taken off nadir will be oblique and may be unusable for mapping due to being difficult if not impossible to georeference.

Proposed Solution

After having some success with using a multicopter and consumer cameras to do vegetation indices, the author chose this as a solution to some of the problems which Anthony Turley encountered in his research. The multicopter was chosen to carry the cameras due to its stability, small take off and landings, as well as its ease of use. It also did not need to have a continuous forward motion to generate lift; it is able to hover in one place and take multiple images. This ability to hover helps to eliminate distortion in the images caused by motion of the aircraft.

Small format aerial photography suffers from radial distortion based on the curvature of a camera's lens. Small format aerial photography also suffers from another setback in the form of relief distortion. Objects that are closer to a camera's lens appear larger in the resulting images. Satellite images also have this drawback but due to their distance from the objects they are viewing the relief displacement is limited. Due to the fact that radio controlled aircraft are limited in how high they are capable of flying, relief displacement is a serious issue in collecting images. With the use of multi view stereo image processing, 3D points can be extracted and used to create a surface model in the form of a raster.

The DJI Phantom FC-40 is a four propeller multicopter made by the DJI corporation. It weighs in at 1000 grams and the manufacturer claims that the takeoff weight is less than 1200 grams. The Canon A2500 cameras used as the imaging system weigh in at approximately 184 grams each.

The DJI Phantom's ability to fly under radio control made it a versatile flying platform for carrying cameras. The DJI Phantom carried a payload of two Canon point and shoot digital A2500 cameras to collect digital images. These digital images were sorted for best characteristics, then using multiple pieces of software, which are free and open source, the images were processed by a system called Scale Invariant Feature Transform (SIFT). The resulting file is opened with Cloud Compare and exported to a raster. At that point the result is a raster with values corresponding to heights of real world objects which were photographed. The raster can be opened in ArcMap or QGIS and georectified then used for surface modeling.

CHAPTER 2

METHODS

Study Sites

Two distinctly different study sites were chosen for this project. The first was Green Bottom Wildlife Management Area in Glenwood, WV (see Fig.1). Glenwood has a small population and there is only one road which passes by the wildlife management area. The relative obscurity of the area helped to reduce members of the public travelling through the location. Human beings moving around on the ground have the potential of being photographed and the resulting images could cause false feature matches. The software cannot differentiate between a tree and a person, so a human travelling in real world 3D space could be perceived by Scale Invariant Feature Transform (SIFT) as a geographical feature that is present in more than one location. The wildlife management area has diverse topography of road, forest, high grass, and wetland areas. The terrain is a good mix of different surfaces and textures with a large number of very recognizable surface features. Hundreds of different plant species are visible to the human eye, creating natural patterns on the earth’s surface. This area was photographed in midsummer when the vegetation was very green and dense.

Fig. 1 Image from Google Earth of Green Bottom Wildlife Management Area.

The second site was a section of Barboursville Park in Cabell County, West Virginia (See Fig. 1.2). Barboursville Park was chosen for its highly visible topography. The area of interest was a steep hillside that drops off just past the park's baseball fields. This area was covered in mowed grass with a visible mowing pattern. Barboursville Park also has some trees, utility poles, a creek, and a hill that drops off steeply then levels off and drops off again before getting to a small road. This area was photographed in mid-fall while the trees still had leaves.

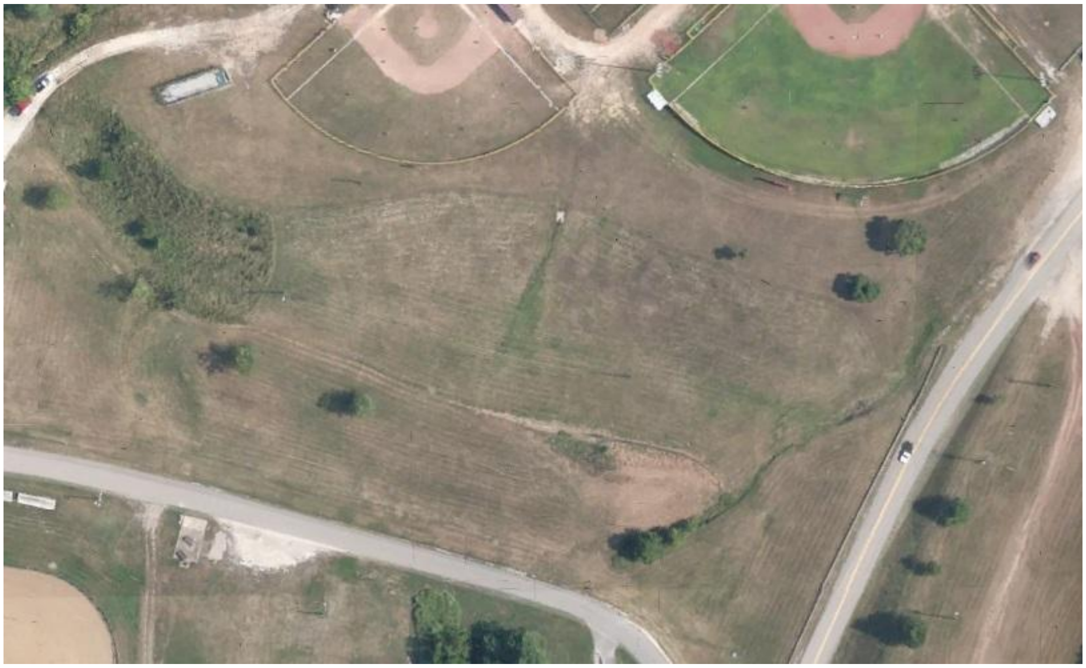


Fig. 1.2 Image of Barboursville Park from Google Earth.

Aircraft Platform Selection and Customization

Following the work of Anthony Turley, some pitfalls were avoided. During his study he repeatedly had an issue with his model airplanes being able to maintain altitude. The aircraft had to have continuous forward motion to stay aloft, and his system used an autopilot to control the flight path. While the aircraft was aloft, it suffered from the force of the wind. In order to avoid a similar fate and to keep cost to a minimum, I used a multicopter for this project. The multicopter did not need to have continuous forward motion to stay aloft and could hover over an area for sufficient time to take multiple photos of the same area. By doing this the operator could give the multicopter time to get several pictures of areas with complex surfaces. Having this as an option was especially helpful with parts of the Green Bottom site. Some areas of the Wildlife

Management area have very dense trees and brush. Having the ability to leave the multicopter hovering over a small area to take several photographs increased the likelihood that they would yield usable information. The multicopter is flown manually, and this provides the benefit of being able to hover over specific areas so that the cameras can capture more images. Flying manually gives the user the ability to move quickly over features which are smooth, and hover over areas with dense features so more images can be taken.

Prior to any flying or aerial photography the DJI Phantom FC-40 had to be retrofitted with a bracket to carry the cameras as a payload. As mentioned earlier the maximum carrying capacity of the multicopter as listed by the manufacturer is “less than 1200 grams” and the multicopter, in its stock configuration, weighs 1000 grams (DJI, 2014). After the cameras were weighed with a postal scale, their combined weight was recorded as 368 grams. This meant that the two cameras put the total weight of the DJI Phantom over the maximum payload, with a total weight of 1368 grams. Despite being overweight the multicopter was able to fly.

A lightweight bracket was constructed from two Ziploc™ sandwich style plastic containers, zip ties and 3M contact strips. The Canon A2500 cameras were also not ready in their stock configurations. One camera was converted to an infrared camera with the aid of a guide retrieved from Publiclabs.org (Best, 2013). The near infrared filter was removed, and the camera was reassembled. The Canon A2500 cameras include a timer feature but it is limited to a three shot burst on a 60 second timer. That option was not sufficient to get the ground coverage needed to cover the areas of interest. The Canon Hacker’s Development Kit (CHDK, available at http://chdk.wikia.com/wiki/CHDK) was installed on each camera’s 2GB SD memory card. CHDK works as a user interface for the Canon Camera. It provides access to additional options that are not otherwise accessible to users due to restrictions in the camera’s proprietary software.

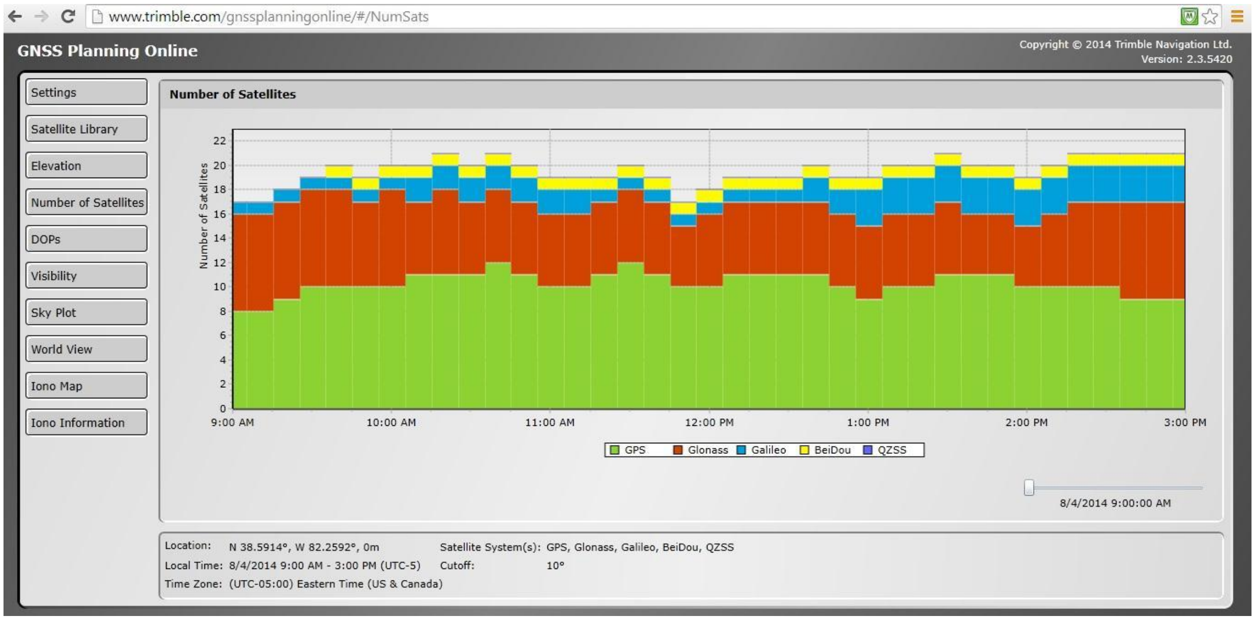
CHDK can run scripts written in uBasic, and includes several common scripts. The script necessary for this project was “Intervalometer” which came included with the CHDK. This script was used to set the camera to take a photo at a set time interval, with the option of repeating x number of times, or setting x to infinity. For this project five seconds was the standard interval between photo shots chosen for both cameras. Cameras were also set to take photos an infinite number of times (until the camera’s battery or memory card were exhausted).

With the added weight of the two cameras and the bracket to hold them, the maximum weight for take offs and landings based on the manufacturer’s documentation was exceeded. The craft was able to fly, but flight times were reduced to approximately eight minutes per battery. There were three batteries purchased, but even with those, the maximum flying time was only about three flights with a duration of eight minutes each. It takes approximately three hours to charge each battery, so all batteries had to be charged before going to areas of interest. After attempting to photograph Green Bottom with no pre planning resulted in large gaps in coverage and unusable images a different method of flying had to be considered.

Limitations in flight time meant that time on target had to be planned out, and pre planned flight paths needed to be decided before going to the area of interest. After a few simple experiments were completed to determine how long each battery would last, eight minutes was decided as the best time to land. Any flights that lasted more than eight minutes resulted in hard landings, or rapid decreases in altitude. There were no crashes, but there was one especially hard landing that broke the cameras free of their housing, yet resulted in no damage except for a few broken zip ties.

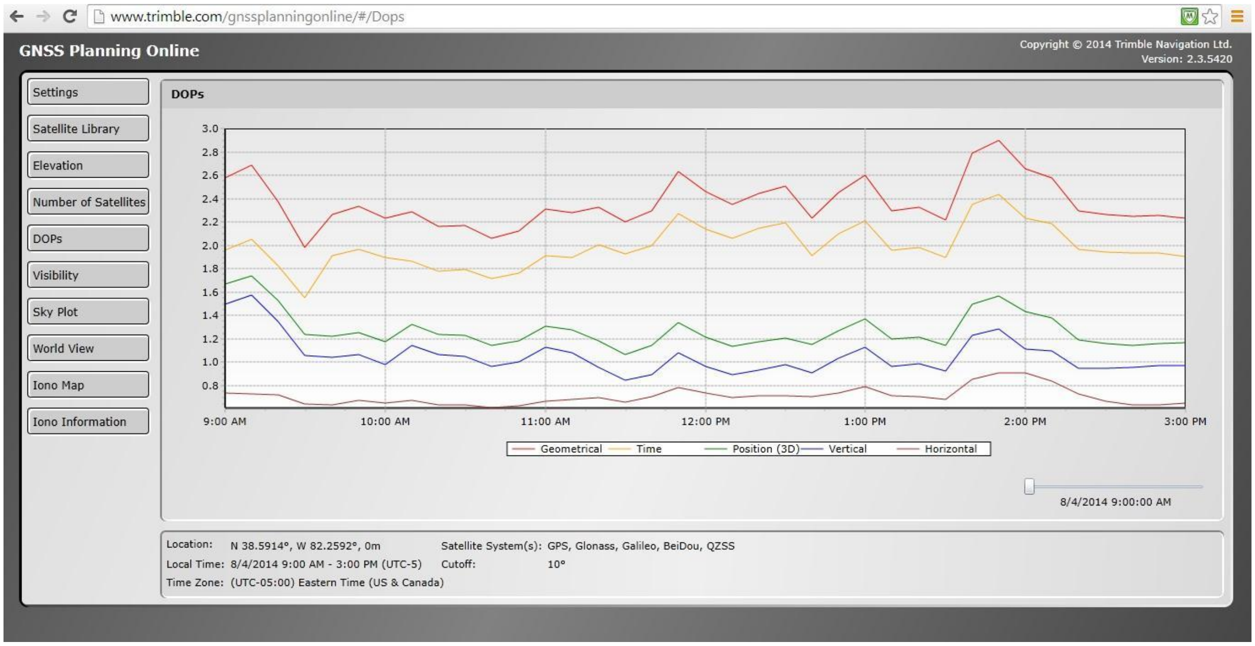
Mission Planning

Some mission planning was required for best results. The DJI Phantom requires six satellites for acquisition of a global positioning system (GPS) ground control point for the Naza-M GPS Lock System (DJI, 2014). The ground control point was used as the starting point for flight, and it needed to be an area where the DJI Phantom could return in the event of an emergency, low battery or loss of connection between the receiver and the transmitter. A ground control point requires acquisition of a GPS location with a very low Positional Dilution of Precision (PDOP). “The Positional Dilution of Position (PDOP) describes how good or bad the satellites' geometry is for a user. PDOP has no measurement unit, but is rather a multiplier of existing error” (U.S. Air Force, 2014). By using Trimble’s GNSS Planning (http://www.trimble.com/gnssplanningonline), users can collect data about satellite availability at their field site (Trimble, 2013). Green Bottom Wildlife Management Area was photographed at 9:00 AM on August 4, 2014. During the Green Bottom flight, at least eight satellites were available, and PDOP was very low at approximately 1.7 (See Fig. 1.3 and 1.4). Barboursville Park was photographed at 10:30 AM on October 19, 2014. During the Barboursville Park flight, at least eight satellites were available, and PDOP was very low approximately 1.3 (See Fig. 2 and 2.2). These flight times were selected due to favorable weather, limited number of human presence, and low PDOP.



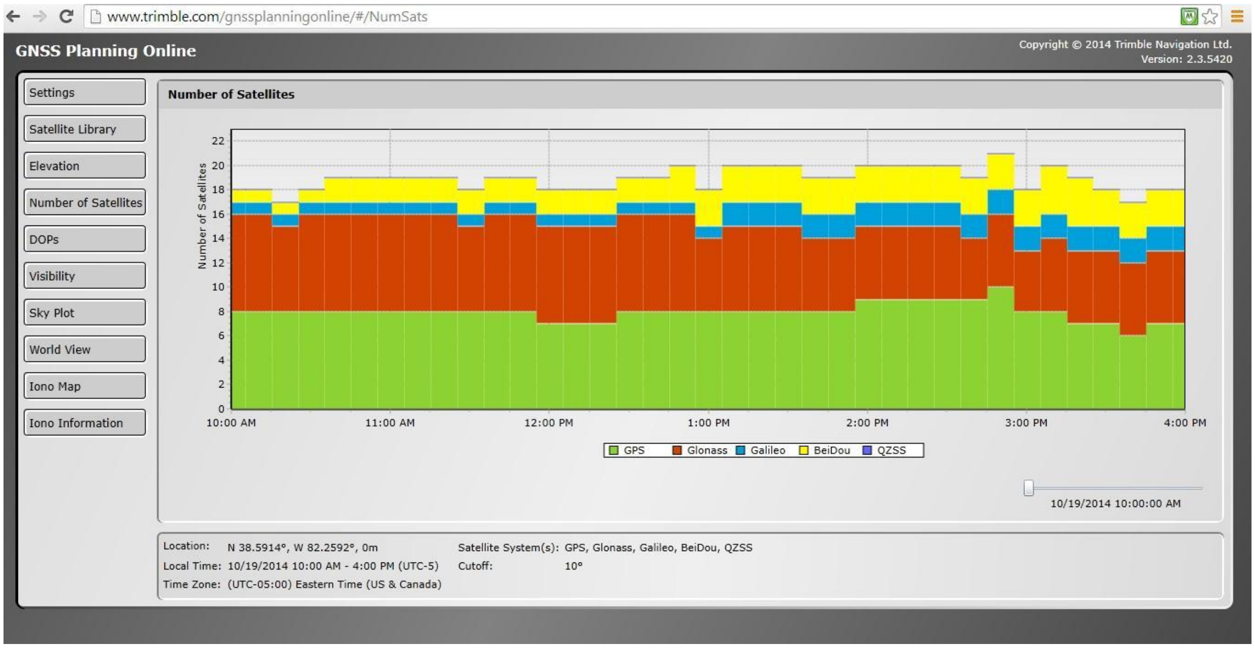
Location: N 38.5914°, W 82.2592°, 0m
Satellite System(s): GPS, Glonass, Galileo, BeiDou, QZSS
Local Time: 8/4/2014 9:00 AM - 3:00 PM (UTC-5)
Cutoff: 10°
Time Zone: (UTC-05:00) Eastern Time (US & Canada)

Fig.1.3 Green Bottom Visible Satellites at 9:00 AM on 8/4/2014. Eight GPS Satellites were visible (Trimble, 2013).



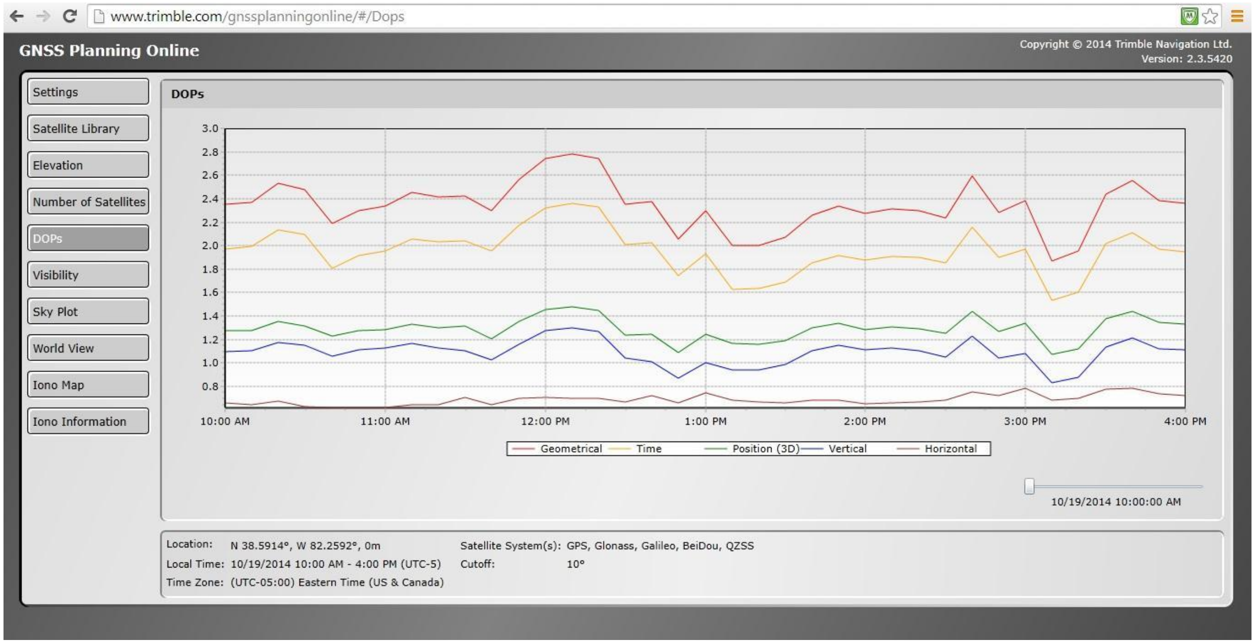
Location: N 38.5914°, W 82.2592°, 0m
Satellite System(s): GPS, Glonass, Galileo, BeiDou, QZSS
Local Time: 8/4/2014 9:00 AM - 3:00 PM (UTC-5)
Cutoff: 10°
Time Zone: (UTC-05:00) Eastern Time (US & Canada)

Fig 1.4 Green Bottom Dilution of Precision at 9:00 AM on 8/4/2014. PDOP was Approx. 1.7 (Trimble, 2013).



Location: N 38.5914°, W 82.2592°, 0m
Local Time: 10/19/2014 10:00 AM - 4:00 PM (UTC-5)
Time Zone: (UTC-05:00) Eastern Time (US & Canada)
Satellite System(s): GPS, Glonass, Galileo, BeiDou, QZSS
Cutoff: 10°

Fig. 2 Barboursville Visible Satellites at 10:30 AM on 10/19/2014. Eight GPS Satellites were visible (Trimble, 2013).



Location: N 38.5914°, W 82.2592°, 0m
Local Time: 10/19/2014 10:00 AM - 4:00 PM (UTC-5)
Time Zone: (UTC-05:00) Eastern Time (US & Canada)
Satellite System(s): GPS, Glonass, Galileo, BeiDou, QZSS
Cutoff: 10°

Fig. 2.2 Barboursville Dilution of Precision at 10:30 AM on 10/19/2014. PDOP was Approx. 1.3 (Trimble, 2013).

In Situ Image Collection

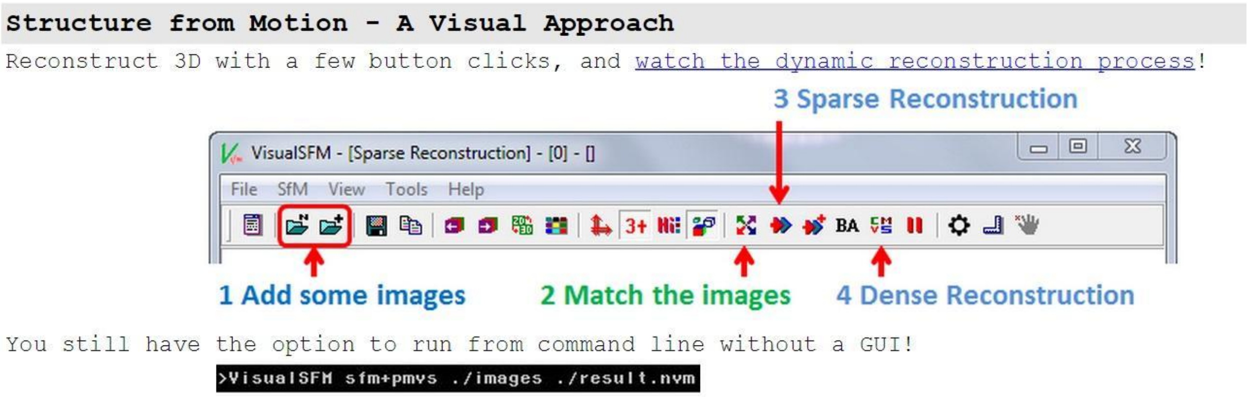
At each area of interest the photography process was the same. The cameras were powered on and synchronized by pushing the shutter buttons on each camera at the same time. They were connected to the DJI Phantom mounting bracket via 3M contact strips. The DJI Phantom's remote control was turned on and the DJI Phantom battery was connected. The NAZA-M GPS Lock System was activated by following the corresponding controls as detailed in the user manual. Using the remote control, the multicopter was flown to an appropriate height based on visual observation. The multicopter was flown in multiple linear overlapping strips, as best as possible via sight and manual operation. There was some rotation along the yaw of the DJI Phantom, with respect to its orientation at its starting point, but it was kept to a minimum so that all resulting images would be in similar orientation.

Image Sorting and Processing and Cloud Point Creation

After the flights, the memory cards were removed from each camera. The images were downloaded to a Windows PC. The images from the infrared camera had high pixel values in the red channel, causing them to appear pink; therefore, images were visually selected from the unaltered RGB camera. Using the time encoding on each of the cameras, the corresponding infrared images were located. When selecting images from the RGB camera, care was taken to select images with very little blur. Rotation and scale were also factors in the selection.

When Anthony Turley completed his project he relied on a GPS tracker to know the location of his craft and compared the timestamps of the image files to the time of the GPS to determine locations. He encountered a problem when he discovered that the GPS (at the consumer level) was not entirely accurate and he was not always able to use it for georectifying his images. This project took another approach, due to the restriction on weight; no additional equipment could be added to the aircraft. Rather than attempting to georectify using GPS tracking, a method of georeferencing to known visual surface features was employed. This was possible through use of Google Earth satellite images captured and exported to ArcMap or QGIS. By extracting an image of each area of interest with its accompanying geographical coordinate system, the raster digital elevation model could be registered to known ground points.

The selected images were opened with Visual Structure from Motion (VSFM) (Wu, 2011). Visual Structure from Motion is a graphical user interface in which a camera location and structure (known as structure from motion) can be estimated using an image and its focal length. (SfM: Structure from Motion 2014). Due to the apparent movement of a camera around an object that is assumed to be stationary, the structure can be approximated (Robertson, et al, 2009). Changchang Wu created an easy-to-follow four part process to help guide users through the process of loading images, matching coordinates, sparse point cloud generation, and dense point cloud generation (See Fig. 3) (Wu, 2011). Following Wu’s tool chain, the images are loaded into the software and displayed and the user then selects “Match the Images.” At this point users can see the images displayed and they have the opportunity to add more images or remove images. Next, the user can manually sort through matched images and remove false matches before they are processed any further. VSFM generates a file for each image called a Scale Invariant Feature Transform (SIFT).



Structure from Motion - A Visual Approach

Reconstruct 3D with a few button clicks, and watch the dynamic reconstruction process!

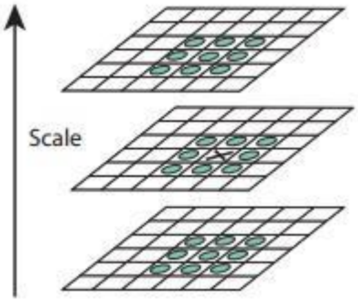
You still have the option to run from command line without a GUI!

```
>VisualSFM sfm+pmvs ./images ./result.nvm
```

Fig. 3 Visual Structure from Motion Steps 1-4 (Wu, 2011).

By using VSFM, the resulting models were in a scale of 0-255 and would require a scaling factor to convert them to feet or meters in elevation. In traditional photogrammetry calculations are made in real world units of measurement such as feet or meters based on commonly accepted equations. Scale = 1/(H/f) where H is the height of the camera above ground level, and f is the focal length of the camera (Sabins 1997). Height of an object can be calculated by h= (H*d)/r where h is the height of the object being measured, H is the height of the camera above ground level, d is the distance from the bottom to the top of the object in the image, and r is the distance from the principal point (the center of the image taken on nadir) to the top of the object being measured. Vertical exaggeration can be calculated with the equation VE = (AB/H)(AVD/EB) where AB is the air base, H is the height above ground level, AVD is the apparent viewing distance, and EB is the average distance between human eyes. With that information accurate measurements for photogrammetry can be made, (Schenk, 2005).

Lowe created an algorithm to process images independent of scale using SIFT (Lowe, 2004). He found that he could use a regular 3x3 kernel to classify features through “Difference of Gaussians.” Through an automated process the software would go up one level in scale and down one level in scale, running the same 3x3 kernel searching for features (see Fig. 3.1).



Maxima and minima of the difference-of-Gaussian images are detected by comparing a pixel (marked with X) to its 26 neighbors in 3x3 regions at the current and adjacent scales (marked with circles).

Fig. 3.1 Example image of SIFT Kernel (Lowe, 2004).

Lowe then had each image compared to every other image. A database of recognizable key points was created to link all related images. Then the software was able to determine each image’s orientation as compared to the real world scene.

Wu’s VSFM can use the SIFT files now associated with each image and reconstruct where in 3D space the camera had to be in order to take each of the images. The software will then create a sparse point cloud, followed by a dense point cloud which can then be exported as a 3D model in a Polygon File Format (.ply format). This is a common format in which 3D models are stored, and it can be opened and exported to more common file formats with a variety of software for 3D editing and modeling.

When importing the point clouds into Cloud Compare there was often an issue with their axes being tilted or some were completely flipped upside down. Care had to be taken to align the point clouds to real world orientation. Alignment was done by visually inspecting the elements and recognizing ground features that in the real world are at 90 degrees to the ground. Then the point clouds were rotated so that the x and y axes would represent length and width, and the z axis would represent height. Sometimes the orientation was not readily apparent, but after some trial and error an easy method to determine the orientation was to generate a scalar field of the model. Scalar generation results in the point cloud being classified in a visible scale from red to green. Red areas represented the highest elevations and the green and blue colors the lowest elevations. Once the orientation is established the models could be flipped or rotated to the correct orientation.

In initial trials which led up to this project, to keep weight down, only a single RGB camera was employed. The resulting point clouds were incomplete and unusable. It was not until the second camera was used to collect near infrared images in conjunction with the RGB camera that complete maps with continuous coverage was possible.

Processing time for point cloud models was lengthy. When only 36 images were used in the process the whole software tool chain only took about an hour to generate a model. When the number of images was increased to 140 processing time jumped to about 12 hours. In order to run SURE and convert the models into .las format that one step in processing took eight hours. Processing was performed on public computers at the Drinko Library and permitted to run all day.

This dense point cloud can be opened in Cloud Compare (CloudCompare (version 2.6.0), 2014), an open source software for 3D modeling. It can at this point be rasterized and exported as a jpeg. An alternative is to open the .ply point cloud with software SURE - Photogrammetric

Surface Reconstruction from Imagery (Rothermel et al., 2012). SURE takes the matched photos and exports a very dense point cloud as a LASer (.las) file format. The .las format is the same format used by laser scanners.

The .las can be opened with Cloud Compare and exported as a raster with x,y,z, values. Due to the higher density of points, .las files yield rasters with better spatial resolution. The exported rasters in jpeg format were then uploaded into ArcMap (ESRI, 2011) or open-source QGIS (QGIS Development Team, 2014) and georeferenced. At that point they were exported as geotiffs with elevation data in a scale from 0-255, 0 being the lowest and 255 being the highest. They can be used as digital elevation models, and are compatible with most tools that process rasters. The geotiffs are compatible with ArcMap and QGIS raster tools. For this project a series of hydrology tools were run to show how water would flow over the surfaces, and topography was run to compare to USGS topographic maps and digital elevation models.

CHAPTER 3

RESULTS

For Green Bottom Wildlife Area 36 usable images were selected from a cache of 762 images (381 RGB and 381 near-infrared). Eighteen images were recorded in near infrared and 18 color images were collected (see Fig. 4).

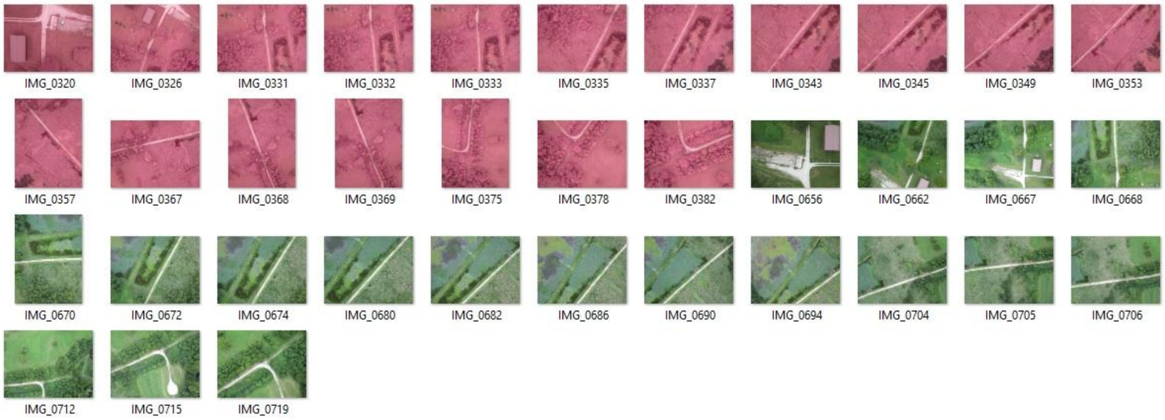
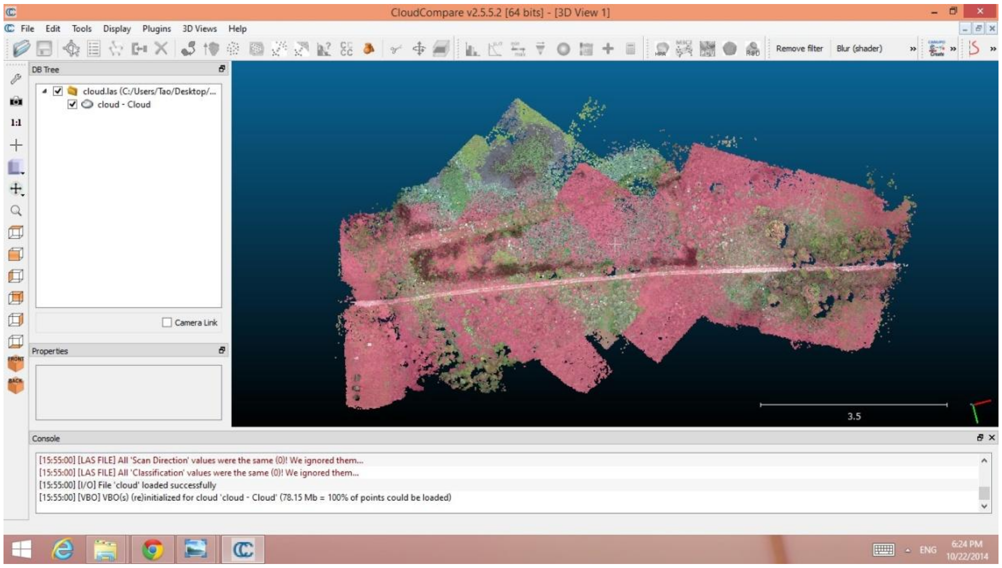


Fig. 4 Near infrared and color images collected at Green Bottom Wildlife Management Area.

These images were not the only images that could have been used, but they did represent a logical progression of overlapping coverage with minimal rotation and blur of the area of interest. The processing time took approximately one hour consisting of 20 minutes in VSFM to create SIFT files and a model (See Fig. 4.1), 25 minutes for SURE to create a very dense point cloud, and about 15 minutes for Cloud Compare to export as a raster in the form of a jpeg (see Fig. 4.2).

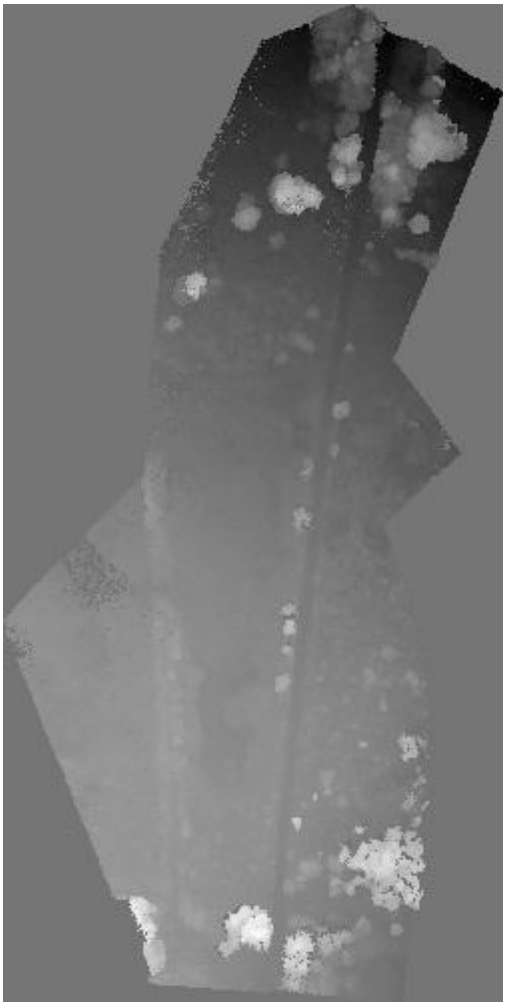


```
[15:55:00] [LAS FILE] All 'Scan Direction' values were the same (0)! We ignored them...
[15:55:00] [LAS FILE] All 'Classification' values were the same (0)! We ignored them...
[15:55:00] [I/O] File 'cloud' loaded successfully
[15:55:00] [VBO] VBO(s) (re)initialized for cloud 'cloud - Cloud' (78.15 Mb = 100% of points could be loaded)
```

Fig. 4.1 Model created with near infrared and color images.

The image produced of Green Bottom was not very useful. Some features could be picked out, such as the main trail through the Wildlife Area, and many trees and areas of dense foliage. USGS topographic maps for the same location were downloaded for comparison, but with 20 foot contour interval the area of interest could not be distinguished from the surrounding area (see Fig. 4.3).

Travelling from south to north across the image there is a small change in elevation according to the surface model. The surface model would indicate that traveling from the road to the river the elevation does slope downward. This raster was not much use for anything else; the area is mostly flat, and there were no visible watersheds.



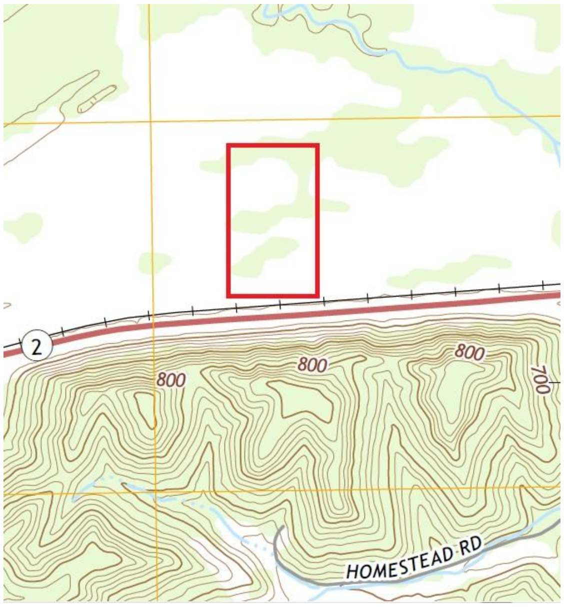
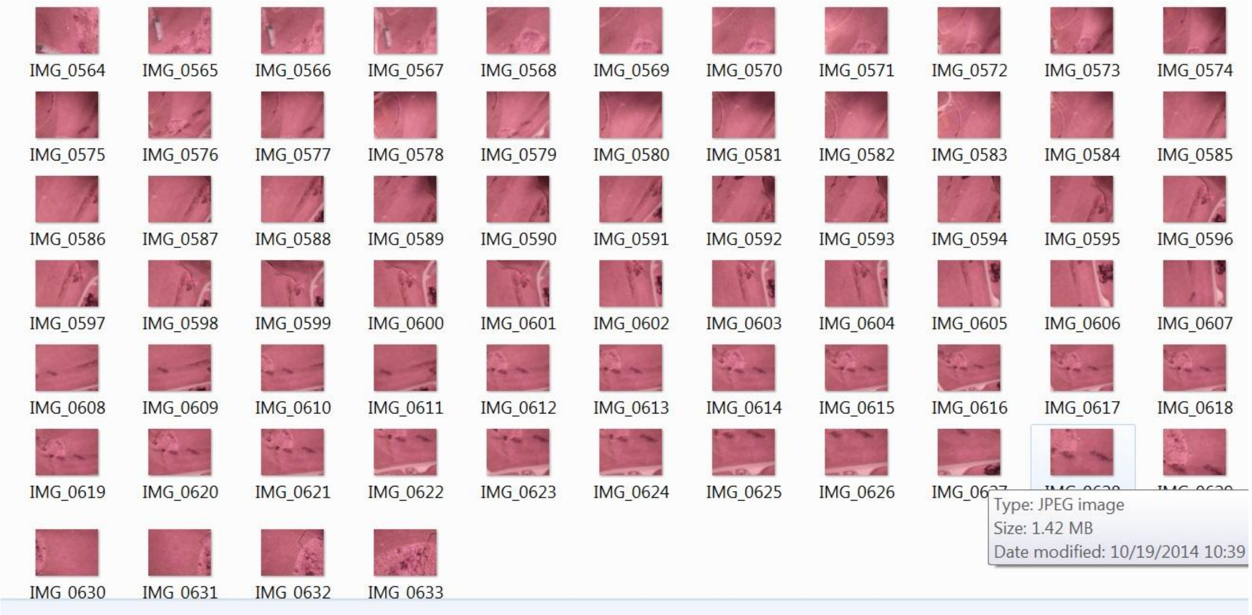


Fig. 4.2 Small Format Aerial Photography to Photogrammetry derived model (left).

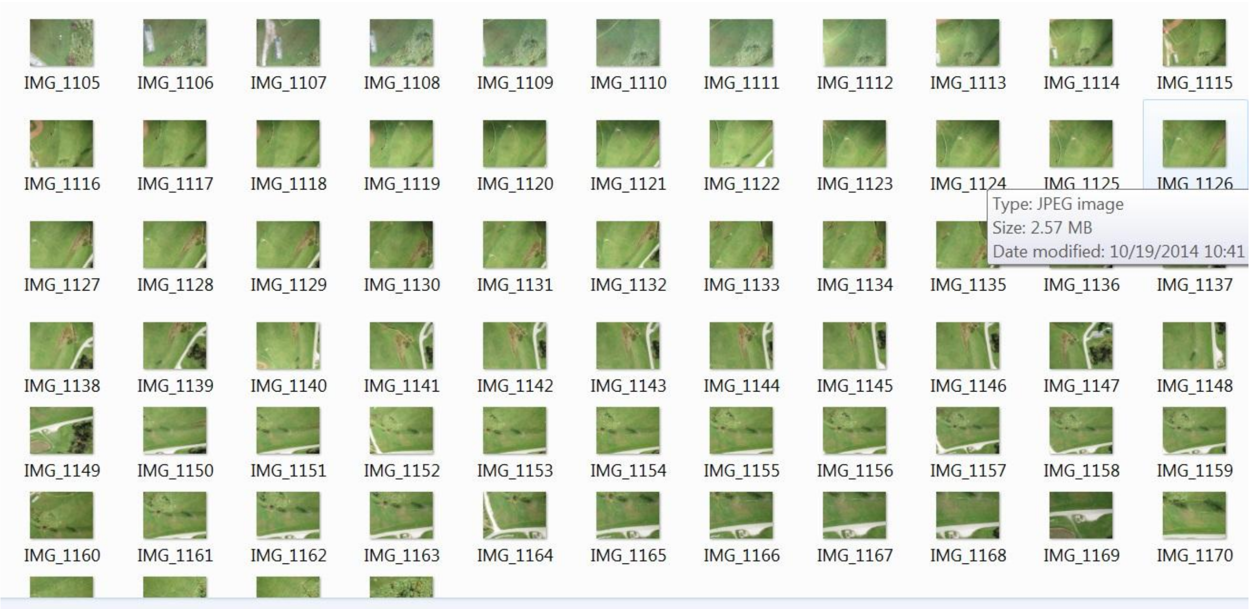
Fig. 4.3 USGS topographic map for Athalia Quad (Right). The red bounding box shows the same (approximate) area covered by the image on the left.

For Barboursville Park there were 140 images selected from a cache of 408 total images. Seventy images were infrared, and seventy were recorded in color (see Fig. 4.4 and 4.5).



Type: JPEG image
Size: 1.42 MB
Date modified: 10/19/2014 10:39

Fig. 4.4 Near infrared images of Barboursville Park.



Type: JPEG image
Size: 2.57 MB
Date modified: 10/19/2014 10:41

Fig. 4.5 Color images of Barboursville Park.

Once again the selected images were not the only images that could have been used, but they did represent a logical progression of overlapping coverage with minimal rotation and blur of the area of interest. Processing time took about 12 hours in total. Approximately three hours were spent in VSFM to convert from images into a dense point cloud. Approximately eight hours were spent in SURE converting into a .las dense point cloud. Another hour was dedicated to orientation and conversion into a raster in Cloud Compare. With a total of 30,625,606 points extracted from Barboursville Park, compared to the 4,944,413 points from Greenbottom, the point cloud was much denser (see Fig. 4.7). The denser point cloud had a benefit, in that viewing the point cloud was almost like viewing a photograph. The higher density also came with an inherent problem. With 30 million distinct points the point cloud weighs significantly on a computer's processing capabilities and was difficult to move and rotate and process. The high density point cloud added an additional hour of processing time to rotate into an orientation for conversion into a raster format. The additional time was worth it. The raster came out with very recognizable features. Part of a chain link fence is visible, a creek, trees; upon close inspection there is even a power pole and power lines visible. For the purposes of comparison (See Fig 4.6), on the top there is an image extracted from Google Earth and on the bottom there is the dense point cloud. The ridges and creeks appear very clear in the point cloud, and even the fence can be seen more clearly. The use of 140 images over a much smaller area with fewer trees and foliage lent to the clarity of the model.

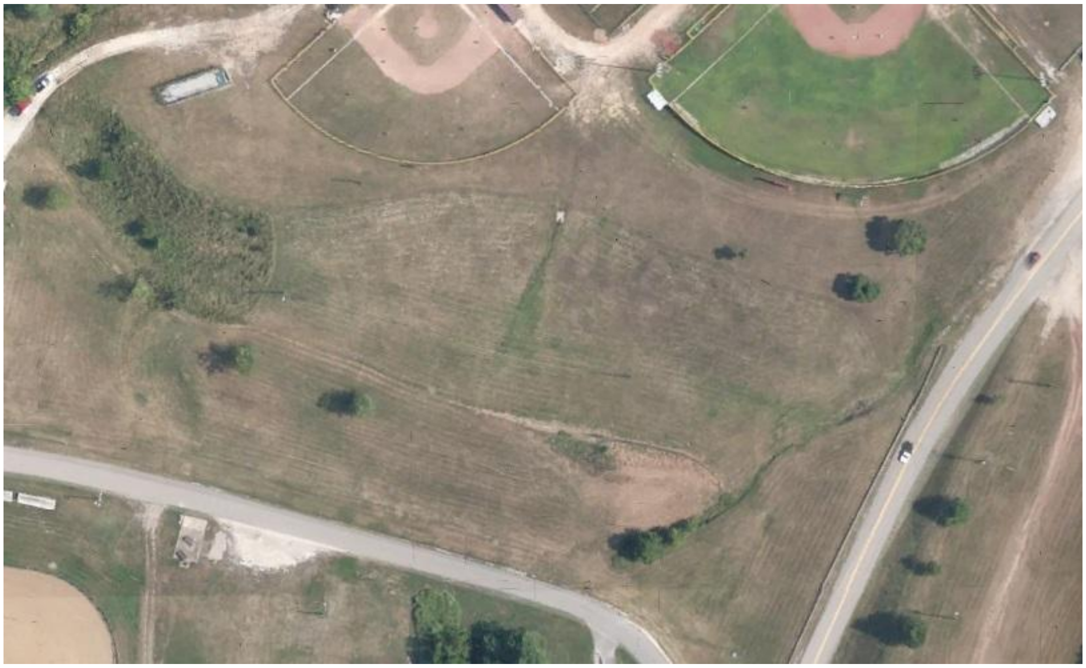


Fig 4.6 Google Earth image of Barboursville Park.

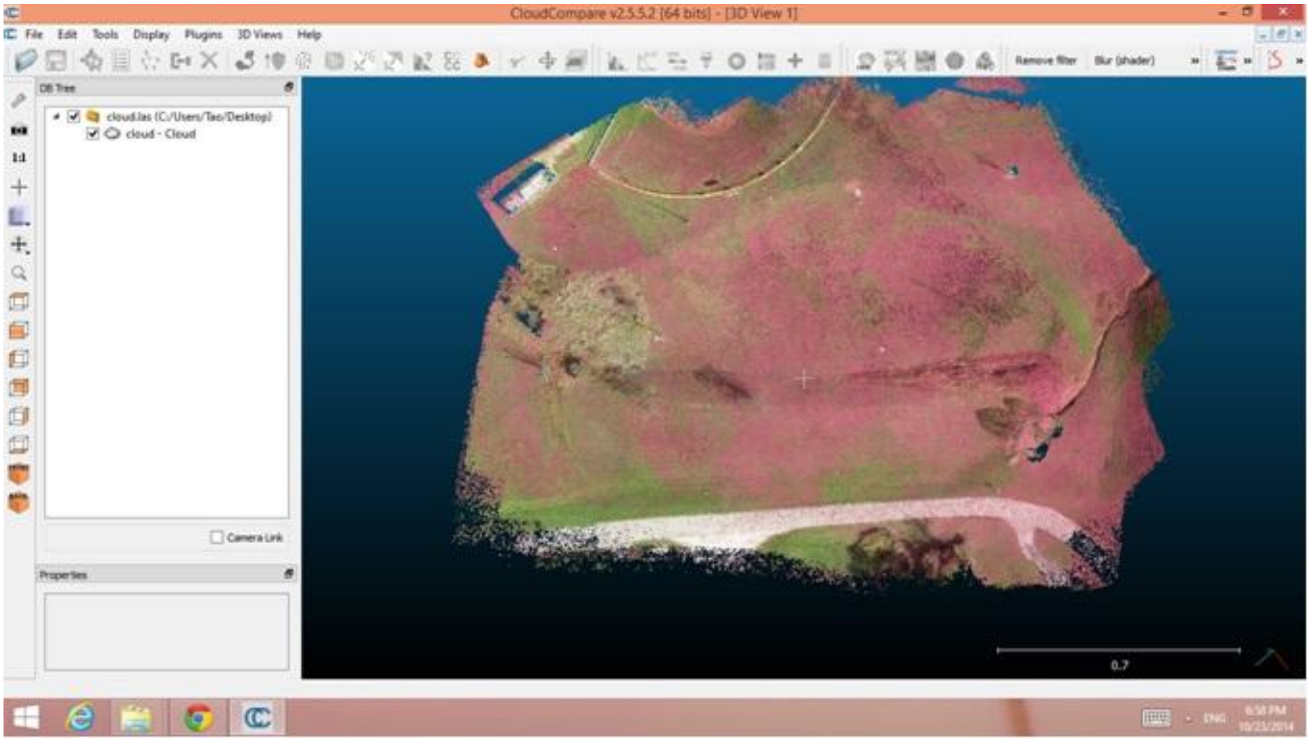


Fig.4.7 Barboursville Park point cloud created from aerial photos.

For another comparison of available data (See Fig 4.8) a LIDAR scan of the same area of interest was retrieved from USGS Earth Explorer (Entity ID WV_CABELLCO_2009_000479 and Entity ID WV_CABELLCO_2009_000479). The red bounding box displays the same area. This required the mosaicking of two models. Here they have been displayed in the scalar fields so that higher elevations appear red and yellow, with the image color transitioning to green and blue for lower elevations.

When zoomed in large artifacts that stretch across the entire model became apparent (See Fig 4.9). The artifact is displayed with the red arrow and the chain link fence can be seen very faintly where the yellow arrow points. At this resolution the features that can be recognized in the aerial photo point cloud cannot be seen in the LIDAR model. The model created from using the multicopter is displayed in a similar manner for comparison (See Fig. 5). This model yields a much clearer surface. Trees, a creek, and the same chain link fence can be seen very clearly.

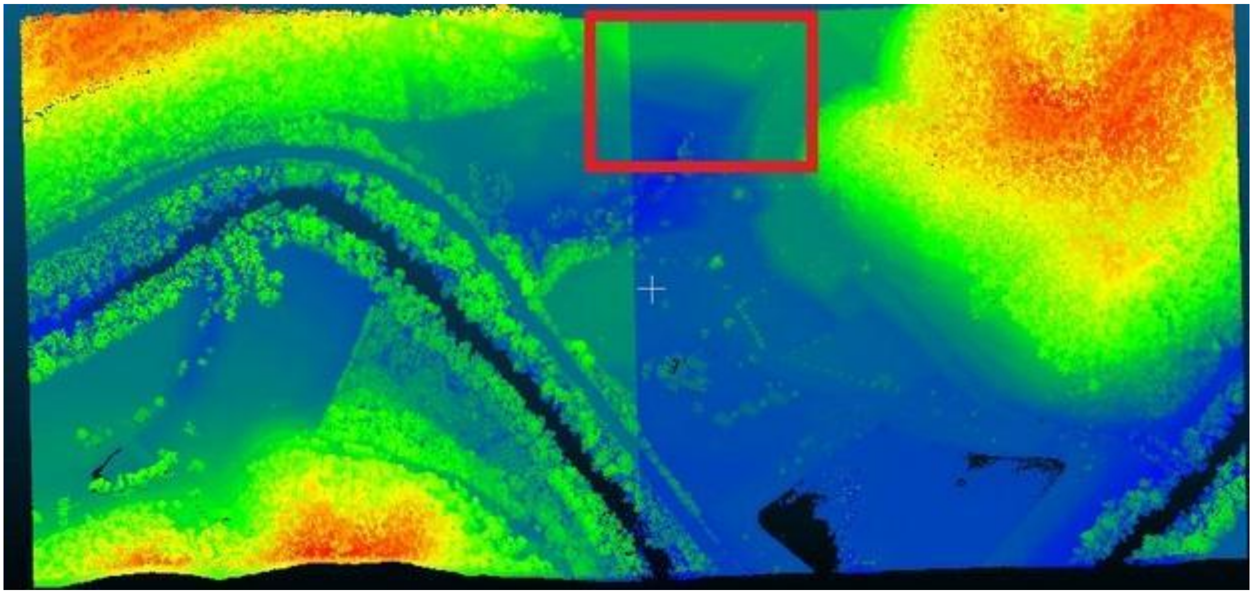


Fig. 4.8 LIDAR models retrieved from USGS Earth Explorer.

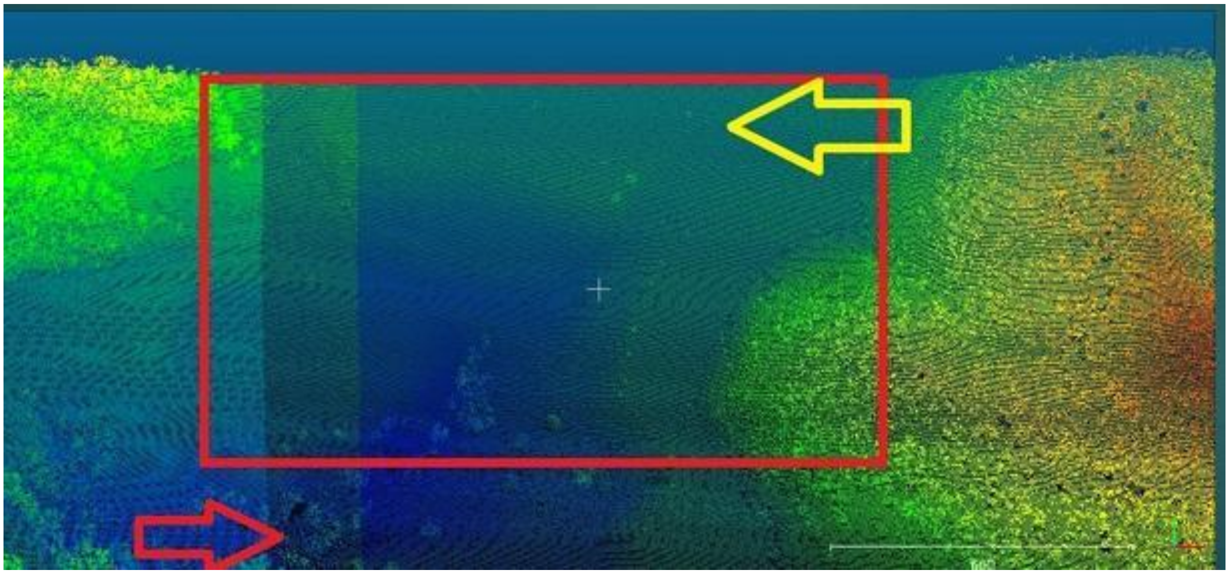


Fig 4.9 LIDAR models retrieved from USGS Earth Explorer magnified. The red arrow shows artifacts, and the yellow arrow shows the chain link fence.

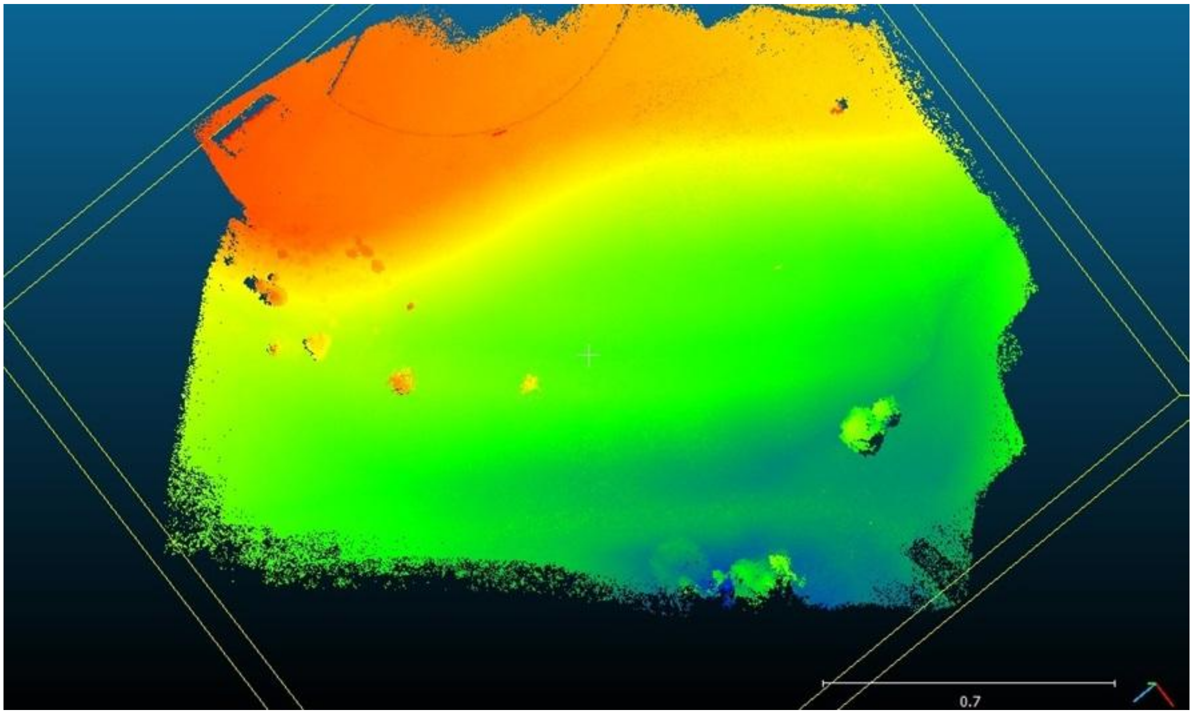


Fig. 5 Point cloud of Barboursville Park created with VSFM and SURE.

After the Barboursville Park images were converted into a model, and georectified in ArcMap, topography was created using ArcMap's spatial analyst toolbox. The Barboursville Park raster was able to be converted into a topographic map based on the 0-255 elevation scale, rather than in real world units (See Fig 5.1 and Fig. 5.2). This raster could be used for surface modeling, and worked with hydrology, basin, and watershed tools in ArcMap.

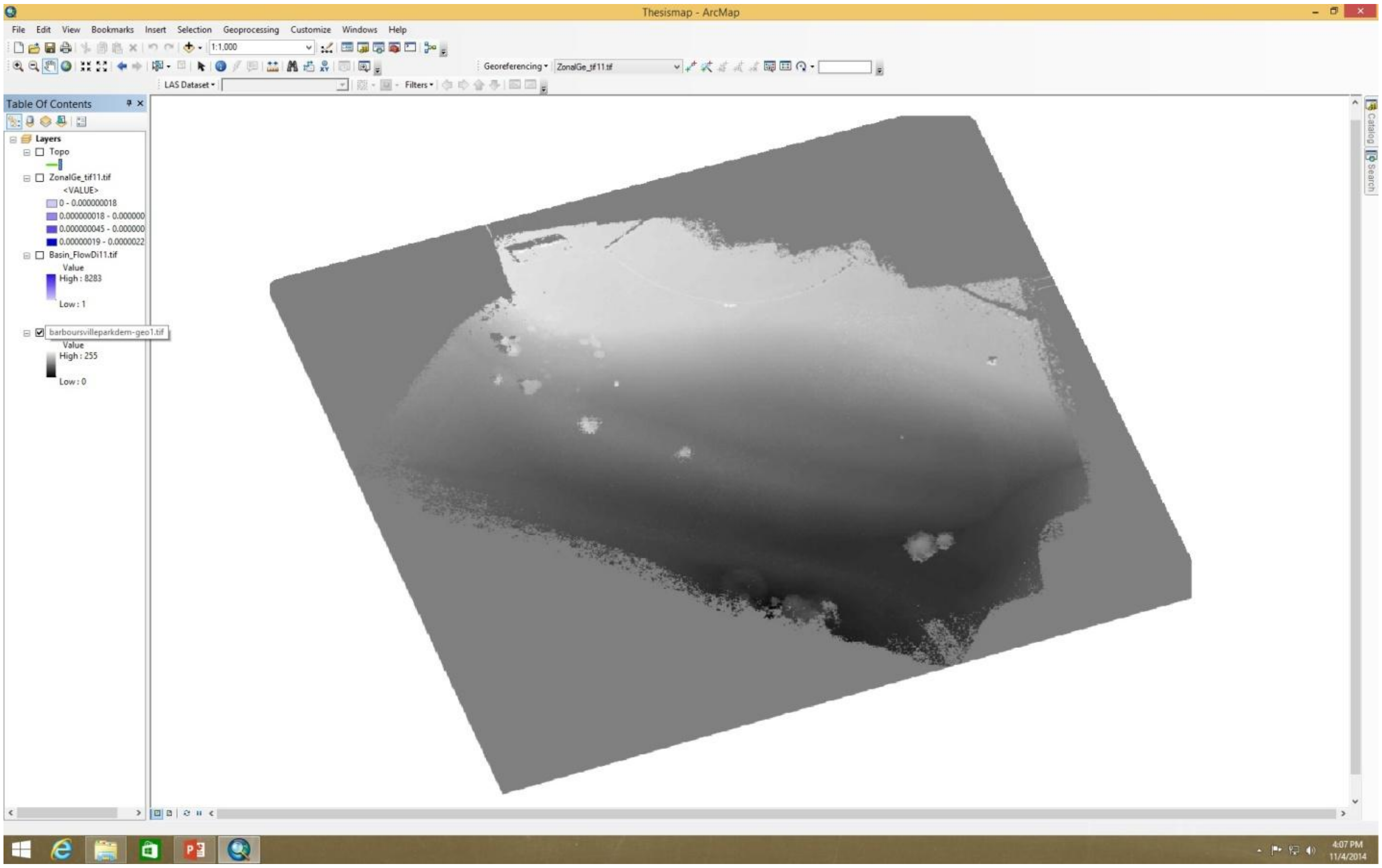


Fig. 5.1 Barboursville Park digital elevation model

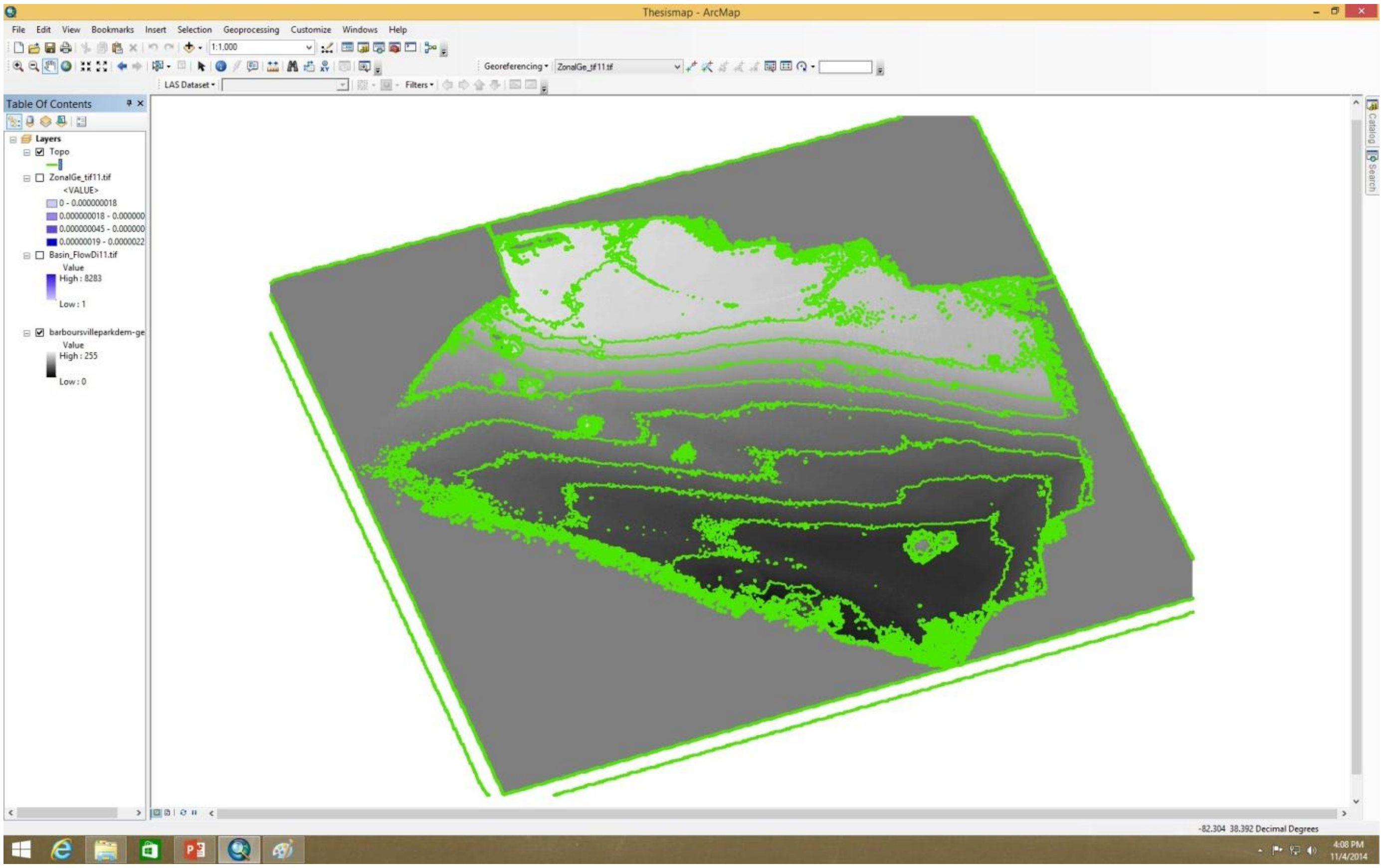


Fig. 5.2 Topographic map overlay.

CHAPTER 4

CONCLUSION

There are serious limitations to modeling with small format aerial photography. It is difficult to get coverage of areas larger than a few hundred meters across. Multicopters use batteries and the duration of flight times are limited by the life of the batteries. Multiple batteries can be used to complete several flights in a sequence. Another solution is to use two batteries for one flight; this increases flight time, but also increases weight. Lighter airframes paired with more efficient electric motors and batteries developed for commercial applications could be the solution to the problem. These improvements would increase the cost and would put it out of reach for most student researchers. Commercial platforms would also require specialized knowledge, which is beyond most people. This project used an off the shelf multicopter to reduce cost, improve reliability, and ease of use.

In addition to the aircraft, the imaging system suffers from limitations in battery life and data storage. The Canon A2500 cameras used in this project require proprietary batteries specific to this make of camera. The batteries are not a common consumer product such as AA batteries. If the batteries run out, the user cannot just go to a store and buy replacements. The batteries are rechargeable, and larger electronics stores sometimes carry them. Fortunately for this project each battery lasted over an hour which was sufficient to photograph each area in its entirety. Canon A2500 cameras use SD memory cards for data storage which are inexpensive and are able to be switched quite quickly. The cameras suffer a limitation due to each card having to be loaded with CHDK to run the intervelometer script so each card must be prepared prior to going into the field, but the functionality of CHDK outweighed this limitation.

There were also issues with processing of images. Areas with dense ground cover require more images to model, which requires longer flight duration. Areas with smooth ground cover were not difficult to model, and less time could be used to photograph those areas. Areas with dense brush, trees or high grass required more images to create complete models. Using a small number of images yielded models with large holes containing no information.

The increased number of images for processing increased processing time. Areas with thick foliage are difficult to model. Flight durations were short, this was caused by heavy payloads. To get sufficient coverage of an area large numbers of images are necessary, but large numbers of images increase processing time exponentially. A model created from 36 images took a few hours, but a model created with 140 images took an entire day and monopolized one computer.

The resulting rasters were able to be used in ArcMap and QGIS for surface analysis. They were compatible based on their file format and DN values, which made it possible to do surface analysis but it came with limitations. Due to the models being created with artificial units due to lack of real world measurements, all analysis resulted in data in the same artificial units of measurement. It is possible that there is a method of conversion based on a combination of real world information and interpolation, but it was beyond the scope of this project.

“The imprecise nature of consumer grade cameras and the potential variability of a model aircraft’s flight path limit the uses of SFAP in applications where precise measurements are required” (Turley, 2012). This method could be used as a supplement to commercial data, or it could be a great solution for research projects on a budget. The method could also be a solution for collecting in situ data in locations where it might not be economically feasible to use high end equipment.

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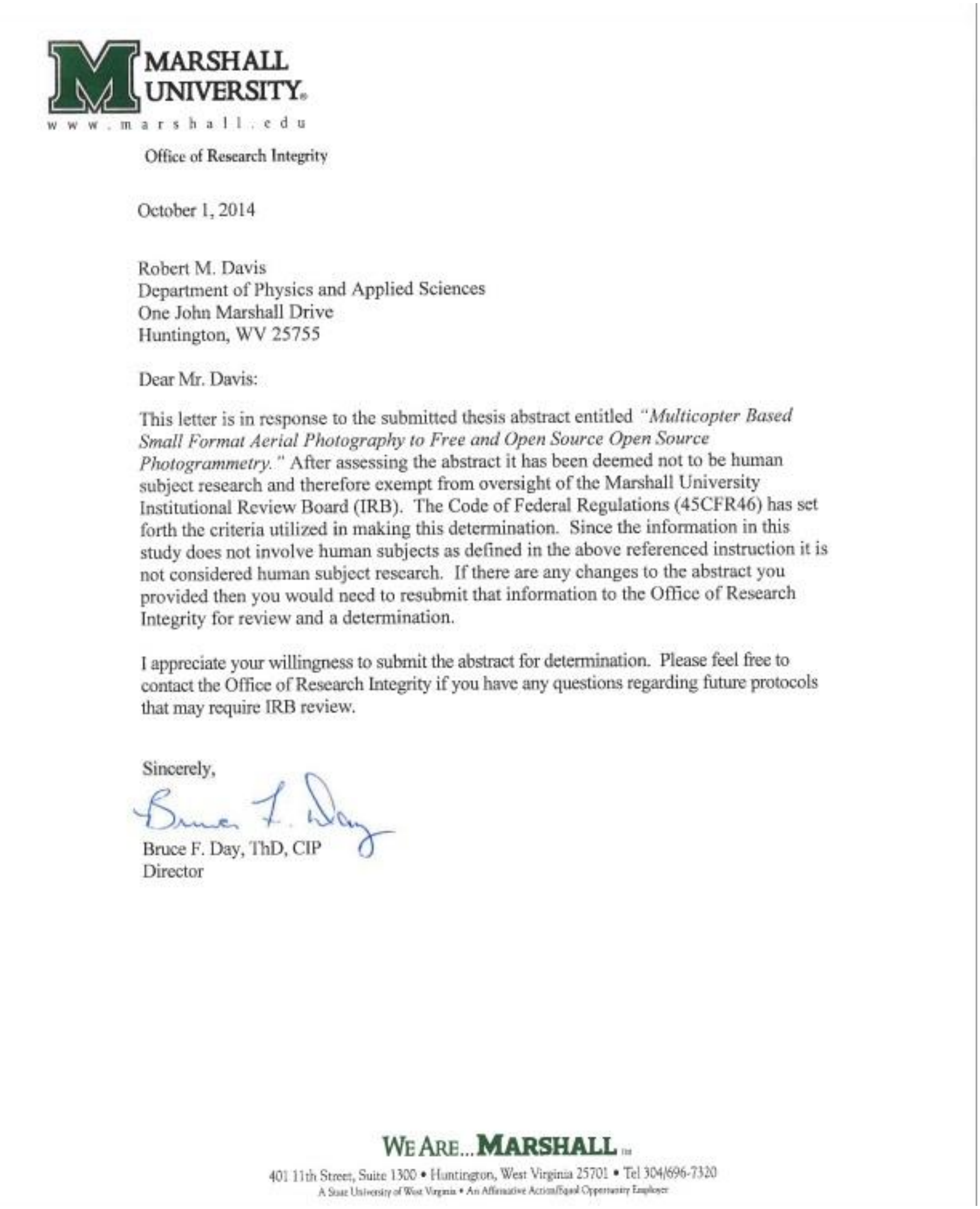
APPENDIX A

INSTITUTIONAL REVIEW BOARD LETTER



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Office of Research Integrity

October 1, 2014

Robert M. Davis
Department of Physics and Applied Sciences
One John Marshall Drive
Huntington, WV 25755

Dear Mr. Davis:

This letter is in response to the submitted thesis abstract entitled *"Multicopter Based Small Format Aerial Photography to Free and Open Source Open Source Photogrammetry."* After assessing the abstract it has been deemed not to be human subject research and therefore exempt from oversight of the Marshall University Institutional Review Board (IRB). The Code of Federal Regulations (45CFR46) has set forth the criteria utilized in making this determination. Since the information in this study does not involve human subjects as defined in the above referenced instruction it is not considered human subject research. If there are any changes to the abstract you provided then you would need to resubmit that information to the Office of Research Integrity for review and a determination.

I appreciate your willingness to submit the abstract for determination. Please feel free to contact the Office of Research Integrity if you have any questions regarding future protocols that may require IRB review.

Sincerely,

Bruce F. Day

Bruce F. Day, ThD, CIP
Director

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