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Suitability of Low Cost Commercial Off-the-Shelf Aerial Platforms and Consumer Grade Digital Cameras for Small Format Aerial Photography

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SUITABILITY OF LOW COST COMMERCIAL OFF-THE-SHELF AERIAL PLATFORMS AND CONSUMER GRADE DIGITAL CAMERAS FOR SMALL FORMAT AERIAL PHOTOGRAPHY

A thesis submitted to
the Graduate College of
Marshall University

In partial fulfillment of
the requirements for the degree of
Master of Science

in

Physical and Applied Sciences

by
Anthony Allen Turley

Approved by
Dr. Ralph Oberly, Committee Chairperson
Dr. Anne Axel
Dr. James Leonard

Marshall University
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This document is dedicated to the memory of my son Andy. I miss you, and I will see you again some day.

No research project can be accomplished in a vacuum. I am indebted to many people who have helped me complete this educational journey, and I would like to express my appreciation:

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ABSTRACT

Many research projects require the use of aerial images. Wetlands evaluation, crop monitoring, wildfire management, environmental change detection, and forest inventory are but a few of the applications of aerial imagery. Low altitude Small Format Aerial Photography (SFAP) is a bridge between satellite and man-carrying aircraft image acquisition and ground-based photography. The author's project evaluates digital images acquired using low cost commercial digital cameras and standard model airplanes to determine their suitability for remote sensing applications. Images from two different sites were obtained. Several photo missions were flown over each site, acquiring images in the visible and near infrared electromagnetic bands. Images were sorted and analyzed to select those with the least distortion, and blended together with Microsoft Image Composite Editor. By selecting images taken within minutes apart, radiometric qualities of the images were virtually identical, yielding no blend lines in the composites. A commercial image stitching program, Autopano Pro, was purchased during the later stages of this study. Autopano Pro was often able to mosaic photos that the free Image Composite Editor was unable to combine. Using telemetry data from an onboard data logger, images were evaluated to calculate scale and spatial resolution. ERDAS ER Mapper and ESRI ArcGIS were used to rectify composite images. Despite the limitations inherent in consumer grade equipment, images of high spatial resolution were obtained. Mosaics of as many as 38 images were created, and the author was able to record detailed aerial images of forest and wetland areas where foot travel was impractical or impossible.

CHAPTER 1
INTRODUCTION

BACKGROUND

Biophysical modeling is the use of remote sensing data to quantify biophysical data measured on or above the earth's surface (Lillesand, *et al.,* 2008). Such data may include vegetation biomass, water depth and/or temperature, soil moisture, weather patterns, tracking hazardous material releases, and many other physical properties. Methods for remote collection of biophysical data are numerous. Satellite observation of the earth began in the 1960s (Sabins, 1997). In the 1950s, full scale military aircraft began carrying radar apparati for the purposes of reconnaissance, and that technology has carried over into the civilian realm. Man-carrying aircraft may carry large format cameras (Sabins, 1997), scanning systems (Jensen, 2005), and lidar (Lillesand, *et al.,* 2008).

Small Format Aerial Photography (SFAP) is the collection of low altitude, large scale photographs using 35- and 70-mm film cameras and their digital equivalents. SFAP image scale fits into a niche between ground-based image collection and traditional full scale image collection (Aber, *et al*., 2010). Low altitude images have high spatial resolution and short turnaround times between images (Berni *et al*., 2009). The techniques and equipment used in SFAP are entirely user controlled, allowing for a great range of both flexibility and challenges. SFAP can be conducted using cameras mounted on stationary masts and kites (Aber *et al*., 2010), balloons (Flores *et al*., 2010), radio controlled airplanes (Aguilar *et al*., 2005), and small full scale aircraft (Gurtner *et al*., 2009). Standard aerial photography (AP) involves the use of one or more cameras mounted on a man-carrying aircraft. Rowe, *et al*. (1999) used a 35-mm film camera mounted on the underside of a Cessna C-150 light aircraft to photograph and measure logging roads in north-central West Virginia. Although man-carrying platforms can cover large areas in a fairly short period of time, their costs can be prohibitive; a light 2- or 4-seat aircraft costs $150+ per hour for rental, plus the cost of the pilot, fuel, and equipment.

Unmanned Aerial Vehicles (UAV) are one type of aerial imaging platform being used in increasing numbers for such purposes as conservation, crop monitoring, forestry, law enforcement, real estate, and archaeology (Aguilar *et al*., 2005). Berni *et al*. (2009) developed a 1.9 m span remote-controlled helicopter and a 3.2 m fixed wing UAV. Grenzdörffer *et al*. (2008) used a commercially available agriculture UAV to capture photogrammetric-quality imagery. Their craft used a programmable autopilot for repeatability of flight tracks and image capture. Watts *et al*. (2008) discussed the use of small UAVs in ecological monitoring and natural resource management, particularly for wildlife census surveys. UAVs may be as simple as an operator-guided radio controlled airplane, or as complex as a military drone with autonomous GPS navigation and real-time video downlink. In July 2011, the U.S. Federal Aviation Administration estimated over 50 institutions – both commercial and government - were producing at least 150 UAV designs. Although the number of designs continues to grow, their target market of commercial and military application often pushes the cost into the tens or even hundreds of thousands of dollars.

Many companies offer commercial-grade cameras suitable for AP. The Tetracam ADC Lite is designed for capturing visible and near infrared (IR) images at high spectral and spatial resolutions (Aguilar *et al*., 2005). Flores *et al*. (2010) mounted JAI Monochrome CV-A50 IR and Point Grey Firefly MV cameras on standard model aircraft. Aguilar *et al*. (2005) mounted a RMK TOP 15 commercial film camera on a light Cessna man-carrying aircraft. Some authors have evaluated consumer-grade digital cameras and found them suitable for use in SFAP. Chandler *et al*. (2005) compared three low cost digital cameras against a proven high end metric camera and found the relatively inexpensive Sony DCS-P10 to have the highest accuracy in recording surface measurements. The Canon D50 was also found to be suitable for photogrammetric measurements over historical sites (Chandler *et al*., 2005). Grenzdörffer *et al*. (2008) used a Canon Powershot 560 mounted on a commercial agriculture UAV. Aber *et al*. (2010) made extensive use of consumer digital Single Lens Reflex (SLR) cameras mounted on kites.

Compared to the cost of calibrated frame cameras, small format cameras are more cost effective for individual researchers, nonprofits, and others on a limited budget. Their ease of use and ease of purchase allow for almost instantaneous acquisition of data. Temporal resolution for a study site of a few dozen to a few hundred acres can be measured in minutes. Spectral resolution of a small format camera is typically limited to RGB and/or near infrared, but the spatial resolution can be very high, on the order of a few millimeters for photos recently obtained by the author with a Nikon (http://www.nikonusa.com) compact camera. At altitudes below approximately 150 m, it is possible to gather information such as crown size and individual tree diameter from a small format camera digital image (Schultz *et al.*, 1999).

The success of SFAP is determined by the user's ingenuity and experience. Viewing angle, coverage, exposure settings, airframe design, project implementation, and image analysis are typically done by only a few people, or even just one person. Flexibility and potential rewards are high, but so is the risk (Aber *et al.*, 2010). The value of using SFAP for remote collection of imagery versus obtaining imagery collected via man-carrying aircraft or satellite must be determined by the user. The hour of the day the photo(s) was/were taken, lens distortion, curvature of the earth, and atmospheric distortions can and will affect the quality of images acquired (Massasati, 2002). For the researcher, SFAP should be considered as a balance between what is most desired (with accompanying higher costs) and what is feasible and affordable (Aber *et al.*, 2010).

Many consumer grade digital cameras have extensive shooting menus, ranging from easy, preprogrammed settings to manual settings allowing adjustment of aperture, shutter speed, and ISO. The author has found that setting the camera for sports or action settings usually yields satisfactory photos, although setting the white balance manually is often necessary. Another factor is shutter delay; most consumer grade pocket cameras require several seconds between exposures.

Numerous factors are to be weighed when considering SFAP. Planning the route of flight of the aerial platform is key to obtaining suitable overlap of photographs. Wind and vibration can ruin a set of otherwise useful images. Some consumer cameras implement anti-shake technology, which may be useful in minimizing image blur, but more important is ensuring the camera is mounted securely to the airframe to reduce bounce and is isolated from vibration. The author has been experimenting with various gel compounds to reduce vibration blur, with mixed results. A sorbothane sheet ¼” thick has been proven to be the most effective in reducing vibration blur from the airframe.

Aerial photos may require one of several steps for presentation and/or analysis. Those steps may include geometric correction, radiometric correction, or image enhancement. Geometric correction establishes the correct planimetric relationship of pixels (Jensen, 2005), and includes correcting errors introduced by the aerial platform (airframe and/or camera). Although satellite imagery may already be registered to a known geographic coordinate system, images collected by a small SFAP platform like a model airplane will require geometric registration if they are to be used in a mapping application or for photogrammetry. Care must be taken in the image registration process to ensure photos are oriented as closely as possible to the actual geographic orientation prior to registration in order to minimize warping of pixels as the image is mathematically transformed to its appropriate cartographic representation. As the image is registered, it is warped to fit a specific geographic grid, and a resampling process takes place as pixel values are transferred between cells and/or admixtures of original pixel values are created. It may be advisable to conduct any image analysis such as classification prior to registration/resampling, in order to ensure pixel value integrity is preserved (Jones and Vaughan, 2010).

Radiometric correction improves the accuracy of surface spectral values in an image (Jensen, 2005) and may be required due to illumination and reflectance variations in the image, which could have an impact on any quantitative analysis of the data (Jones and Vaughan, 2010). These variations may be caused by atmospheric phenomena such as clouds, haze, fog, or mist. Solar angle variation may cause differences in contrast in what should be homogeneous features. Reflectance differences are also caused by surface angle and shading effects, and the untrained or inexperienced photo interpreter may overlook key variations in surface features (Fensham *et al.*, 2002). It should be noted that for many – if not most – smaller studies involving small areas, or the identification of single features such as weed tracts, atmospheric correction is neither necessary nor feasible. Information about the energy incident on the surface may not be available, nor will data concerning the state of the atmosphere at the time of image acquisition (Jones and Vaughan, 2010). Such information requires complex radiative transfer models, which are typically beyond the scope of SFAP studies.

A histogram is a graphical representation of the data content of an image, depicting the frequency of occurrence of each brightness value in an image (Jensen, 2005). Image enhancement is the process of ensuring image brightness values cover the entire range of possible values in the histogram (Horning *et al.*, 2010). For an 8-bit image, the bit depth is 2^8, or 256 brightness values, ranging from 0 (darkest) to 255 (brightest). For a 24-bit RGB image, each band in the color space will have a value range of 0-255. It is not uncommon to see an image with poor contrast that does not utilize the full range of values. The goal of image enhancement is to improve visual interpretation and feature identification. Simply put, image enhancement should make it easier to distinguish between features in an image (Lillesand, *et al.,* 2008).There are a variety of image enhancement techniques that modify the image's appearance. Each set of human eyes is different, and there is no single best method of modifying the appearance of an image. The author often uses Microsoft Photo Editor to improve the appearance of aerial photos. Caution is urged to ensure photos aren't modified to the point that join lines are evident if two or more photos are to be joined in a composite image.

STATEMENT OF PROBLEM

SFAP from UAVs can be a cost-effective method of collecting timely aerial imagery. The costs of using full scale aircraft for AP can add up quickly (Berni *et al.*, 2009). Traditional satellite images have a low temporal resolution, typically about 16 days between passes. Traditional UAV application development was driven by military requirements; however, civilian conservation activities are driving the development of small commercial UAV platforms (Grenzdörffer *et al.*, 2008). Commercial UAV solutions can be expensive; CropCam (http://www.cropcam.com) costs approximately $7,000 USD; MicroPilot MP (http://www.micropilot.com) costs approximately $9,500 USD; the Tetracam ADC Lite (http://www.tetracam.com), a multispectral camera capable of capturing both visible and infrared images, is approximately $4,800 USD. Other commercial UAVs and multispectral cameras cost from the tens of thousands to the hundreds of thousands of dollars. The author investigated whether low-cost components (total cost less than $1000 USD) easily available to the public can be used to obtain aerial imagery suitable for biophysical modeling. Specific attention was given to calculating photo scale and ground sampling distance (GSD), as well as determining the feasibility of calibrating consumer digital cameras.

PROPOSED SOLUTION

The author has had much success over the years collecting oblique aerial photographs using model airplanes and inexpensive cameras. The use of a radio controlled aircraft to carry the camera negates the effect of cloud cover and allows faster turn-around time between image capture (Flores *et al.*, 2010). Particularly useful for SFAP is the Multiplex Easystar (http://www.multiplexusa.com). Targeted toward beginning flyers, the Easystar's slow speed and gentle handling characteristics make it particularly suitable as an aerial photography vehicle. The Easystar is manufactured from a blend of expanded polyolefin foam that is lightweight and very resistant to damage. The Easystar is shown in Color Plate 1. A second model, the Multiplex Mentor, was used during the later phases of this study. Although heavier and slightly more expensive than the Easystar, the Mentor is less affected by wind gusts, and mounting a camera on the Mentor for nadir shots is much simpler. The Mentor is shown in Color Plate 2.

Wind can be a significant factor in obtaining airborne images (Flores *et al.*, 2010), (Grenzdörffer *et al.*, 2008), (Nebiker *et al.*, 2009). The Easystar fully loaded with a camera, remote switch, and other necessary electronics weighs approximately 900g. With a wingspan of 1.4m, the low wing loading of the Easystar makes it susceptible to fluctuations in aircraft attitude on windy days. The author has installed a FyeTech FY-20A Flight Stabilization System in the Easystar. Available in the U.S. from ReadyMade RC (http://www.readymaderc.com), the FY-20A provides 3-axis stabilization to the aircraft via 3 sets of gyros and accelerometers. When the FY-20A detects a fluctuation in roll, pitch, or yaw, it feeds opposite control inputs to the radio servos to level the aircraft. In practice, oscillations in the plane's flight attitude are reduced greatly but not removed entirely. For flights with the Mentor, a Universal Development Board v.3 (UDB3) autopilot from www.sparkfun.com was installed. The UDB3 provides the capability of setting pre-programmed waypoints, as well as providing 3-axis stabilization capability. Furthermore, UDB3 provides for programmable altitude and airspeed, enhancing the collection of photos at a consistent scale.

GPS data are required to georeference photos (Berni *et al.*, 2009), (Grenzdörffer *et al.*, 2008), (Jensen *et al.*, 2008). A handheld Garmin eTrex H (http://www.garmin.com) was used to collect Ground Control Points (GCP). A Canmore GT-730-FL-S (http://www.canmore.com.tw) data logger was used to record the Easystar's flight path. Its data can be output to many common consumer mapping products for viewing of flight tracks, and its GPS data can be used to synchronize photos. The author uses free GeoSetter software (http://www.geosetter.de) to assign GPS coordinates to photos. A zLog barometric altimeter (http://www.hexpertsystems.com) was used to record the Easystar's altitude. The UDB3 system installed in the Mentor includes a module called OpenLog, which records flight parameters such as altitude, airspeed, wind speed and direction, and tip/tilt of the aerial platform.

Many different consumer digital cameras have been used to capture aerial imagery (Chandler *et al.*, 2005), (Habib *et al.*, 2006), (Jensen *et al.*, 2008). In the early phases of this study, the author used a 5 megapixel Nikon Coolpix L3 (http://www.nikonusa.com), which is no longer produced. Later missions added two versions of the 10 megapixel Nikon L20: one camera was unmodified, and another camera was professionally modified to remove the IR blocking filter and insert an infrared band-pass filter with an approximate window of 720 nm to 1100 nm. Of particular interest is that these cameras allow remote operation from the mini USB port. The author controls all cameras with an URBI interface, available from Blip IT Pty, Ltd (http://www.blip.com.au). The URBI connects to the mini USB port and can be set up for manual shutter trigger or intervalometer function with programmable intervals from 1 - 999 seconds.

CHAPTER 2
METHODS

Two different study sites were photographed for this project. Both sites were initially photographed in winter months in full leaf-off condition. Follow-up sets of photos were obtained in late spring once vegetation had reached full leaf-on condition. The first site is a hilltop community park of approximately 74 acres in Scott Depot, WV. The site is characterized by a large open central grassy area sloping away from the peak on all sides, surrounded by steep, wooded ravines containing mixed deciduous/evergreen forests. There are smaller areas of scrub bushy growth, open sandy slopes, pavement, standing water, small tributaries, and a playground/picnic area.

The second site is a protected wetland on low, fertile ground adjacent to the Kanawha River near Winfield, WV. As previously mentioned, SFAP is useful in areas such as wetlands where *in situ* data collection is not feasible. The author obtained permission from the utility company that owns the land upon which the wetlands are located to conduct several aerial photography missions over the wetlands. The dominant species in the wetlands is Buttonbush (*Cephelanthus occidentalis*), which is clearly seen in the photos. The wetlands are surrounded by mixed deciduous/evergreen forests and abandoned cornfields. Nearby are several acres of open, mowed grass, from which the author was able to take off and land.

The initial study area was the 74 acre hilltop parcel. Flights were flown at altitudes of 100-125m to obtain aerial photographs. The Nikon L3 camera was oriented with its lens looking straight down (nadir view). The URBI switch was programmed to trigger the camera at 3-second intervals. The Canmore GPS was used to record the aircraft's flight path (Color Plate 3). Initially, the author was not successful in maintaining a steady altitude with the aircraft during the collection process (Figure 1). Varying altitude of the Easystar led to photos of varying scale.

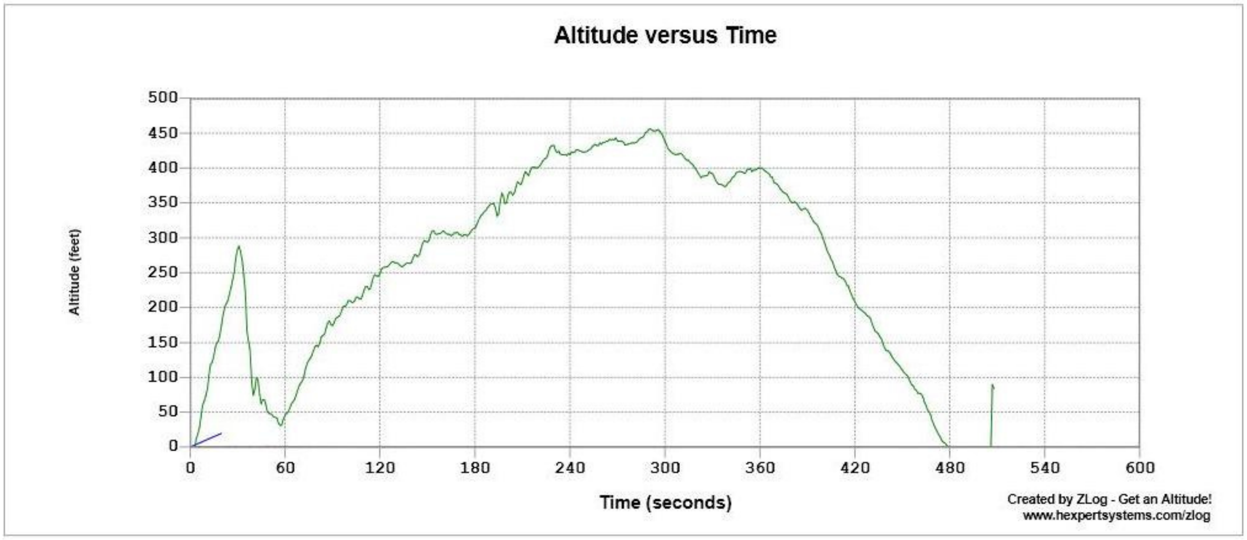

Figure 1. zLog altitude profile.

The second aircraft used by the author, the Multiplex Mentor, is a high wing trainer aircraft with a 1.6 m wing span, weighing approximately 2 kg fully loaded for a photo mission. The author has installed an autopilot system, Universal Development Board v.3 (UDB3), to assist with stabilizing the aircraft and lining up photo shots. UDB3 is open source, requiring a considerable investment in time for configuration, and results when used on aerial photo missions have been mixed. A series of waypoints were programmed into UDB3 so the aircraft would make several passes over each site in an attempt to obtain the best overlap of photos. Connected to UDB3 is a flight recorder that records altitude, airspeed, aircraft roll and pitch, wind speed and direction, and GPS coordinates. Initial flights over the wetlands were programmed for an altitude of 130 m

AGL. That altitude proved to be too low for optimum coverage, so subsequent flights were programmed for 150 m AGL. The Mentor was used in several photo missions over the hilltop site, as well as all missions over the wetlands. Photo missions were flown over both sites in periods of full senescence (late winter), as well as full leaf-on (mid spring).

Three different cameras have been used in the author's photo missions. The Nikon L3, discontinued for several years, has a resolution of 2592 x 1944 pixels, or approximately 5 Mp. Its focal length is 38 - 116 mm. The Nikon L20 has a resolution of 3648 x 2736 pixels, or approximately 10 Mp. Its focal length is 41 - 145 mm. The author's L20 has been professionally converted to take near infrared photos by removing the IR blocking filter and inserting a band-pass filter with a range of approximately 720 nm - 1100 nm. In later flights, a second Nikon L20 was purchased to collect standard visible images. A summary of the photo missions is shown in Table 1.

Date	Location	Aircraft	Camera	EM Band	Number of photos	Number of useable photos
03/01/2011	Hilltop	Easystar	Nikon L3	Visible	93	41
01/16/2012	Hilltop	Easystar	Nikon L3	Visible	77	7
02/15/2012	Wetlands	Mentor	Nikon L3	Visible	79	32
02/15/2012	Wetlands	Mentor	Nikon L20	Infrared	50	17
02/20/2012	Wetlands	Mentor	Nikon L3	Visible	113	48
02/20/2012	Wetlands	Mentor	Nikon L20	Infrared	77	21
02/23/2012	Hilltop	Mentor	Nikon L3	Visible	92	12
02/23/2012	Hilltop	Mentor	Nikon L20	Infrared	58	21
03/03/2012	Hilltop	Mentor	Nikon L3	Visible	174	44
03/10/2012	Hilltop	Mentor	Nikon L20	Visible	86	53
03/10/2012	Hilltop	Mentor	Nikon L20	Infrared	80	52
05/03/2012	Wetlands	Mentor	Nikon L20	Visible	72	61
05/03/2012	Wetlands	Mentor	Nikon L20	Infrared	98	71
06/08/2012	Hilltop	Mentor	Nikon L20	Visible	100	81
06/08/2012	Hilltop	Mentor	Nikon L20	Infrared	81	74

Table 1. Summary of photo missions.

Images were visually sorted into groups of 10-15 images of approximately the same scale and then fed into Image Composite Editor for stitching. Image Composite Editor’s algorithms compare pixel brightness values and feature patterns to form composite images. Initial attempts to rectify the Image Composite Editor composites using the IDRISI module RESAMPLE were unsuccessful; the author discovered RESAMPLE will not accept RGB images as input. Early Image Composite Editor composites were rectified using ER Mapper's Geocoding Wizard. Later composites were rectified with ESRI ArcGIS.

Autopano Pro (www.kolor.com) is a commercial image stitching software package. Although its output images are indistinguishable from the ones produced by Image Composite Editor, Autopano Pro adds the ability to manually edit tie points, adjust image brightness/contrast, and it will handle many more images than Image Composite Editor. The author purchased Autopano Pro during the later stages of this study in an effort to improve upon the image stitching process. Image composites in Color Plates 14-17 were created with Autopano Pro.

CHAPTER 3

RESULTS AND DISCUSSION

Several problems were expected to be encountered during this study. First is the aircraft’s flight attitude. It is very difficult to maintain precise heading and altitude with a slow flying model airplane, especially in windy conditions. Careful throttle management is required to hold a steady altitude. Due to equipment layout considerations, the camera had to be mounted off the right side of the Easystar, which caused a strong tendency for the model to roll to the right. Even with the FY-20A activated, the right turn tendency was strong, which led to difficulty keeping a straight flight path with the model (Color Plate 3). Varying end-lap and side-lap among successive photographs was encountered. The author discovered that data from the Canmore GPS were insufficient for rectifying images; the data were only suitable for geotagging photos and displaying their location on a map like Google Earth. Minute changes in aircraft altitude and attitude (roll and pitch) also affected the orientation of the camera, resulting in inconsistent scale among photographs

Images obtained using the second aircraft, the Multiplex Mentor, were more consistent. Once it was properly calibrated, the UDB3 autopilot was successful in maintaining consistent altitude and airspeed, reducing motion blur and scale variations. However, like other lower cost autopilots, UDB3 sometimes will overshoot or bypass waypoints, resulting in inconsistent flight paths. It had been the author’s intention to use images obtained in winter and spring to evaluate the airborne system’s ability to detect change in vegetation biomass; unfortunately, there was not enough spatial overlap in image sets to accomplish the task.

Well-distributed GCP are essential for rubber sheeting image interpolation to work accurately (Aguilar *et al*., 2005). Although individual items such as trees, posts, and poles are easily identified at ground level, accurately identifying those items in a photograph taken from 130 meters was not a trivial task. The stitching and rectification of images captured took the bulk of time in project development. Microsoft Image Composite Editor software created composite images that were visually pleasing, and if the images were chosen carefully, the composites contained minimal distortion. However, when the resulting composite images were rectified using ER Mapper, significant distortion in the rectified images was observed (Color Plates 6 and 7). Two possibilities are theorized for the distortion: 1) Microsoft Image Composite Editor introduces geometric distortions into the composites it assembles, and 2) observation and /or recording errors were introduced during the collection of GCP. The author observed that severe distortion was introduced during the rectification process even after the unregistered images had been rotated to approximate true geographic compass directions before rectification. Further rectification attempts with ESRI ArcGIS and ER Mapper yielded more satisfactory results (Color Plates 8 and 9). Those subsequent attempts indicated that meticulous placement of GCP during the rectification process is essential. Orthorectification, or the geospatial correction of images to correct relief displacement, was not possible within the parameters of the author's research. Note the differences in tonal values between Color Plates 6 and 8. The rectification warps pixels as they are arranged into their correct planimetric orientation, and admixtures of pixels may be created during the warping process. It is suggested that feature extraction steps such as classification take place prior to image rectification to ensure image processing software is using unmodified brightness values (Jensen, 2005).

Scale is an essential factor to determine for aerial photographs. Without scale, it is impossible to use aerial photographs for measuring distances on photographs (photogrammetry) or for mapping. Scale (S) can be defined as a representative fraction (RF), such as 1:24,000. Other ways to define scale are equivalence (1 cm = 1 km), and photo scale reciprocal (PSR). Multiplying photo distance by PSR results in real-world distance. In other words, PSR = 1 / RF (Paine and Kiser, 2012).

Focal length (*f*) is another critical value to know in aerial photo interpretation. Most, if not all, manufacturers of consumer digital cameras publish technical specifications that include the camera's focal length. Focal length is the distance from the sensor plane to the center of the lens when focused at infinity (Paine and Kiser, 2012). Area of coverage in the image is directly proportional to the focal length. As *f* increases, area of coverage decreases, but greater detail is visible. As *f* decreases, area of coverage increases, but less detail is available.

Scale (S) is defined as the ratio photo distance (d) / ground distance (D) (Aber *et al.*, 2010**)**. Scale is also directly related to the focal length (*f)* and height above ground (Hg), with the relationship S = *f* / Hg. For vertical photographs, the ideal condition would be for the sensor plane and terrain to be perfectly level, in which case the scale would be the same throughout each photograph. In reality, that rarely - if ever - happens. In the majority of cases, scale in a vertical photo is only approximate throughout.

Numerous factors affect the scale of an aerial photo. Even if the aerial platform achieves a perfectly level trajectory (which is difficult to achieve), terrain typically is uneven. For a level image plane, the center of the photo is the principal point (P). A vertical line drawn from P through the focal point intersects the sensor plane at its center, as shown in Figure 2 (Aber *et al.*, 2010).

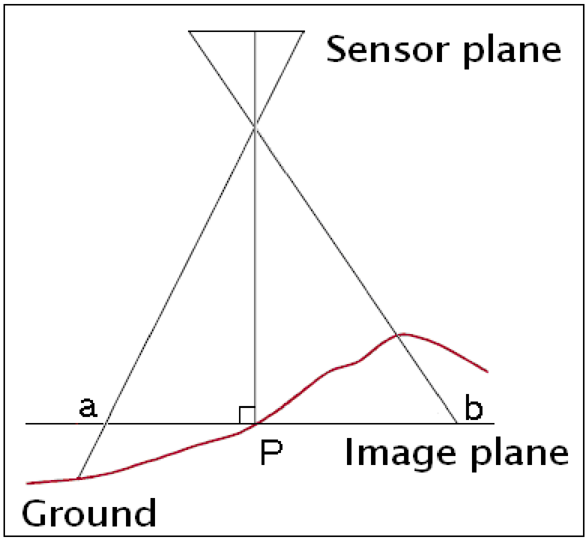

Figure 2. Level image plane + uneven terrain

If both the sensor plane and terrain were level, the scale at a, P, and b would be the same. With uneven terrain, it is readily apparent that for terrain higher than P, the scale is larger (larger representative fraction and smaller area of coverage), and for terrain lower than P, the scale is smaller (smaller representative fraction and larger area of coverage). Relief displacement is also affected, as objects higher in elevation than P will slant radially outward, whereas objects lower than P will slant radially inward (Aber *et al.*, 2010).

Rarely, if ever, will the sensor plane and terrain be parallel. Wind or pilot error can easily lead to an aircraft tilted along its roll and/or pitch axis. The best case scenario is usually a nadir photo, with the image plane tilted <3°. If the sensor plane is tilted from 3° - 90°, the photo is called an oblique photo, and is not suitable for photogrammetry or orthorectification due to excessive relief displacement. Oblique photos are more familiar to viewers of typical landscape photography, and do have value in providing the viewer a frame of reference for evaluating placement of landscape features. In an oblique photo, objects such as trees, buildings, towers, and bridges are easier to identify. Caves, overhangs, and objects under a forest edge are more likely to be visible, as well (Paine and Kiser, 2012).

Photos other than true vertical (tilt = 0°) have three centers: the principal point (P), as previously defined, the nadir point, and the isocenter. The tilt in Figure 2 is exaggerated for clarity. The nadir is the point where a true vertical line from the center of the camera lens intersects the image. Relief displacement radiates from the nadir point. If a line is drawn on the image from P to the nadir point, the isocenter is on that line at the halfway point between nadir and P. Tilt displacement radiates from the isocenter. Tilt displacement is seen when the image platform is not perfectly level (Paine and Kiser, 2012).

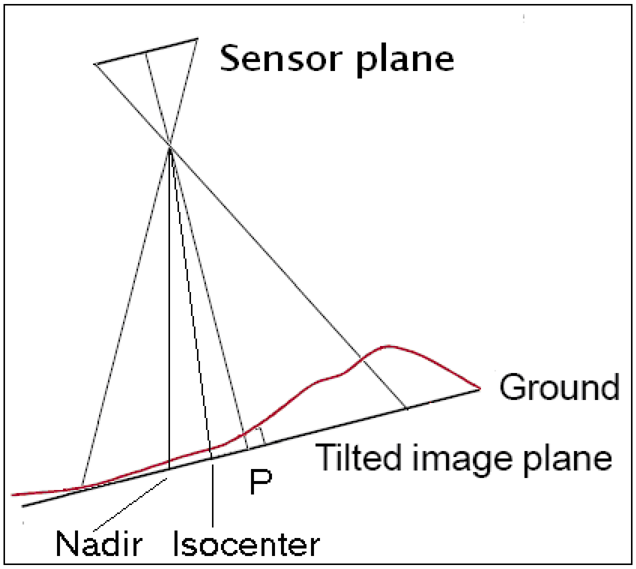

Figure 3. Tilted image plane + uneven terrain

The interior orientation of consumer cameras can also affect the quality of an aerial image. Lower quality lenses can be sources of radial distortion in an image. Chandler *et al.* (2005) discussed the importance of measuring and modeling the radial distortion errors in a consumer camera. For the purpose of photogrammetry, camera calibration is an important consideration. Unfortunately, camera calibration reports for consumer grade cameras are not easily obtained. However, calculating approximate locations and measurements is sufficient for all but the most precise mapping projects, negating the necessity for obtaining a precise distortion curve (Paine and Kiser, 2012).

. Another factor to consider in the interpretation of aerial photos is ground sampling distance (GSD), another name for the spatial resolution of the image (Aber *et al.*, 2010). Ideally, GSD should be one-half the size of the smallest objects to be identified (Sabins, 1997). GSD is defined by the expression GSD = (pixel element size) x Hg / *f* (Aber *et al.*, 2010). Pixel element size is determined by the sensor size (eg. 5.33 mm x 4.77 mm) and the sensor resolution in pixels; (eg. 1024 x 768), as provided by the manufacturer. The Nikon L3 has a sensor size of 5.744 mm x 4.308 mm. At a resolution of 2592 x 1944, the pixel size is 5.744 mm / 2592, or 4.308 mm / 1944, both of which calculate to 0.002216 mm. The focal length at infinity is 38 mm or 0.038m. For a 17-photo composite taken at the wetlands on March 2, 2012 (Color Plate 10) at an average height of 116.44 m, GSD was calculated as:

$$0.002216 \text{ mm} \times \frac{116.44 \text{ m}}{0.038 \text{ m}} = 6.79 \text{ mm}$$

The scale of the 17-photo composite was *f* / Hg, or

$$\frac{0.038 \text{ m}}{116.44 \text{ m}} = 0.0003263, \text{ or } 1{:}3{,}065$$

The calculated scale can be considered as approximately average throughout the photo, since the terrain was nearly flat, and the airplane was flying at an approximately level altitude.

A 38-photo composite was created from photos taken at the hilltop site on March 3, 2012 (Color Plate 11). Although the aircraft was flying at an approximately level altitude of 166.28 m (average), the terrain at this site varies precipitously, so the calculated scale is for the point from which the author was flying the airplane:

$$S = \frac{0.038 \text{ m}}{166.28 \text{ m}} = 0.0002285, \text{ or } 1{:}4{,}376$$

GSD was calculated as:

$$0.002216 \text{ mm} \times \frac{166.28 \text{ m}}{0.038 \text{ m}} = 9.7 \text{ mm}$$

Without further surveying of the hilltop site to measure other altitudes along the terrain, it is impossible to determine the average scale of the photograph. Color Plate 12 shows a close-up of the area around the pumping station in visible bandwidths, and Color Plate 13 shows the same general area in near infrared.

The near infrared converted Nikon L20 has a sensor size of 6.08 mm x 4.56 mm. At a resolution of 3648 x 2736, the pixel size is 6.08 mm / 3648, or 4.56 mm / 2736, both of which calculate to 0.001667 mm. The focal length at infinity is 41 mm or 0.041m. For the near infrared composite taken at the hilltop property (Color Plate 13) at an average height of 166.28 m, GSD was calculated as:

$$0.\ 001667 \text{ mm} \times \frac{166.28 \text{ m}}{0.041 \text{ m}} = 6.76 \text{ mm}$$

The scale of the near infrared composite was *f* / Hg, or

$$\frac{0.041 \text{ m}}{166.28 \text{ m}} = 0.0002465, \text{ or } 1:4{,}057$$

For the purposes of visual inspection or feature recognition, geometric correction of aerial photos is not strictly necessary. However, if an aerial photo is to be used for measuring or mapping, registering the photo with a known geospatial reference is necessary. Geometric correction can be done in one of two ways: by registering the photo to another photo of known geospatial reference using identifiable tie points, or by registering the photo using ground control points (GCP). A key factor in photo registration using GCPs is selecting objects that will be easily identifiable in a photo taken from 100 or more meters in the air. The author has found that objects that are easily identifiable when standing beside them may blend into the surroundings when viewed in an aerial photo. For higher accuracy, the more GCP defined the better (Aguilar *et al*., 2005). GCP were collected using a hand-held Garmin GPS. The author collected a total of 60 GCP at the hilltop site; due to the inaccessible nature of the wetlands and the homogenous grasslands surrounding them, less than a dozen suitable GCP were found. Due to insufficient overlap in photo sets over the wetlands, only a few mosaics were successfully created. Of those, only two had sufficient identifiable GCP to be able to place them in their proper geographic orientation (Color Plates 10 and 15). Note the similarities between the unrectified near infrared composite in Color Plate 14 and the rectified visible composite in Color Plate 15. There was enough drift in the track of the aerial platform that several key GCP that are visible in Color Plate 15 are not visible in Color Plate 14, making rectification of that image impossible, nor was the author successful when attempting image-to-image rectification between Color Plates 15 and 14.

COLOR PLATES

Plate 1. Multiplex Easystar with Nikon L3 rigged for taking oblique photos.

Plate 2. Multiplex Mentor. GPS antenna is directly behind propeller.

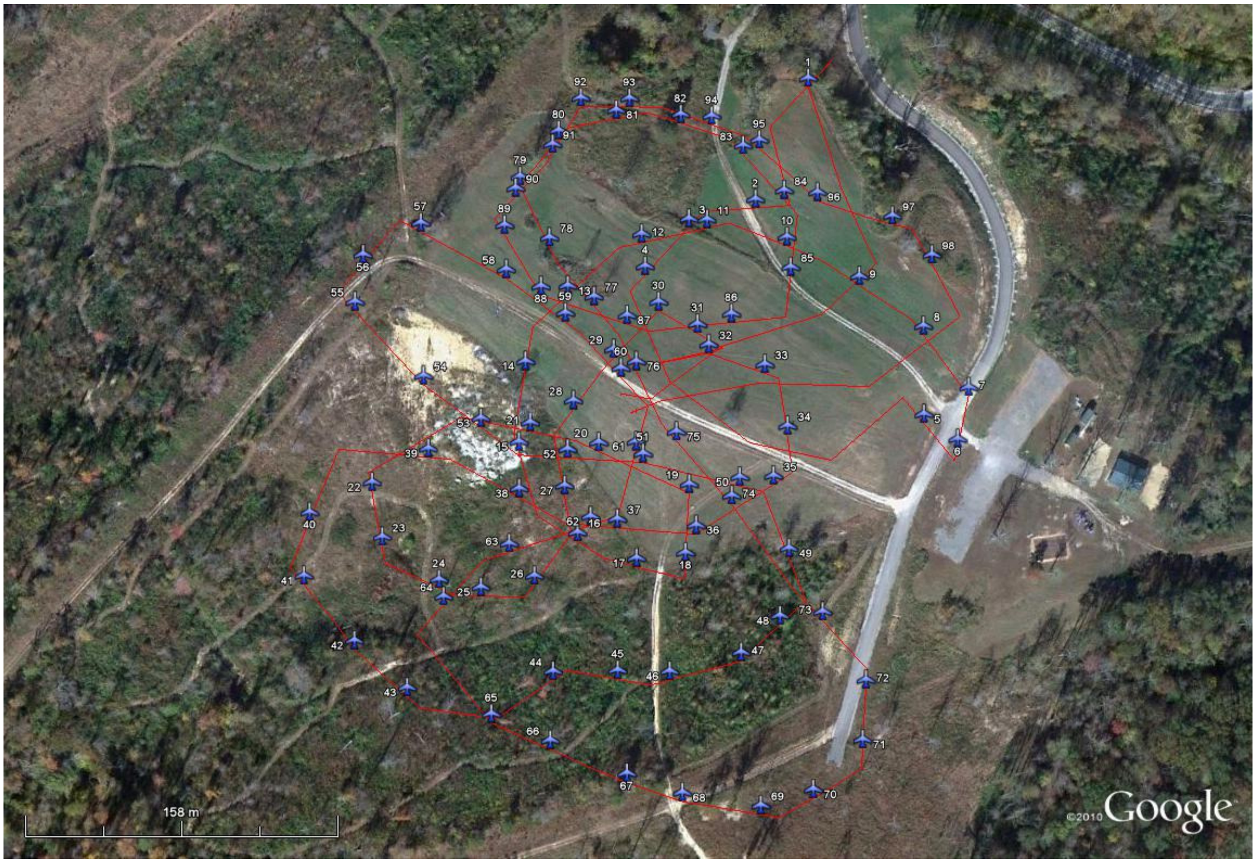

Plate 3. Sample GPS plot of aircraft flight path with locations of photos.

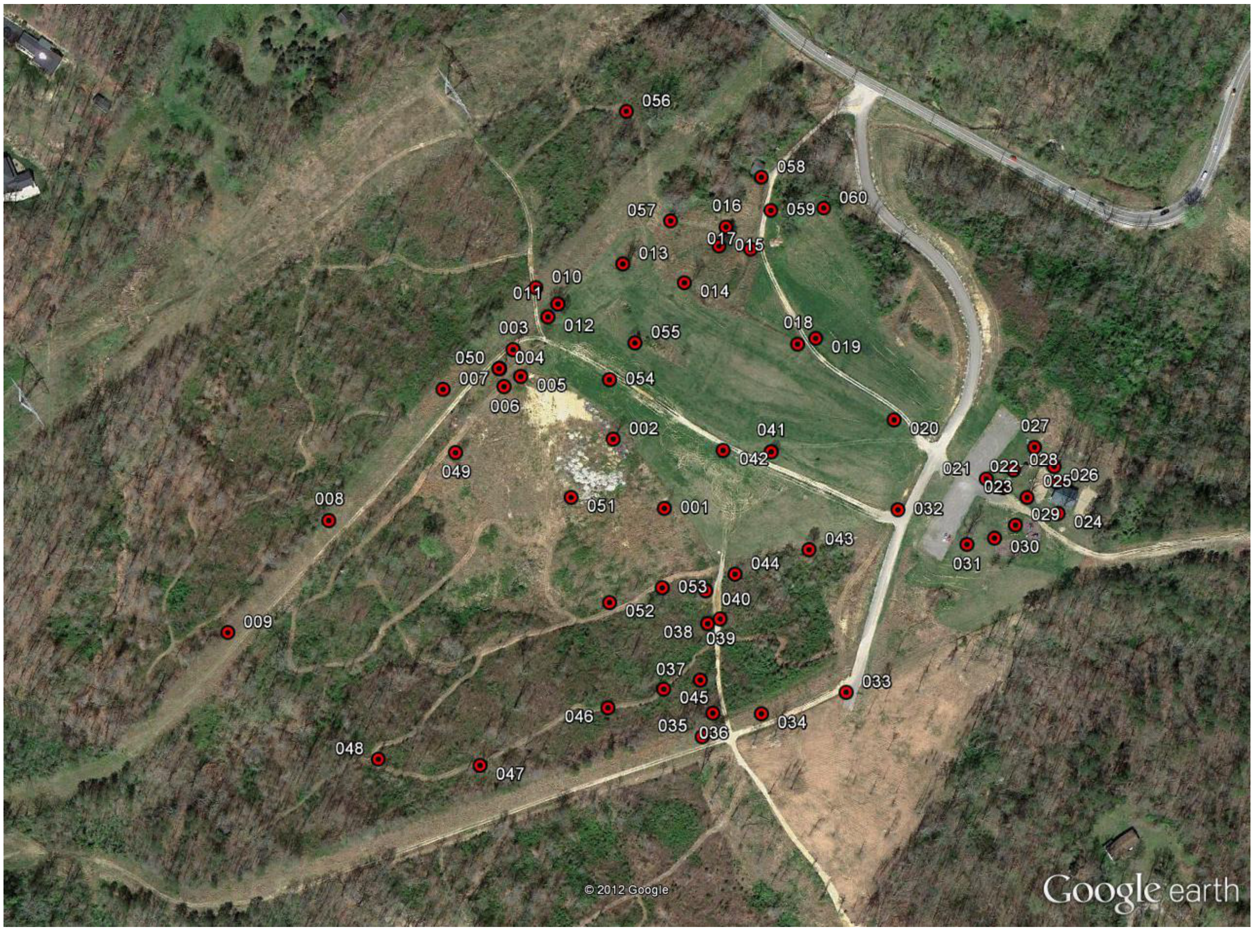

Plate 4. Plot of Ground Control Points at hilltop site.

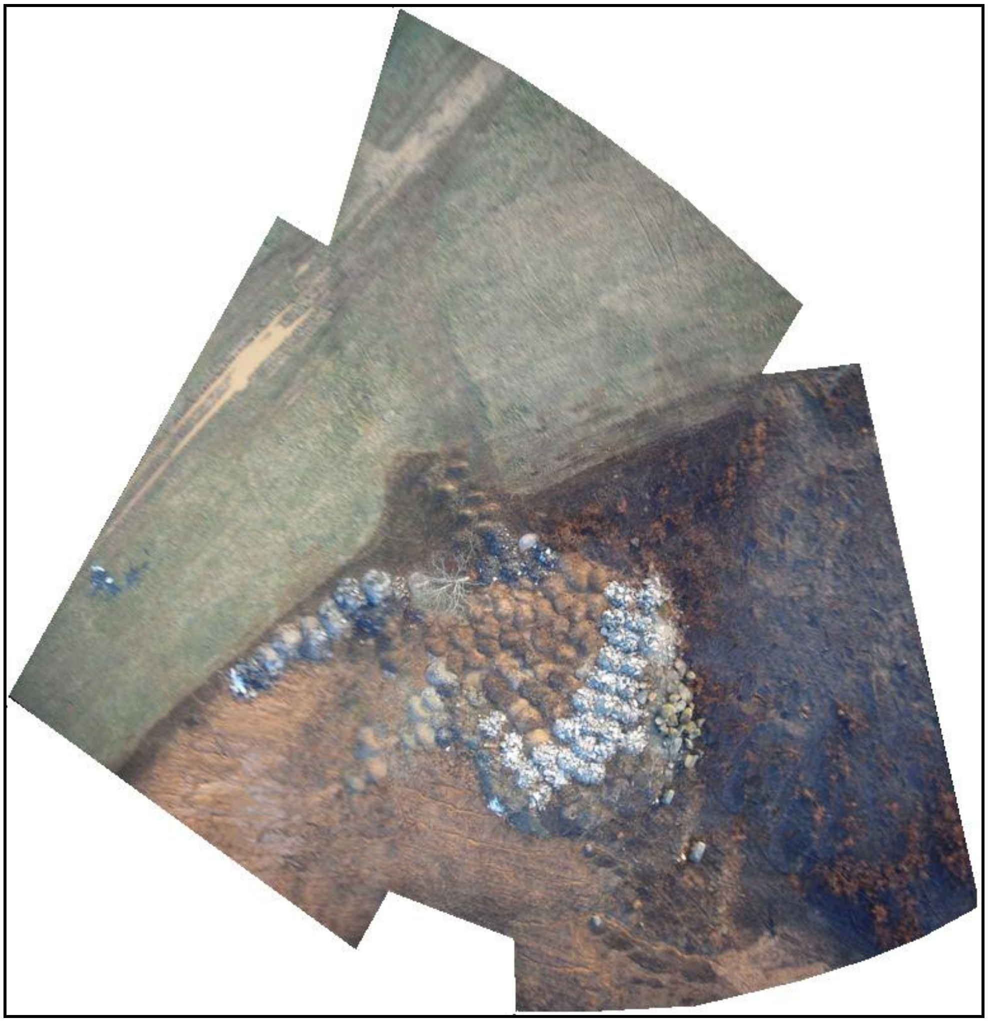

Plate 5. Unrectified hilltop composite from Microsoft Image Composite Editor.

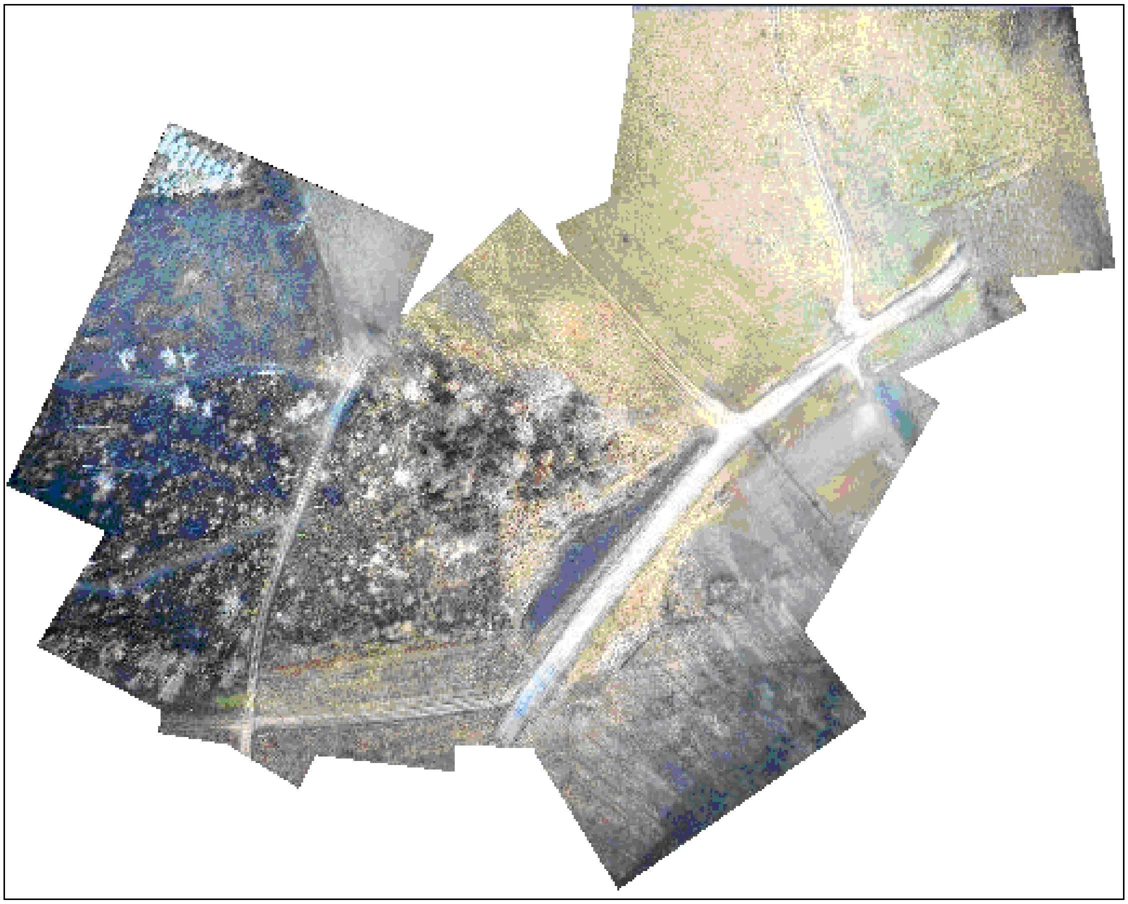

Plate 6. Unrectified Image Composite Editor composite.

Plate 7. First rectification attempt with ER Mapper (Compare to Plate 6).

Plate 8. Previous image rectified to WGS84 with ESRI ArcGIS 9.3.

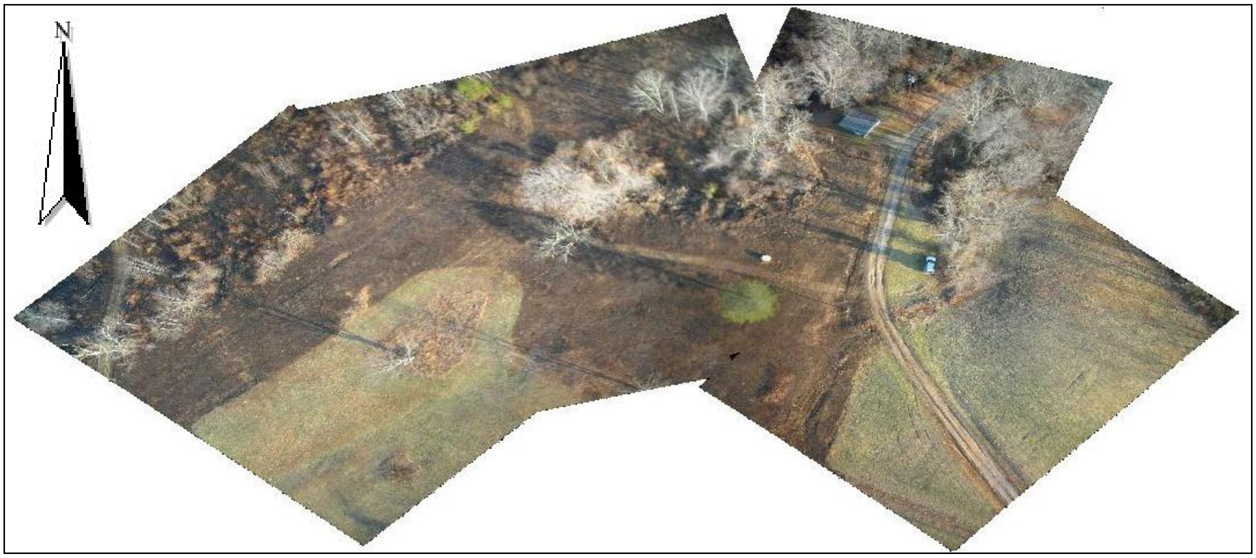

Plate 9. Hilltop composite rectified to WGS84 with ER Mapper.

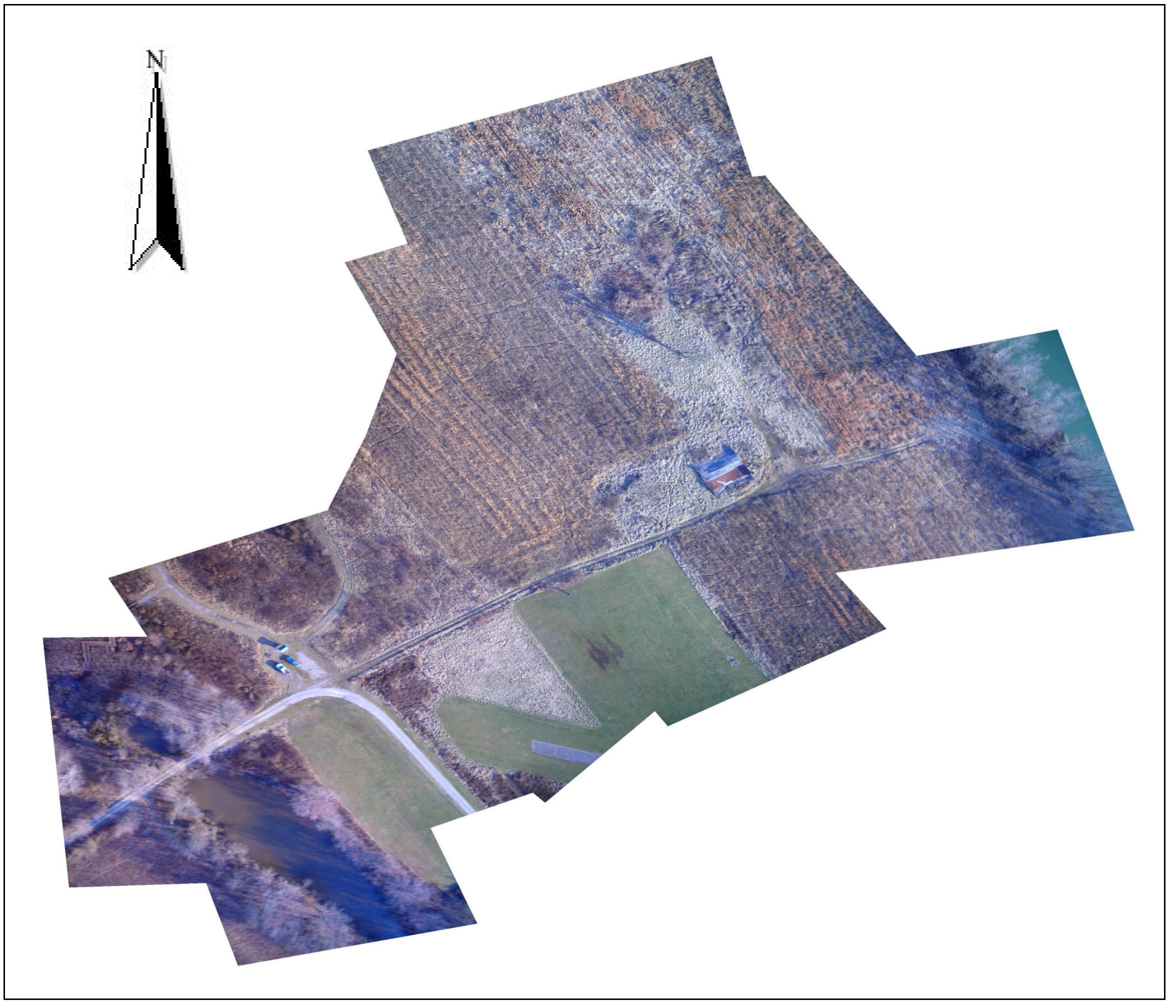

Plate 10. 17-photo composite near wetlands rectified to WGS84 with ESRI ArcGIS 10.0.

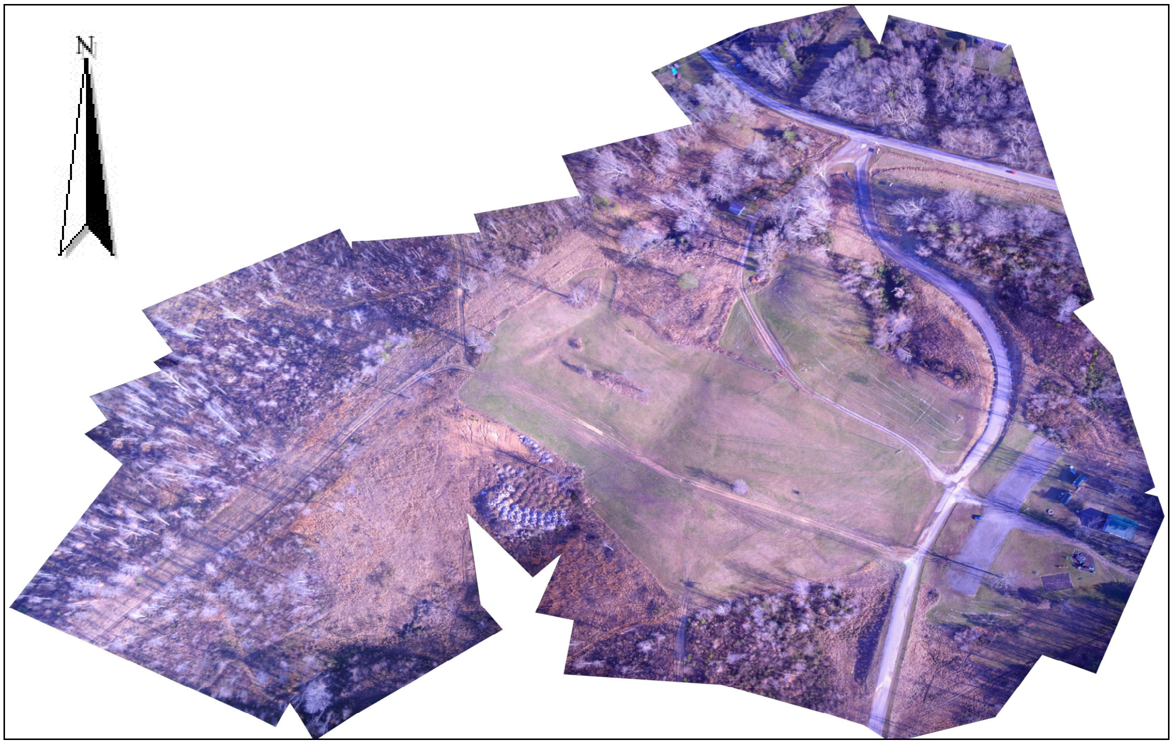

Plate 11. 38-photo hilltop composite rectified to WGS84 with ESRI ArcGIS 10.0.

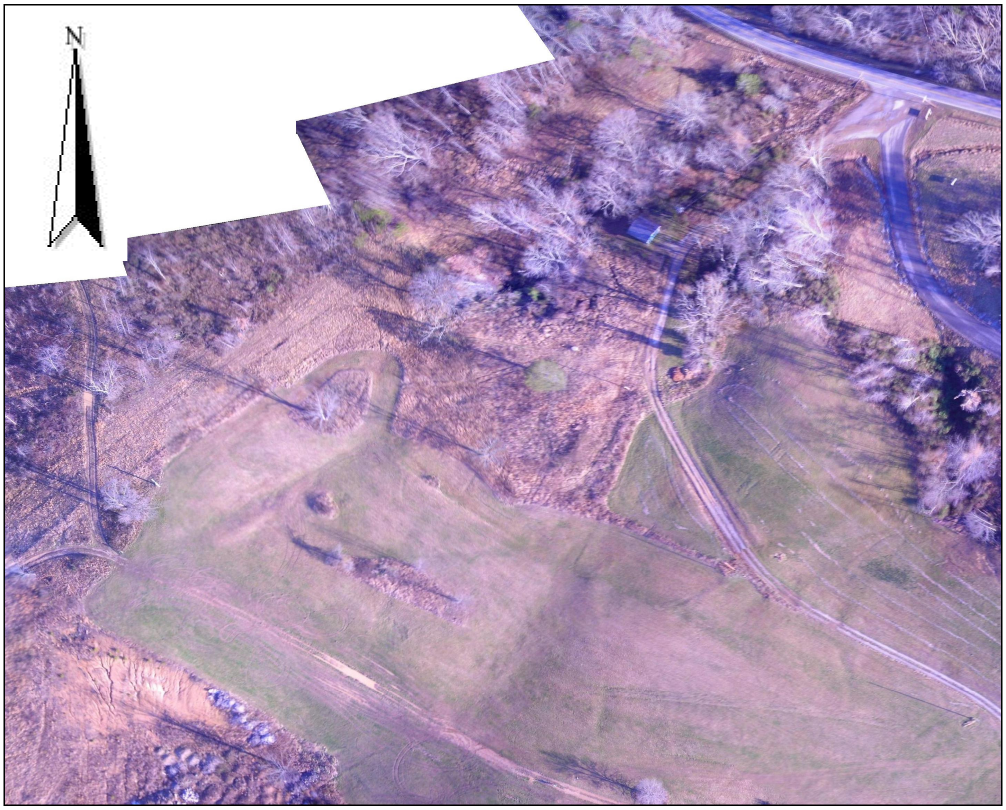

Plate 12. Close-up of hilltop pumping station area (See Plate 11).

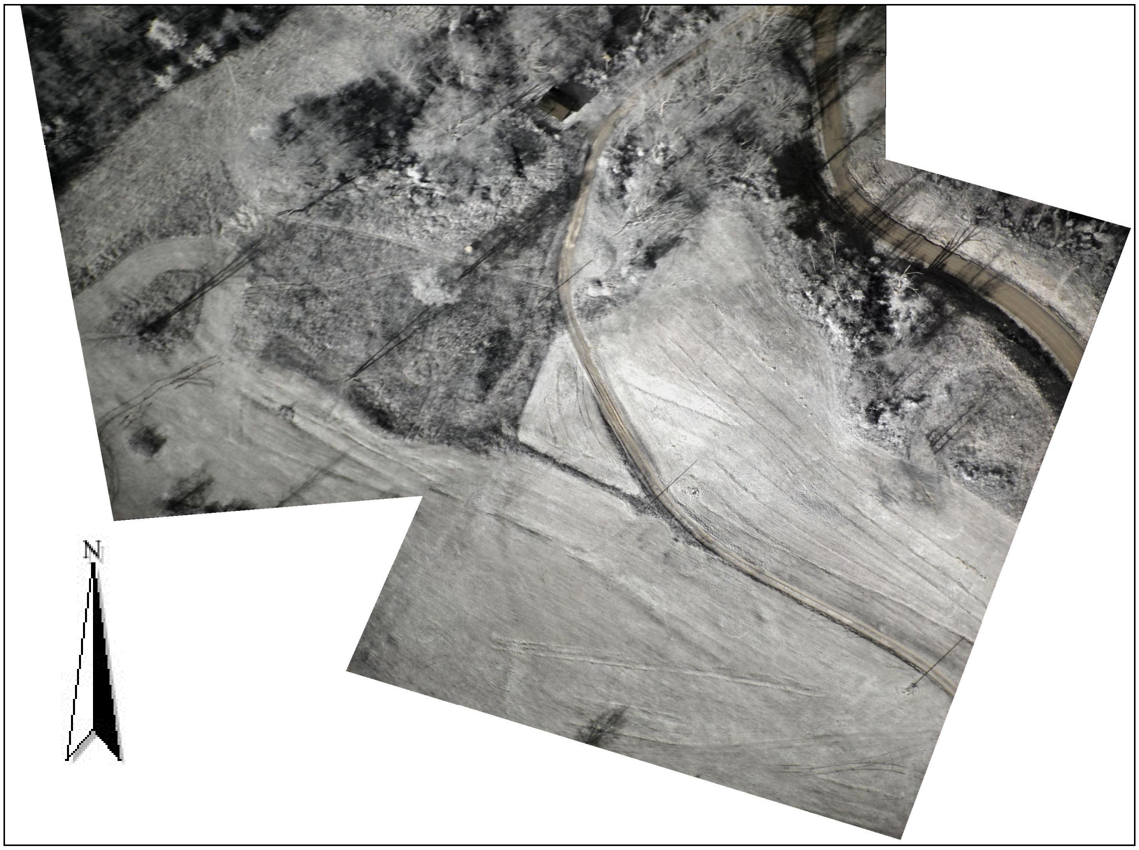

Plate 13. Close-up of hilltop pumping station area in near infrared (Compare to Plate 12).

Plate 14. Unrectified near infrared composite of wetlands in mid spring.

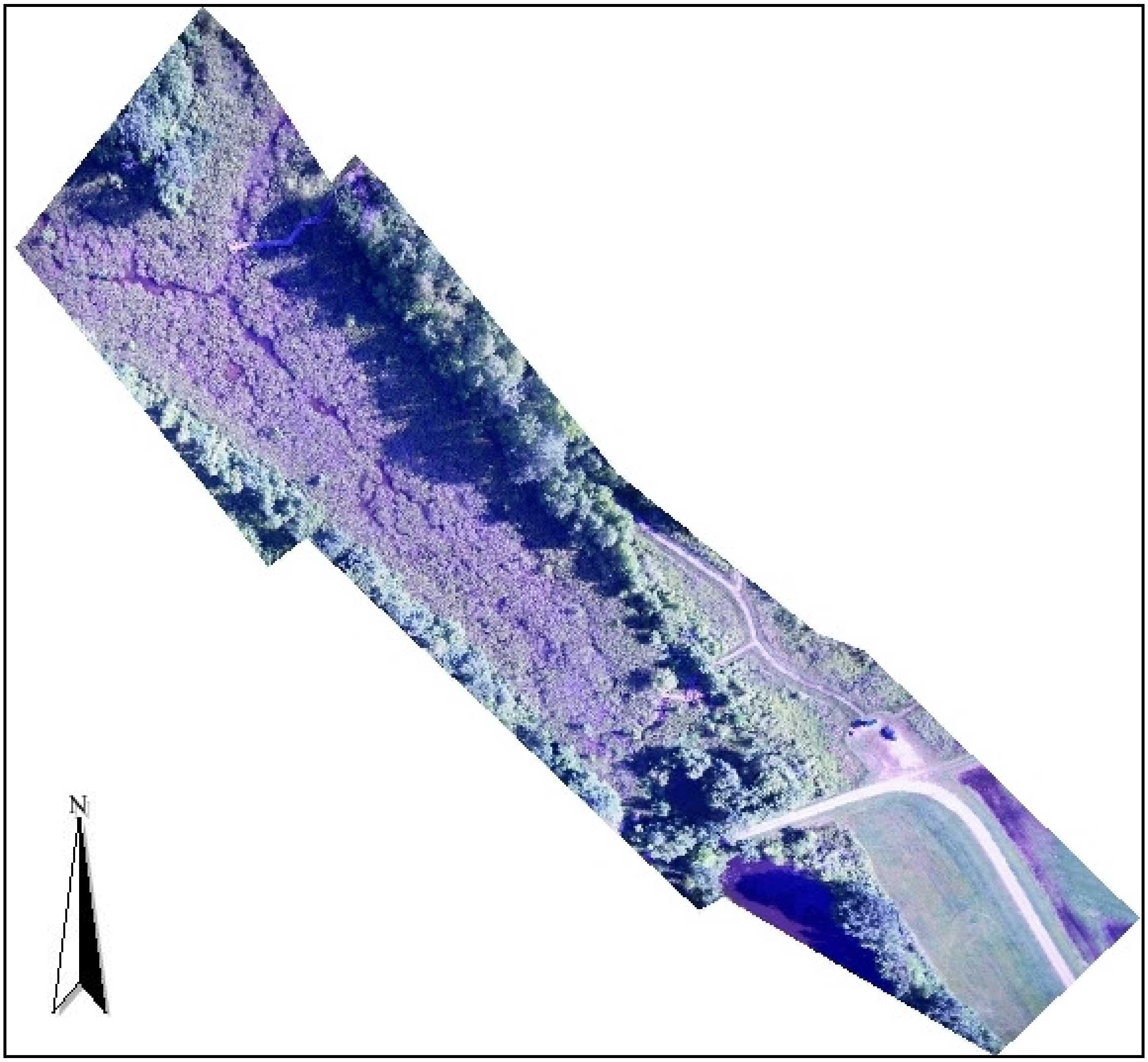

Plate 15. Rectified composite of wetlands in mid spring (Compare to Plate 14).

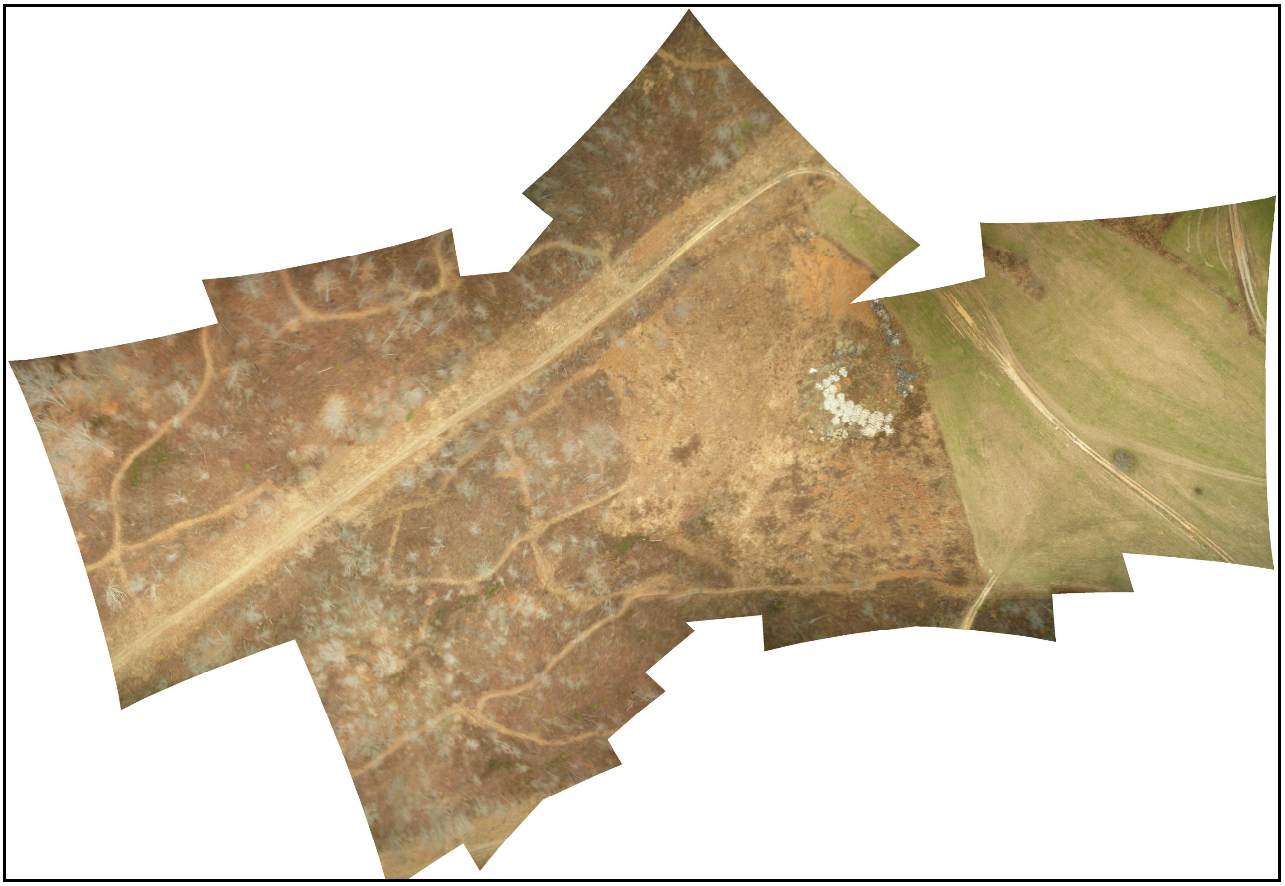

Plate 16. Unrectified mid-winter composite over hilltop site. Note lack of contrast due to low ambient light.

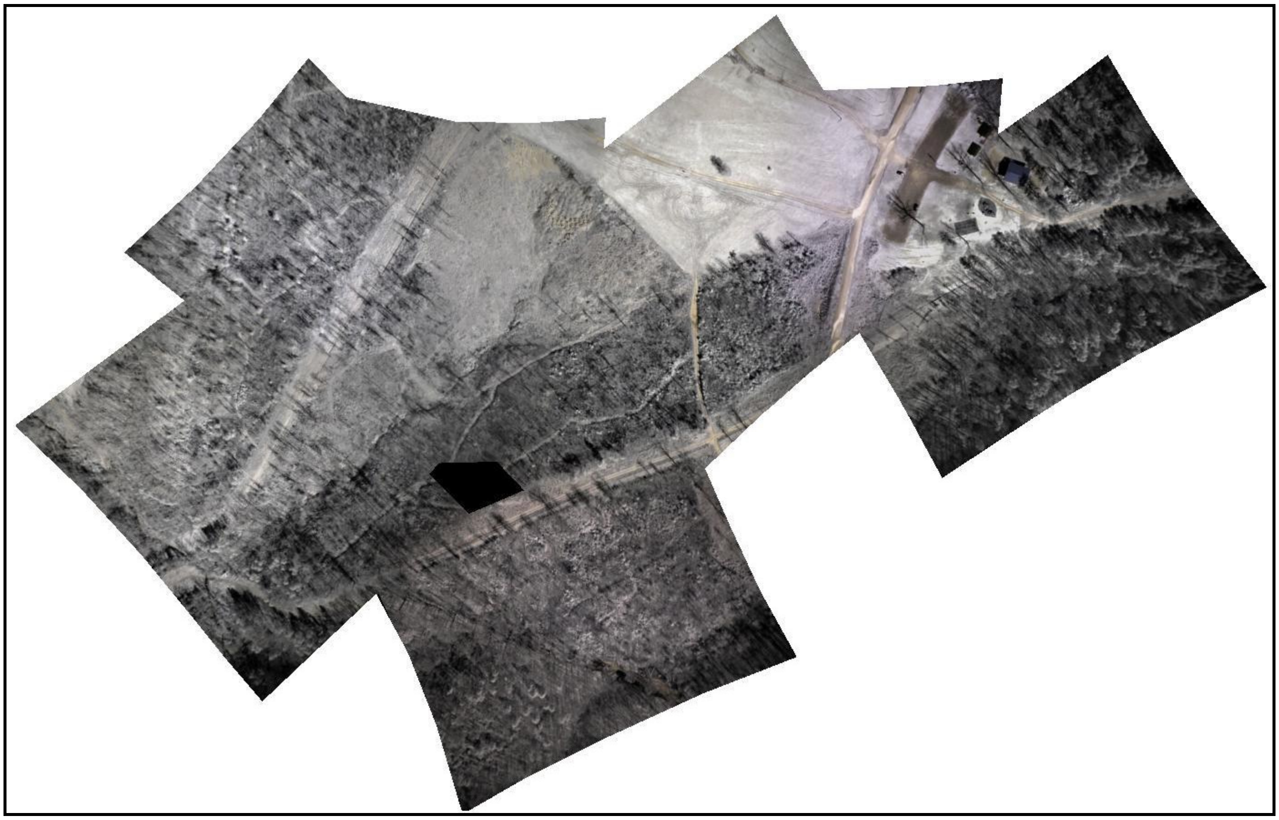

Plate 17. Unrectified late winter near infrared composite over hilltop site.

CHAPTER 4
CONCLUSIONS

The author has found radio controlled aircraft to be useful vehicles for carrying cameras for aerial imagery. Lighter weight, slower flying aircraft such as gliders help reduce the possibility of motion blur in photographs. A disadvantage of lighter weight, slower flying aircraft is they are more affected by wind. The aircraft's flight path can drift in the wind, and roll/pitch oscillations can induce variations in scale in captured images. Gyroscopic stabilization reduces oscillations around the aircraft's roll, pitch, and yaw axes, but does not eliminate them entirely. The use of a common consumer digital camera yielded images with sufficient resolution for identifying features; however, tip and tilt of the aircraft resulted in severe relief displacement in some images. Furthermore, orthorectification was not possible due to the lack of fiducial points in the consumer-grade cameras.

The use of a common GPS logger on the aircraft enabled the plotting of the aircraft's track in Google Earth, but identification of known GCP was necessary for registering aerial images to a geographic reference system. Finding suitable GCP can be difficult in homogenous features such as deciduous forests, grasslands, and wetlands; identification of those GCP from images taken 100 meters or more above the surface was difficult. If not enough GCP are used, or if features are not carefully identified in the aerial images, residual errors in the resampled images can be high, resulting in severe geographic displacement of features.

Various authors have used auto-navigation to control the path of their UAVs (Berni *et al*., 2009), (Grenzdörffer *et al*., 2008), (Nebiker *et al*., 2009). GPS-enabled auto-navigation allows preset waypoints to be programmed into the flight path. Additionally, auto-navigation helps maintain a near-constant aircraft altitude, which is important for maintaining the image scale among a set of aerial photographs. The UDB3 autopilot used by the author required several hours of programming and flight testing to achieve suitable performance. Once that was accomplished, UDB3 was successful in maintaining a steady altitude and airspeed. However, UDB3 at times tends to "hunt" for its programmed waypoints. The tendency to wander between waypoints at times led to the aircraft's flight path being insufficient to achieve enough photo overlap for mosaics larger than approximately 10 acres. Numerous commercial autopilots are available in addition to UDB3. Some of those are purported to be extremely accurate in their use of waypoint navigation, with correspondingly higher costs ($500 - $3,000+).

Small format aerial images offer an alternative to images obtained from satellites or man-carrying aircraft. SFAP images can have spatial resolution in the sub-centimeter range, and temporal resolution can be measured in minutes if the researcher has a portable computer and a means of transferring the images from the camera to the computer at their disposal. Although SFAP affords the ability to tailor image acquisition to specific needs, image processing can take up much more time than the actual collection of images (Morgan *et al*., 2010). For the purposes of image processing, image interpretation and feature identification, it is essential to establish a consistent work flow and adhere to it strictly. The progression of steps in the image processing work flow is important; for example, georeferencing a photo or set of photos usually warps pixels, and may create admixtures of digital brightness values. Therefore, certain tasks such as feature classification may need to be accomplished prior to image rectification (Morgan *et al*., 2010).

Spectral resolution of SFAP images is typically limited to four bands (R, G, B, and near infrared), although a project with a slightly larger budget may consider a small multi-spectral camera such as the Tetracam ADC Lite, at a cost of approximately $5,000. Wind is a factor to consider at all times for a small camera platform, and the author has found winds above 10 mph tend to make aerial photography difficult. Calibration measurements of consumer cameras tend to be difficult – if not impossible – to obtain, and lens distortion in inexpensive cameras can be a factor.

There are many applications where low cost, low altitude digital images will provide valuable data for the researcher. In areas of precipitous terrain, or areas where foot travel is impermissible, such as wetlands, a low flying aerial platform carrying a digital camera can collect images with a spatial resolution better than most satellite images. An aerial platform with an electric power system is also environmentally friendly, and ideal for sensitive areas such as wetlands, or where noise must be minimized, such as monitoring wildlife or livestock. Because of the short turn-around time possible between image sets, SFAP is useful for monitoring sites with homogenous land cover – such as prairie, crops, or forest – for short-term changes due to pests, disease, fire damage, storm damage, etc. Low cost SFAP may be the best option for obtaining low altitude aerial images in applications where precise photogrammetric measurements are not required.

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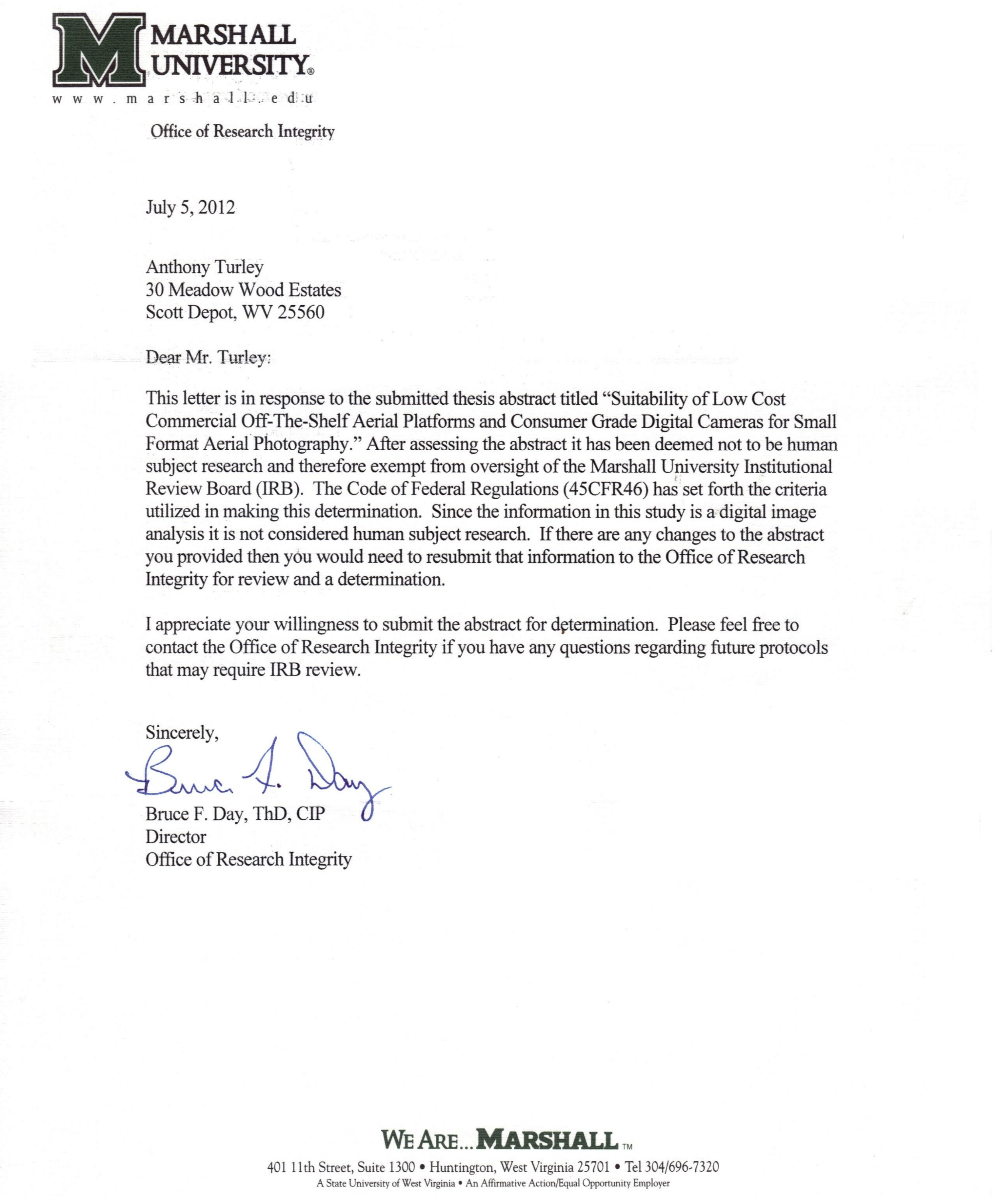
APPENDIX A
INSTITUTIONAL REVIEW BOARD LETTER



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Office of Research Integrity

July 5, 2012

Anthony Turley
30 Meadow Wood Estates
Scott Depot, WV 25560

Dear Mr. Turley:

This letter is in response to the submitted thesis abstract titled "Suitability of Low Cost Commercial Off-The-Shelf Aerial Platforms and Consumer Grade Digital Cameras for Small Format Aerial Photography." 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 is a digital image analysis 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
Office of Research Integrity

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