2019

Evaluating consumer grade UAVs and their potential applications and implications in Ontario consulting archaeology

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Evaluating Consumer Grade UAVs and their Potential Applications and Implications in Ontario Consulting Archaeology

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Submitted to the Faculty of Graduate Studies in Partial Fulfillment of the Requirements for the Degree of Masters of Environmental Studies in Northern Environments and Cultures

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ABSTRACT

Archaeological investigation is an inherently destructive process that threatens permanent data loss if archaeological sites are inadequately recorded. While archaeologists strive to develop innovative methods to ensure adequate data capture, they are often inhibited by funding and training in new methodologies. Limited funding is exacerbated in a consulting archaeology framework in Ontario where budgets are competitively determined and offer little flexibility or incentive to exceed the minimum standards enforced by the Ministry of Tourism, Culture and Sport (MTCS). This thesis critically examines consumer-grade unmanned aerial vehicles (UAVs) as a potential site recording and prospecting tool. Through four case studies, the UAVs efficacy is evaluated and UAV-derived data products are outlined to determine whether the aerial platform is a suitable technological innovation that increases data capture while remaining affordable for Ontario consultant archaeologists.

DEDICATION

This thesis is dedicated to Dr. Terry Gibson, who sadly passed away before this thesis was completed. Terry was an innovator in the archaeological community who continually integrated new technologies into all of his surveys for the betterment of the discipline. His enthusiasm for my thesis topic was truly appreciated.

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my supervisor, Dr. Scott Hamilton (Dept. of Anthropology, Lakehead University) who not only provided his guidance and support throughout my post-secondary education, but also provided equipment and transport throughout this thesis. His mentorship has been integral to my academic career and his ethics and guiding principles were key in the development of my professional career in consulting archaeology.

Thank you to my internal reviewers, Douglas Yahn (WSP Canada Inc., Professional Associate – Lakehead University), and Dr. Matthew Boyd (Dept. of Anthropology, Lakehead University) for their valuable and prompt reviews. I would also like to thank Dr. Peter Whitridge (Dept. of Archaeology, Memorial University) who provided essential insight as the external examiner for this thesis.

I am especially grateful for Douglas Yahn and Dan Mohr of WSP Canada Inc. for their insurmountable interest in being the sponsoring organization for the Natural Sciences and Engineering Research Council of Canada (NSERC) Industrial Postgraduate Scholarship (IPS) Program and for providing access to office space and professional-grade equipment. The financial contribution from NSERC was integral to my success and for that I am incredibly thankful. Another thank you to Douglas for his business acumen and for continuing to invest in my professional development.

Others that I would like to thank are: Eleanor Hamilton who provided food, shelter, and alcohol during the Manitoba surveys; and, Jennifer McKee (Dept. of Anthropology/Geography, Lakehead University) who ensured everything stayed on track, as she is masterful in the graduate thesis process.

Lastly, I would like to thank my wife, Jacqueline, who endures all my bad puns and portmanteaus. She provided valuable edits and unwavering support throughout the production of this thesis.

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LIST OF ABBREVIATIONS

AOI	Area of Interest
ASI	Archaeological Services Inc.
ASL	Above Sea Level
CARs	*Civil Aviation Regulations*
dGPS	Differentially corrected GPS
DEM	Digital Elevation Model
EM	Electro-magnetic
FIR	Far Infrared
GCP	Ground Control Point
GIS	Geographic Information System
GPS	Global Positioning System
GSD	Ground Sampling Distance
IR	Infrared
IMU	Inertial Measurement Unit
LHC	Letourneau Heritage Consulting Inc.
LiDAR	Light Detection and Ranging
LWIR	Long-wavelength Infrared
MNCFN	Mississaugas of the New Credit First Nation
MSS	Multispectral Scanner
MTCS	Ministry of Tourism, Culture and Sport
MWIR	Mid-wavelength Infrared
MVS	Multi-View Stereo
ND	Neutral Density
NIR	Near Infrared
NOTAM	Notice to Airmen
PPI	Pixels Per Inch
RAF	Royal Air Force
RC	Remote Control
RFC	Royal Flying Corps
RPAS	Remotely Piloted Aerial System
RTK	Real-time Kinematics
S&Gs	*Standards and Guidelines for Consultant Archaeologists*
SEM	Scanning Electron Microscopy
SfM	Structure From Motion
SFOC	Special Flight Operations Certificate
SON	Saugeen Ojibway Nation
UAV	Unmanned Aerial Vehicle
VLOS	Visual Line-of-Sight
VPS	Visual Positioning System

1 INTRODUCTION

While archaeology concerns the study of the past, the field requires innovative methods and emerging technologies to strengthen its scientific and quantitative foundations. Be it utilization of GPS for field documentation, ground penetrating radar for site detection, or artifact analysis using scanning electron microscopy (SEM), many archaeologists integrate innovative technologies to further expand the archaeological record. However, archaeological research is often hindered by funding availability. Moreover, time and financial constraints are compounded for consultant archaeologists working in a competitive bidding environment. This encourages efforts to identify efficiencies in field data collection and analysis.

Unmanned Aerial Vehicles (UAVs; or Remotely Piloted Aerial Systems (RPAS)) are a comparatively new and rapidly transforming technology, resulting in highly sophisticated instruments with improved accessibility and quality of hardware. Their widespread popularity has simultaneously decreased costs and increased the availability for the average consumer. Professional-grade UAVs can cost between $3000 and $300,000, but their consumer-grade counterparts, typically costing between $600 and $2500, can now collect similar, high quality data. This thesis critically evaluates consumer-grade UAVs as a tool that might offer technological efficiencies in Ontario consulting archaeology. It examines how UAVs can be integrated by archaeologists for a more cost-effective collection of better quality data. Also considered are the types of data that can be collected using UAVs, and whether such data can improve current consulting archaeology practices.

Consulting archaeology in Ontario is mandated by the *Ontario Heritage Act, 1990* and is typically triggered by a proponent's application for development under the *Environmental*

Assessment Act or *Planning Act.* Archaeological methodology in these development contexts is prescriptive as all fieldwork and reporting must adhere to the Ministry of Tourism, Culture and Sport's (MTCS) *Standards and Guidelines for Consultant Archaeologists* (*S&Gs*) (2011). The *S&Gs* provides a minimum benchmark for carrying out archaeological consulting work, but conversely introduces few incentives for archaeologists to transcend these standards in any way. Under this legal framework, multiple archaeologists may bid on a client's call for tenders, resulting in highly competitive budgets. As success in bidding is often driven by projected cost, the minimum methodological standard often becomes the benchmark. As a consequence, comparatively new site characterization methods that might be more common practice among academic archaeologists (e.g. ground penetrating radar or electromagnetic resistivity) are seldom integrated into commercial consulting operations because they are not a requirement of the *S&Gs*. Since the *S&Gs* are highly prescriptive, the consulting business in Ontario has become narrowly focused on simply complying with these base standards, rather than surpassing them. Consulting archaeological assessments make up the vast majority of archaeological field work in Ontario (an average of 3000 assessments completed *per annum),* and are completed rapidly in a rather formulaic fashion. This is contributing to fieldwork becoming 'frozen' at the standards common several decades ago.

The insufficient methodology used in Ontario consulting archaeology has been critiqued extensively (see Ferris, 2009; Timmins, 2012, 2013; Kapyrka, 2014; Kapyrka & Migizi, 2016, MNCFN, 2018), but it is still the predominant means of collecting new archaeological data in the province. Given the inherently destructive nature of archaeological excavation, data loss as a result of poor methodology used in the time- and budget-sensitive consulting process is a frequent risk. Thus, tools to effectively increase data capture that do not incur additional expenditures or increased time requirements are paramount.

In Ontario there is also little framework or direction offered for addressing an archaeological site's geographic placement within a landscape. Much of the *S&Gs* reflect an emphasis on documentation of physical artifacts and features found within a site. However, as Bruno & Thomas state: "the lived in world is not simply a backdrop to everyday action but integral to all human activity. Thus, landscape becomes a source of reference and a context of meaning, central to archaeological theorizing" (2008, p. 25). Landscape is also a key component of the First Nations perspective (FOFGA, 2012 citing Buggey, 1999):

> An Aboriginal cultural landscape is a place valued by an Aboriginal group (or groups) because of their long and complex relationship with the land. It expresses their unity with the natural and spiritual environment. It embodies their traditional knowledge of spirits, places, land uses, and ecology. Material remains of the association may be prominent, but will often be minimal or absent.

As such, landscapes are an important element in archaeological research and should be considered to further explore the context of archaeological sites. Consultant archaeologists do not necessarily disregard the landscape from their analysis; however, the *S&Gs* offer limited latitude within a competitive bidding process to experiment with new tools to assist archaeologists in landscape recording. Consequently, mapping often relies upon published maps, aerial photography, or satellite imagery, but there have been comparatively few efforts at augmenting interpretation with output at a finer resolution and larger scale.

Airplane-based aerial photography and high-resolution satellite imagery are standard tools used by archaeologists outside of Ontario. Scollar et al. (1990, p. 28) have affirmed aerial photography "is unquestionably the cheapest form of archaeological prospecting per unit area and per working hour. It also produces the highest rate of return on money invested, and archaeologists usually accept the results without the need for detailed explanations or complex mathematical evaluation techniques”. Despite this outlook, commissioned airplane-based aerial photography requires considerable planning to initiate and incurs considerable costs by Ontario consulting archaeology standards. Satellite imagery is in a similar state in that high-resolution imagery can be expensive to purchase and requires specialized skill and software to process. If these data are utilized, archaeologists tend to rely upon already existing (often freely available) imagery that might be comparatively low resolution and captured in less than optimal conditions (e.g. at times when there is dense foliage, cloud cover, or snow cover) to facilitate archaeological interpretation. High-resolution commercial satellite imagery cannot yet reach the spatial resolution associated with aerial photography, and the satellite datasets that near this quality are expensive (Parcak, 2009). Consumer-grade UAVs may balance the cost/spatial-resolution disparity and provide Ontario consultant archaeologists with a flexible, portable platform that captures inexpensive high-resolution data.

1.1 Research Objectives

This thesis reviews the history of aerial photography and its archaeological application, and summarizes current attempts in utilizing UAVs in academic archaeology realms. It then assesses the functionality of UAVs and potential methodologies that can be used to retrieve data from the platform with special consideration of constraints that are often placed on consulting archaeologists. This research features a series of low-budget case studies conducted in Ontario and Manitoba that provide examples of situations consulting archaeologists may encounter. User-accessibility and manipulation of UAV-derived data will also be discussed.

In sum, the thesis will:

1. Address the state of UAV use in Ontario consulting archaeology;
2. Assess the potential and value-added utility of UAVs in consulting archaeology and its implications for landscape considerations;
3. Refine methodologies to balance ease-of-use and maximize data return for the non-remote sensing specialist; and
4. Outline needs for future research and development in UAV-based aerial photography.

1.2 Thesis Outline

The following chapters in this thesis provide context and a framework to evaluate the efficacy of UAVs in Ontario consulting archaeology. Chapter 2 outlines the use of optics and the electromagnetic spectrum in remote sensing applications. It then discusses the history of aerial photography and its importance in archaeological research with the natural progression towards digital and satellite-based data collection. A summary of current UAV utilization in archaeology across the globe is presented, including the methods that are currently employed. Initial attempts at assessing UAVs efficacy deriving from Stephenson's undergraduate thesis are also discussed.

With the foundation offered by Chapter 2, Chapter 3 outlines the materials and methods that may be best adapted by consulting archaeologists in the immediate future. Hardware, software, data processing, and their accuracy implications are discussed. Cost and accessibility in each aspect are noted with a focus on consulting archaeology's limitations. Litigation surrounding UAV use in Canada, and its subsequent hurdles are also presented.

Chapter 4 employs the materials and methods described in the previous chapter in a series of four case studies conducted in Ontario and Manitoba. The case studies become increasingly complex: from initial assessments establishing UAVs potential applications to land-use and viewshed analysis using digital UAV-derived data. Considerations of consulting archaeology are foregrounded, and metadata and resources used to achieve each case study are outlined.

Chapter 5 reflects on the case studies and evaluates UAVs' efficacy in current consulting practices. Implications of UAV-derived data and how it may affect consulting practices are also discussed. The chapter identifies trends that may affect UAVs in archaeology in the near future and considers potential technological advancements not yet achievable that will further progress UAV-derived data.

Conclusions regarding the accessibility, fiscal practicality, and value in UAV use in consulting archaeology are made in Chapter 6. The thesis will determine whether UAVs can be adopted immediately by Ontario consultant archaeologists, whether improvements will be required, or whether UAVs are not useful in any capacity.

2 AERIAL PHOTOGRAPHY HISTORY

2.1 INTRODUCTION

This chapter summarizes ideas and conceptualizations about gaining aerial perspectives that date from before the invention of cameras and airplanes, through to modern technological developments. While technology has transformed dramatically, a historical review provides important context to appreciate contemporary aerial archaeology. The chapter first discusses the electromagnetic spectrum. It then provides an overview of the development of aerial photography with a discussion of historical archaeology applications. The development of satellite imagery is also discussed, followed by recent examples of UAV utilization, including Hamilton and Stephenson's early attempts in UAV research.

2.2 OPTICS AND THE ELECTROMAGNETIC SPECTRUM

Ultimately, this thesis explores interpretation of light and its interactions with matter. All imagery collected by UAVs, airplanes, or satellites, involves the collection of electromagnetic (EM) waves. By understanding the physics of EM waves, this imagery can be used to generate unique data that may otherwise remain invisible to the archaeological record.

Humans perceive the world through a narrow portion of the EM spectrum representing the 'visible light spectrum' (i.e. between 390 to 700 nm). Colours from violet to deep red are found within this spectrum and are detectable by most cameras that typically collect EM waves from 350 to 950 nm (Beck, 2010) (Figure 2-1). While most humans perceive this spectrum, the EM spectrum exists well beyond it, and can offer considerably more information about archaeological sites and other features.

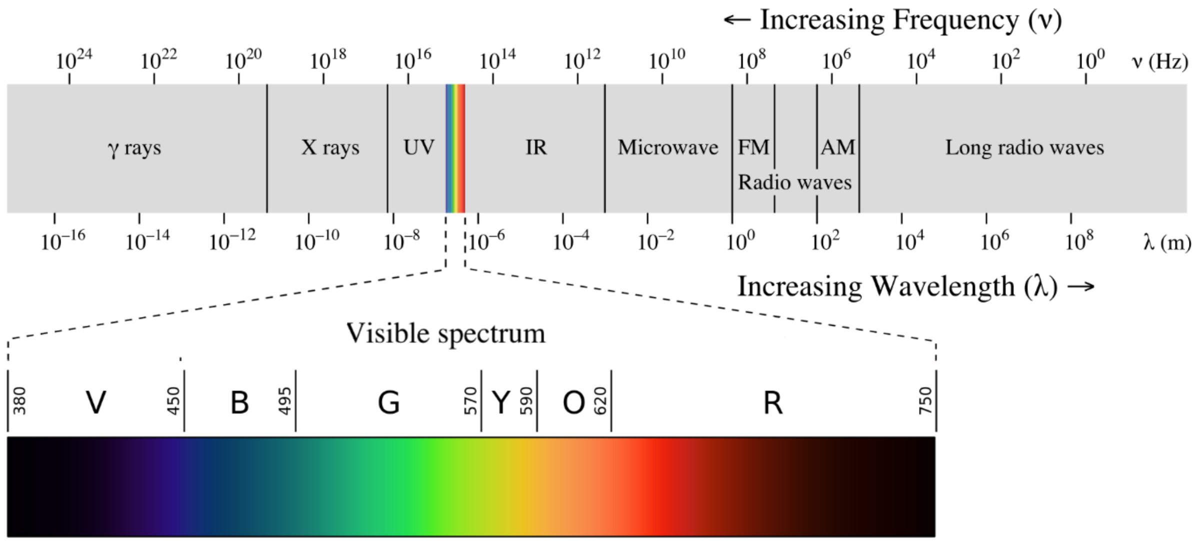

Figure 2-1 Electromagnetic Spectrum (Granger, n.d.)

Typically, in remote sensing applications, wavelengths beyond visible light are exploited. In this context, the infrared spectrum is frequently used since it has a vast array of applications. This spectrum contains five divisions: near-infrared (NIR), short-wavelength infrared (SWIR), mid-wavelength infrared (MWIR), long-wavelength infrared (LWIR), and far infrared (FIR). NIR and SWIR are defined as "reflected infrared" and indirectly indicate plant health based on the IR light reflections caused by the plant's water content. In a natural environment, NIR reflections can indicated physiologically stressed vegetation (Knipling, 1970). Though stressors may include diseases or non-conducive soils, stress can also be caused by materials buried in the sediments. This has archaeological applications as it might suggest the presence and nature of archaeological features that might skew a plant's typical NIR signature (Verhoeven, 2008). SWIR is more typically used for distinguishing water content in the ground; however, this wavelength has geological implications as rocks and soils are often highly contrasted in SWIR imagery (Lloyd, 2013; Cavalli et al. 2007).

MWIR and LWIR are often defined as thermal infrared as these wavelengths detect thermal radiation emitted from matter (Lloyd, 2013). In an archaeological framework, thermal imaging can detect archaeological features that may otherwise be invisible. Differing chemical compositions, density, and moisture content of various buried materials result in unique thermal signatures that can be detected using thermal cameras (Casana et al*.,* 2014; Berlin et al*.,* 1977).

FIR is predominantly used in astronomy, and has no defined utility in field archaeology. However, the Fourier-transform infrared spectromicroscopy method is used in some lab-based archaeological synchrotron microscopy applications (Bertrand et al*.,* 2011).

Other remote sensing methods describe ultraviolet, hyperspectral, and panchromatic imagery. Ultraviolet light is composed of wavelengths shorter than visible light. Many multispectral scanners (MSS) detect ultraviolet, visible light, and near-infrared spectrums, although ultraviolet has not been widely adopted in archaeological research (Verhoeven & Schmitt, 2010).

Hyperspectral imagery does not specifically refer to any EM wavelength interval, like the defined NIR or SWIR intervals. Instead, hyperspectral imagery is made of small sampling intervals in narrow nm sizes through multiple bands. Non-specialized or true colour sensors common in most consumer-grade cameras typically have sampling intervals of approximately 100 nm producing 3 to 4 bands[1]: blue, red, green, and NIR. Hyperspectral sensors have the ability to sample at intervals of 5-10 nm, producing hundreds of bands. The bands can include portions of both visible light and NIR spectra, but sensors can also be designed to work throughout the remaining infrared spectrum (Cavalli et al*.,* 2007). Further, hyperspectral imaging

[1] Bands are defined by the range of wavelength frequency along the EM spectrum that can be separated by a sensor (Lloyd, 2013).

can detect differing vegetation and mineral chemical compositions that would otherwise be undetected by the wide bands of other sensors (Beck, 2010; PrecisionHawk, n.d.). The hyperspectral sensors are typically satellite-based and have been utilized by archaeologists in site prospection, particularly in search of architectural features (Parcak, 2009; Doneus et al., 2014; more details will be provided in Section 2.4).

Panchromatic, like hyperspectral, is not a defined range within the EM spectrum. Instead, panchromatic (pan) is a wide-range band within the visible light spectrum. The wide range includes blue, green, and red light, and is presented in a single band. This, in effect, creates a black and white image. These images are analytically valuable because, instead of separating visible colours, pan sensors can collect more light *en masse* and can therefore produce higher resolution imagery (Lloyd, 2013; Beck, 2010).

Certain wavelengths within the EM spectrum have also been utilized for the development of LiDAR (light detection and ranging). Instead of using camera sensors to passively collect light, LiDAR uses laser pulses at defined EM frequencies to create a 3D image. The reflections of the pulsed lasers (i.e. returns) are ranged and collected by a sensor. Coupled with GPS and/or Inertial Measurement Units (IMU), each return then becomes attributed to X, Y, and Z axes in a cartesian space. The lasers are typically attenuated between 600-1000 nm wavelengths within the visible and NIR spectrums. LiDAR provides multiple benefits: 1) it produces high-precision, highly detailed data; 2) it can be used to document large areas of interest (AOI); and 3) the fine laser can be tuned to penetrate through vegetation to reveal the ground's surface below the canopy (Crutchley, 2010). LiDAR has been affixed to satellites, piloted aircraft, terrestrial scanners, and is being expanded for UAV platforms (Chase et al., 2010; Bendea et al. 2007; Remondino et al. 2011).

2.3 Aerial Perspectives

Aerial views were conceptualized long before the invention of the camera or airplane. God’s-eye views have been a predominant theme in Judeo-Christian traditions (Amad, 2012). During the Renaissance, Secular aerial conceptions became more commonplace- with thinkers like Leonardo da Vinci who studied birds’ flights to design flying contraptions (Amad, 2012) or Wenceslaus Hollar who produced numerous ‘bird’s-eye views’ of London, providing alternative perspectives of the City (Barber, 2011, p. 10) (Figure 2-2).

Figure 2-2 Bird's-eye plan of the west central district of London, an early aerial view *(Hollar, ca. 1660)*

Bird’s-eye views remained popular in Europe but were ultimately ideational concepts. None of the artists created these pictorial records based on perspectives that they could physically achieve. This began to change shortly after the first piloted balloon ascents in 1783 when Thomas Baldwin published the *Airopaidia* after his 1785 flight (Barber, 2011, p. 11). In the publication, Baldwin includes illustrations made during his time in the air, providing some of the first aerial perspectives based on sight instead of conceptualization (Figure 2-3).

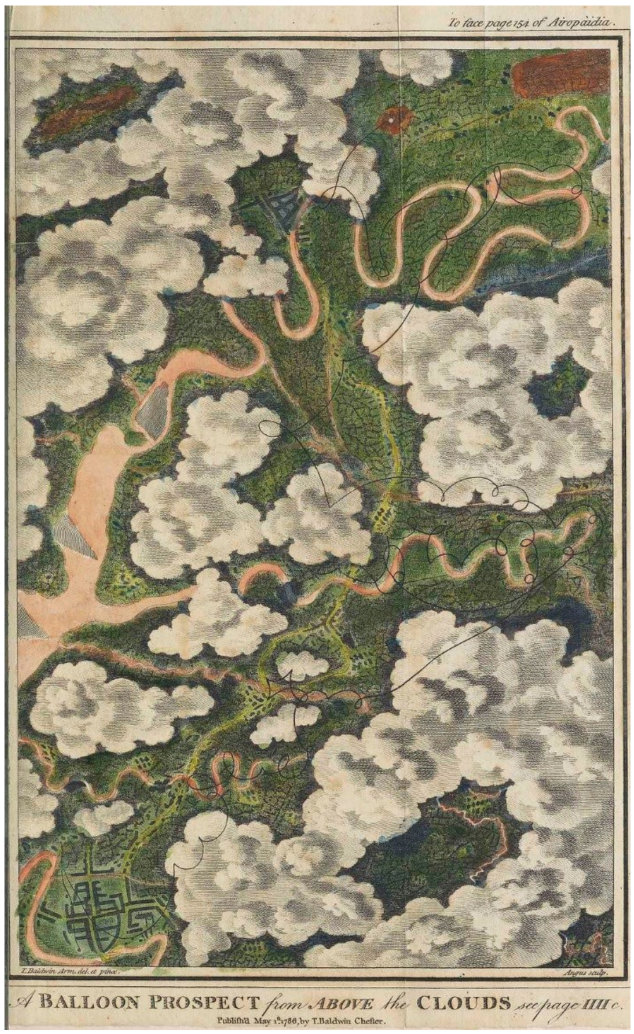

Figure 2-3 One of Thomas Baldwin's illustrations during a balloon flight (Baldwin, 1786)

Landscapes derived from early balloon flights remained interpretative, being drawn or painted by the balloonist. Objective representations of aerial perspectives did not occur until the Daguerreotype camera created the first lasting image in 1837 (The Center for Photogrammetric Training, 1977). Balloonists were able to use these early cameras to capture objective imagery, with the first photograph taken from a balloon attributed to Gaspard-Félix Tournachon in 1858 (Verhoeven et al. 2013; Amad, 2012; Barber, 2011, p. 66). Perhaps the earliest example of this method in North America occurred during the American Civil War (1861-1865). Union and Confederate soldiers employed Daguerreotype camera-equipped balloons for land survey and to observe the movements of the opposing force (Deuel, 1973, p. 32-33; Beaumont 1863). However, such attempts at aerial photography often failed since Daguerreotype cameras required stationary platforms and long exposure in order to create an image. Balloons often proved too unstable to fulfill these requirements.

Nitrocellulose film, first introduced in 1889, did not have the same stability constraints as the silver-coated copper plates used in Daguerreotype cameras (Fennichell, 1996). It was quickly utilized by balloonists as the preferred photographic material. Compared to the Daguerreotype, film cameras did not require large camera components, thereby enabling alternative methods for sending the cameras into the air. Kite photography also gained popularity at the end of the nineteenth century. Another unorthodox method developed during this time involved affixing cameras to carrier pigeons (Saner, 2013).

These early experiments with aerial photography did not involve archaeological research since photographic equipment suitable for archaeology was not yet available. Fox Talbot and other antiquarians began taking photographs of manuscripts, engravings, and busts in the 1850s (Dorrell, 1989, p. 1). However, early photographic processes required that the photo plates be coated in developing solution immediately, proving difficult for field photography (Dorrell, 1989, p. 1) (Figure 2-4). While Middle Eastern archaeologists overcame these difficulties (Dorrell, 1989, pp. 2-6), it was not until the 1870s that American archaeologists adopted the practice as more reliable processes became available. W.H. Jackson began taking photographs to record the Mesa Verde site in the late-1870s, and F.W. Putnam began photographing excavations in 1890 (Dorrell, 1989, pp. 6-7).

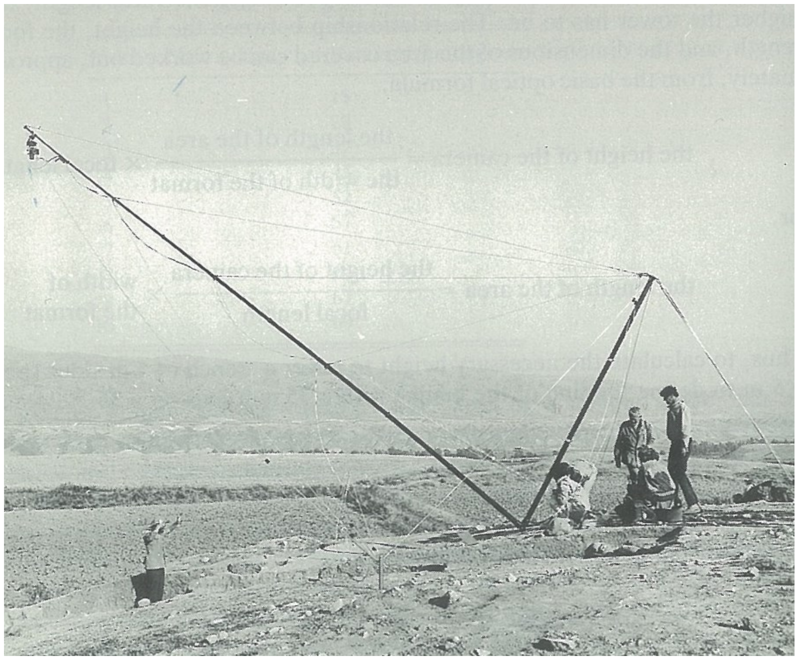

Figure 2-4 An intricate camera rig to capture vertical photographs (Dorrell, 1989)

The integration of land-based photography into the field of archaeology progressed slowly, but aerial photography was rarely utilized. In Britain, photographs of Stonehenge were taken by balloon as early as 1906 (Wilson, 1982, p. 10; Barber, 2011, p. 16), and early archaeological aerial photographs of the Roman Forum were captured as early as 1889 (Boemi, 2011), but the medium was not effectively employed until after WWI.

Members of the Royal Engineers conducted balloon-based aerial photography during the First Boer War over 30 years prior to WWI. Shortly before WWI, the newly commissioned Royal Flying Corps (RFC) began using airplanes for aerial photography. Frederick Laws, air mechanic first class, was an experienced photographer who had been experimenting with oblique and nadir[2] aerial photography for military use while in the Coldstream Guards in 1912 (Barber, 2011, p. 85). Although Laws recalled aerial photography was often an afterthought in the RFC (Laws, 1959, p. 25), he continued experimenting with cameras affixed to planes, including the Watson Air Camera that was designed to take overlapping images (Gamble, 1927). The Watson Air Camera did not provide products that conformed to survey specifications, but eventually illustrated the value of photographs in stereo sequence to derive topographic representations of battlefields.

Although experiments with aerial photography were conducted before the outbreak of WWI, the RFC did not truly begin to see the value in this photographic perspective until 1915. In January of that year, the French Air Force had produced a map of German trenches along the Western Front. This piqued the RFC's interest and they soon dispatched an officer to study the French camera configurations (Barber, 2011, p. 86). By that summer, the RFC had obtained a semi-automatic plate-changing camera system that was affixed to a plane's fuselage. A slot was made in the plane's wing to enable a near-vertical camera placement. (Barber, 2011, pp. 86-87). Aerial photography grew exponentially from this time, with 2nd Lieutenant JTC Moore-Brabazon recalling "though it took us nearly six months to get the first 100 aerial photographs taken, it is not an uncommon thing now in the summer days during the war for the Flying Corps to take over 4,000 photographs in one day" (Moore-Brabazon, 1918). British aerial photographers grew from a team of three to over three thousand, and by the end of the war over 5.6 million photographic plates had been printed (Barber, 2011, p. 105).

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[2] In aerial photography, nadir is the near vertical focus from the center of the photograph, otherwise pointing down in a directly vertical fashion.

OGS Crawford was part of the growing aerial photographer team. An archaeologist before WWI, Crawford became an RFC observer in 1917 (Barber, 2011, pp. 89-90). His archaeological knowledge assisted the British during the war, but the knowledge gained during his enlistment was more valuable to the archaeological field. Once the war ended, Crawford became the first Archaeology Officer for the Ordnance Survey (Wilson, 1982 p. 10; Barber, 2011, p. 111). His aerial photography knowledge was applied immediately. Throughout the 1920s, Crawford published his research demonstrating the value and potential of aerial archaeology (Crawford, 1924, 1929, 1933; Crawford and Keiller, 1928). Crawford and other aerial photographers/archaeologists saw the significance of aerial views in detecting archaeological features indicated by crop marks or soil discolourations. Lt. Col. G.A. Beazeley was interested in this new perspective around the same time as Crawford. In Iraq, Beazeley began searching for sites attributed to ancient Mesopotamia. He recounted the value in aerial perspectives (1919):

> had I not been in possession of these air photographs the city would probably have been merely shown by meaningless low mounds scattered here and there, for much of the detail was not recognizable on the ground but was well shown up in the photographs, as the slight difference in the colour of the soil came out with marked effect on the sensitive film, and the larger properties of the nobles and rich merchants could be plainly made out along the banks of the Tigris.

It was around this time that aerial archaeology became a more feasible method. Although governments were uneasy with their countries being photographed in a post-war period, and legislation was tabled to limit civilians from taking photographs of civic centres, aerial photography continued its advancement (Barber, 2011, pp. 145-146).

The outbreak of World War II accelerated the pace of aerial photography development. During the war, the RAF and *Luftwaffe* developed new planes and camera systems to effectively document landscape and enemy positions (Barber, 2011, pp. 197-199). Although many of the same principles were used, the technology and air-photo interpretations continued to be refined.

After the war, aerial photography continued to develop with more sophisticated cameras and planes. In Britain, this allowed aerial archaeology to be employed to locate and document notable Roman and Medieval sites. Aerial archaeology was augmented by the growth in private and commercial flying as a result of aerial efforts during the war (Riley, 1987, p. 15).

Interestingly, aerial archaeology was slow to develop in North America. Notable exceptions include: Cahokia, which was photographed frequently between 1922 and 1977 (Fowler, 1977); Chaco Canyon which was flown in 1963 (Riley, 1987, p. 16); and Poverty Point that was photographed in 1934 (Deuel, 1971, p. 253-254; Kidder, 2002). It is also important to note that the first application of Infrared (IR) photography was conducted in North Carolina in 1954 (Buettner-Januch, 1954; Parcak, 2009, p. 18). Overall, North America did not adopt aerial archaeology as readily as European countries. This was not necessarily because of lack of interest, or that value was not placed on aerial perspectives, rather much of the public funding required for aerial image capture was diverted to the US Space Program following the USSR's Sputnik launch in 1957 (Parcak, 2009, p.18).

In combination with limited funding, the apparent lack of aerial photography utilization in North America is also likely attributable to the types of archaeological sites found on the continent. Many subjects of aerial survey documented in non-American contexts consist of crop marks highlighting buried structures in open fields, monumental architecture, or ruins (Moore, 2009; St. Joseph, 1945; Palmer 1947; Leisz, 2013). Similar archaeological features in North America are comparatively less common, and often archaeological surveys are completed in densely vegetated areas that would not be visible from the air.

Aerial perspectives in North America were instead achieved by more analog, inexpensive means. Ladders and camera cranes were often used when the need for an aerial perspective arose (Figure 2-4 and Figure 2-5). Figure 2-5 shows efforts taken to achieve aerial perspectives using a precarious system of ladders and guy lines. This photo was taken during the Missouri River Basin salvage project (Wedel, 1949). This project sought to find, document, and salvage as many archaeological sites as possible that were about to be impacted by a series of proposed dams along the Missouri River and its tributaries. The project began in 1946 and continued, under various guises, until 1975 (Thiessen, 1999). The project was well-funded, with approximately 2.5 million USD in expenditures by 1967 (Wedel, 1967). Accounting for inflation since 1967, the project would cost approximately 18.8 million USD today. This funding enabled modest aerial photography to be employed (Thiessen, 1999), but ladders were still required to generate aerial views of archaeological sites of sufficient spatial resolution.

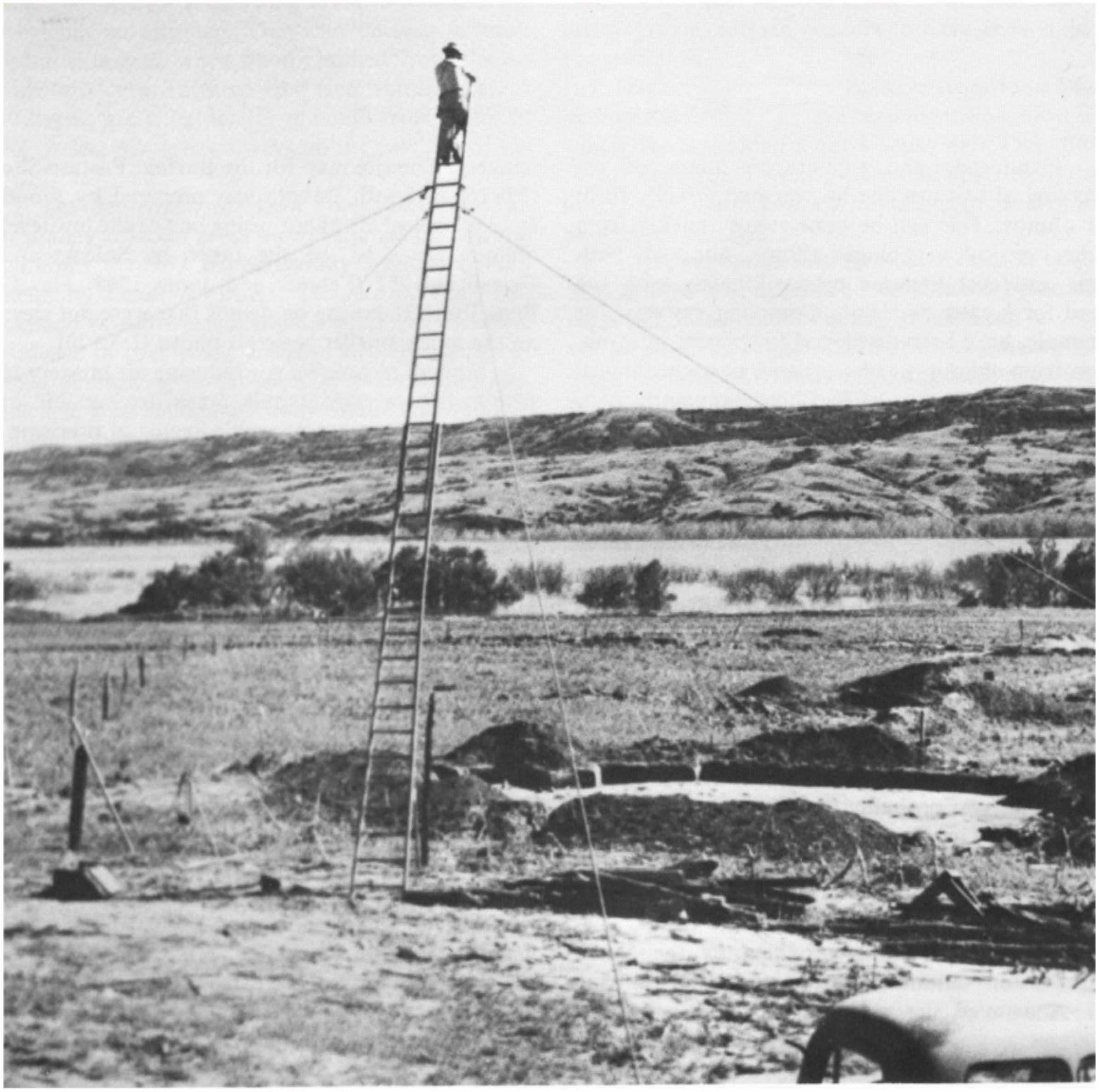


Figure 2-5 Vertical photo taken precariously on a ladder during the Missouri River Basin salvage project (Huscher, 1954; from National Anthropological Archives, Smithsonian Institution)

A notably funded Canadian project, L'Anse Amour Mound, was completed by Drs. McGhee and Tuck in southern Labrador. The project was undertaken by the National Museum of Man (now the Canadian Museum of History) between 1973 and 1974 (McGhee and Tuck, 1975). Ladders were used to capture elevated views of important archaeological features instead of employing aerial photography (Figure 2-6).

Figure 2-6 Vertical photography using a ladder during southern Labrador survey (Renouf collection, Memorial University; retrieved from nlarchaeology, 2014)

Interestingly, a rare example of aerial photography stems from the Boreal Forest in northwestern Ontario where the trees are densely packed and do not allow views of the forest floor. The Kaministikwia Intaglio Dog Effigy Mound (Dog Lake Effigy) was obliquely photographed by the Department of Lands and Forests (now Ministry of Natural Resources and Forestry) during its archaeological study completed by Ken Dawson in 1962 (Dawson, 1965). To enable visibility, surrounding trees first had to be removed. Dawson and team then outlined the effigy in flour in advance of the flight to ensure visibility from the air through the forest canopy (Figure 2-7). Further discussion of this project is presented in Section 4.3.

Figure 2-7 1960s aerial photograph of the Dog Lake Effigy. Perhaps one of the only early aerial photographs of an archaeological site in the northwestern Ontario Boreal Forest (Dawson, 1965)

2.4 Satellite Imagery

The space age began in 1957 with the USSR's Sputnik launch. As previously discussed, the US dedicated funds to compete with the USSR in developing satellites and rockets. These developments triggered the rapid development of satellite imagery. By 1959, the US military launched the first satellite under the CORONA satellite program. However, imagery collected from the CORONA program was unavailable for public use until the project was declassified in 1995 (Leisz, 2013). The imagery's best spatial resolution ranged from 1.8 m at its finest to 140 m at its coarsest. The imagery was used by archaeologists immediately after declassification.

Before CORONA's declassification, archaeologists used the US Landsat satellite first launched in 1972, and the French SPOT launched in 1984 (Leisz, 2013). Landsat 1-3 was operational from 1972 to 1982. The satellites collected green, red, and NIR data at a 79 m spatial resolution. These satellites were followed by the thematic mapper series (Landsat 4, 5 and 7) which collected information in true colour (blue, green, and red), NIR, MWIR, and LWIR with a general 28.5 m spatial resolution. In contrast, SPOT's spatial resolution is 10 m panchromatic, and 20 m multispectral (Leisz, 2013). With these early satellites' coarse spatial resolutions, archaeologists were not able to remotely detect archaeological sites with certainty. Instead, archaeologists detected EM anomalies in the satellite imagery that may be indicative of possible sites. Once an anomaly was found, it would then be compared to EM signatures of known sites nearby in an attempt to discern their spatial relationship. These possible sites were largely inferred and would require later excavation to confirm their presence.

Despite the futuristic appeal of satellite imagery and its early utilization in approximately six archaeological investigations in the USA (Scalera, 1970), few archaeologists immediately adopted remote sensing techniques. In the first published overview of satellite use in archaeology, Limp (1989) notes a nine-year gap in archaeological publications discussing satellite imagery's utility. However, as spatial resolutions improved, and efforts by Sever and Wiseman (1985) highlighted the value of satellite imagery, satellite-based archaeological research and publication became more prevalent (Mahanta, 1999).

Beginning in the 1990s, archaeological application of satellite imagery became widely known, including the supposed discovery of Ubar in the Rub al'Khali desert (Fiennes, 1991; Blom, 1992), and the mapping of prehistoric Arizonian canal systems (Showater, 1993). Satellite imagery became more enticing with the launch of SPOT 4 (5 m spatial resolution) in 1998, Landsat 7 in 1999, and IKONOS (1 m spatial resolution) in 1999 (Parcak, 2009). By 2009, at least four satellites were producing current imagery with a 1 m spatial resolution or better: SPOT's spatial resolution was improved to 0.8 m; SRTM produced topographical data at 0.3 m; Quickbird had a 0.6 m resolution (decommissioned 2015); and IKONOS had a resolution of 1 m (decommissioned 2015) (Parcak, 2009). While SPOT, SRTM, and IKONOS have multispectral payloads at high resolution, these datasets are expensive to obtain, with SPOT imagery costing upwards of 11,750 USD for a high-resolution, 60 km swath (Airbus, n.d.; Parcak, 2009). These high costs for a spatial resolution—which is less than what can be achieved through aerial photography—severely limited the application to archaeological research, despite its value for site prospection.

2.5 Unmanned Aerial Vehicles

Recreational use of remote-controlled (RC) aircraft has occurred since the 1930s (Gutiérrez & Searcy, 2016). As telemetric controls, camera quality, and redundant systems advanced, RC aircraft became more valuable to the 'pro-sumer'[3]. Over the past decade technically sophisticated UAVs, predominantly engineered and marketed for the general population, have become widely available and eagerly embraced by consumers, filmmakers, and researchers.

Archaeological UAV experiments began in the early 2000s with early adopters such as Eisenbeiss (2004), Eisenbeiss et al. (2005, 2006) and Eisenbeiss & Zhang (2006) using an RC helicopter in Peru, and Quilter & Anderson (2000) using a fixed-wing UAV in Utah. However, these UAVs were prototypes and were limited by heavy mid-flight vibrations, rudimentary navigation equipment, and frequent maintenance requirements to keep their combustion engines operational (Gutiérrez & Searcy, 2016). Commercial electric-motor UAVs were marketed beginning in 2008, but with high initial costs (10,000 to 40,000 USD) (Gutiérrez & Searcy, 2016). These UAVs were not widely adopted (see Oczipka et al., 2009) as they were too

[3] Pro-sumer has multiple meanings. In this thesis, it is meant as a portmanteau of "professional consumers".

expensive for most archaeological budgets. However, the hobbyist market responded quickly to this technology and developed low-cost kits with computer systems and telemetric controls. These kits were available for a fraction of the cost at 1000 USD but required the UAV to be assembled by the consumer (Quilter & Anderson, 2000; Gutiérrez & Searcy, 2016).

A dramatic increase in international publications of archaeological case studies using UAVs appeared after the introduction of these more robust hobbyist kits and the first ready-to-fly UAVs marketed for the general population. The most prominent of the latter include models produced by DJI, 3DR, and Yuneec. Archaeological investigators in Europe and the Near East are primarily responsible for the increase in these publications (see The Digital Archaeological Record, 2015; Greenwood, 2015; Remondino et al., 2011; Mouget & Lucet, 2014; Prentiss, 2016). The rapid growth in UAV popularity has fuelled competition among producers of UAVs to remain innovative and relevant. UAVs are now being produced with redundant telemetric and safety systems, higher resolution camera payloads, and increased flight-time capabilities. As UAVs are ultimately an aerial platform, multispectral, hyperspectral, and LiDAR sensors are also becoming common elements in UAV development and commercial availability. Although there is variance in hardware, software, and data, the methodology employed is generally consistent in these archaeological investigations.

Fernández-Hernandez et al. (2015) summarizes the general approach that has been predominantly employed in recent UAV research. This case study used a UAV with a consumer camera to document a Celtic settlement in Spain. They captured 30 images with a forward overlap of 80% to create a 3D surface model and orthoimage of the AOI to great effect.

Smith et al. (2014) have been using UAVs in Saudi Arabia in conjunction with LiDAR laser scanning to digitally document the ruins of Dedan, the ancient capital of the Dedanite kingdom. They found that occluded surfaces were too difficult to document using ground-based LiDAR. To fill in these data gaps, they deployed two UAVs with true-colour cameras to capture nadir and oblique photos at elevations between 30-100 m (Figure 2-8). The UAVs were flown between 2.5-3.0 m/s to capture overlapping photos to produce 3D models of their AOI to successfully integrate with the LiDAR data.

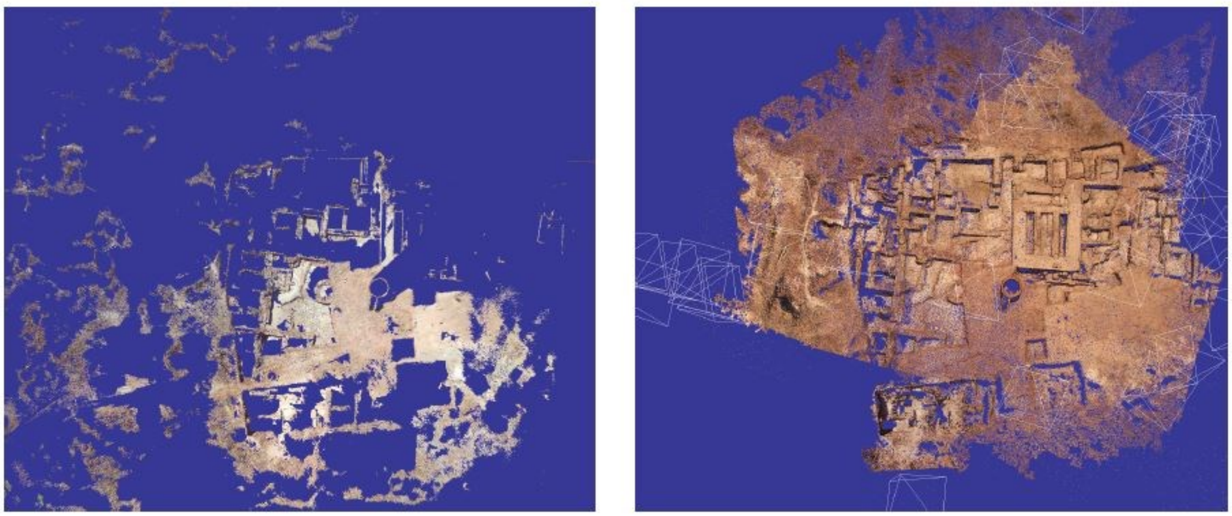


Figure 2-8 Laser scanned imagery (left) with UAV based imagery (right) showing the ruins of Dedan (Smith et al., 2014)

In the USA, Casana et al. (2014) have experimented with UAV-based aerial photography. The drastic temperature changes in the New Mexico desert allowed for the detection of the Chaco-era Blue J community using aerial thermography. The researchers used a LWIR thermal camera attached to an eight-rotor octocopter to record temperature changes across the AOI's surface throughout the day. In recording the temperature fluctuations, the researchers were able to remotely detect subsurface remains including walls, room blocks, and features associated with the Chaco-era community. The UAV was used to capture true colour and LWIR photos at regular intervals with 80% photo overlap at a speed of 5 km/h. The images were processed using Agisoft PhotoScan and Microsoft ICE to create 3D models and orthophoto mosaics.

Publications in Canada have been minimal, but this is not due to a lack of research on the subject. Dr. Amanda Crompton and Marc Bolli of Memorial University, Newfoundland have been exploring UAV utility (CBC News, 2018) although a search in relevant journals did not indicate any of their findings have been published. James Williamson, a PhD candidate at Memorial University has also been exploring UAV utility in mapping Beothuk House-pits in the Exploits River Valley (Memorial University, n.d.). From Nunatsiavut, Michelle Davies has presented a paper at the 47th Annual Canadian Archaeological Association in St. Johns, Newfoundland (CAA, 2016).

Dr. Peter Dawson of University of Calgary has been exploring UAV-based laser-scanning as a side-product of laser-scanned 3D modelling (Bell, 2017). Again, Dr. Dawson's research specifically regarding UAV applications has not yet been published. Katherine Nichols partly explored UAV utility in her graduate thesis for the University of Manitoba (2015). Amundson *et al.* (2017) have been exploring UAVs in the Northern Plains.

Of the published works, Stephen Berquist, Giles Spence-Morrow, Branden Rizzuto of University of Toronto, Felipe Gonzalez-Macqueen of Western University, and Willy Yépez Álzarez of the Royal Ontario Museum have published an article describing their efforts recording inaccessible rock art using UAVs in Peru (Berquist et al., 2018). The only published works discussing UAV applications for directly Canadian archaeological investigations have been by Hamilton & Stephenson (2017a, 2017b), and Hamilton (2017), albeit the former is in the 'grey literature'.

Of course, the lack of publications does not directly correlate to the lack of utilization of UAVs by consulting archaeology companies in Ontario. A review was undertaken of the prominent consulting firms' marketing in both archaeology and cultural heritage (i.e. built heritage in Ontario) to determine if UAVs are utilized during assessments but that the data is simply not being published. In archaeology, only one firm, Paterson Group, explicitly markets UAV use (Paterson Group, n.d.), though Archaeological Services Inc (ASI) markets aerial photography[4] as a value-added deliverable (ASI, n.d.). In cultural heritage, Letourneau Heritage Consulting Inc. (LHC) is the sole business that boasts UAV utilization (LHC, n.d.). This begs the question of why UAVs have not been widely adopted in Ontario consulting archaeology. Do consultant archaeologists see little value in their use, or are there other factors inhibiting UAV adoption?

2.6 Initial Attempts

Under Dr. Hamilton[5]'s supervision, early investigation of the utility of UAVs in archaeological contexts began in 2014. The research was multifaceted: the first objective was to explore consumer grade UAVs' efficacy in archaeological research, and the second component was to explore the uses of 3D modelling software. A Blade 350QX consumer-grade quadcopter UAV was purchased as the primary aerial platform for the experiments. The UAV had a 16 megapixel (MP) camera integrated with a 3-axis gimbal that could be controlled remotely. The camera captured comparatively high-resolution images. However, the camera featured a 150° 'fisheye' field-of-view that severely distorted the images it produced (Figure 2-9). Although it can be corrected in post-processing software, the fisheye distortion introduced a confounding variable that significantly increased the margin of error in final image production, particularly

[4] A distinction is not made whether aerial photography is UAV, airplane, or satellite-based.

[5] Professor, Anthropology, Lakehead University

when this aimed at producing planimetrically correct and scaled site plans of archaeological sites.

Figure 2-9 Photo taken from the Blade 350QX showing severe fisheye distortion

Another critical limitation with this UAV was its lack of telemetric information. Although the UAV remained stable in high winds and the internal GPS was as precise as modern handheld GPS units, variables such as airspeed, elevation, and battery-life were not displayed in the UAV's proprietary mobile software. The latter ultimately led to the UAV's demise when the battery died mid-flight (Figure 2-10). The lack of telemetric information was not conducive to creating measurable datasets of acceptable accuracy.

Figure 2-10 The Blade 350QX after losing battery power and crashing

The Blade 350QX, despite its severe limitations, offered sufficient proof of concept to Hamilton and Stephenson of the potential for UAV use in archaeological applications in Canada. This also resulted in some informal publications of early results (Hamilton et al., 2015; Hamilton & Stephenson, 2016). In addition to the evaluation of the Blade 350QX during this research, a DJI Phantom 3 and Skywalker fixed-wing UAV were also considered for future applications, and informed Hamilton and Stephenson of the technology necessary for future research at the outset of this graduate thesis. These UAVs will be discussed further in Section 3.3.1.

2.7 Summary

Concepts of bird's-eye views were documented before the invention of the camera and airplane. Aerial photography began with early camera-types in balloons, before airplanes became more prevalent. WWI advanced aerial photography technology with innovations in cameras and their platforms (planes) as well as early experiments with stereoscopic images. During the interwar period, archaeologists who had become familiar with the aerial photography process applied the technique to their archaeological research. At the outbreak of WWII, airplane-based archaeological research slowed, but the war effort continued refining the aerial photography process. However, aerial photography was not widely adopted in North America after the war. Instead, a focus in satellite imagery began in the 1950s. Satellites drove data capture using many ranges within the EM spectrum, including hyperspectral imagery. Unfortunately, high-resolution satellite imagery has been cost-prohibitive for widespread adoption in archaeology.

Archaeologists have now begun using UAVs to collect high-resolution imagery globally. An apparent gap exists in Canada, especially in Ontario, but early experiments have begun to demonstrate UAVs applications in Canadian archaeology as a potential tool to overcome the preceding technology's shortcomings.

3 MATERIALS AND METHODS

3.1 INTRODUCTION

This chapter first discusses the legislation governing UAV flight in Canada and its ramifications for archaeology, and details the hardware and software used for the case studies described in Chapter 4. It reviews methods for data capture and processing, with commentary on operational potential for Ontario consulting archaeologists. A UAV's primary use is to capture still photographs of an AOI, but methods to derive other valuable data will be discussed. The costs associated with the materials and methods will be presented throughout this chapter, and reviewed in the summary to illustrate the initial start-up costs to begin UAV operations in Ontario archaeology.

3.2 LEGISLATION IN CANADA[6]

In Canada, all flight operations are regulated by the *Canadian Aviation Regulations* (*CARs*) (SOR/96-433) pursuant to the *Aeronautics Act* (R.S., 1985, c. A-2) and administered by the Minister of Transport, Minister of National Defence, and the Minister of Public Safety and Emergency Preparedness. UAVs, as devices intended for flight, are regulated by the *CARs*. Transport Canada is the regulatory agency for UAV operations and has published *Knowledge requirements for UAV (drone) pilots (TP 15263)* and *General Safety Practices – Model Aircraft and Unmanned Air Vehicle Systems (Advisory Circular 600-002)* to inform prospective UAV pilots.

[6] This section is used for illustrative purposes and is not intended as legal advice. The author claims no responsibility or liability of any use or misuse of information presented herein.

Currently, to legally operate UAVs for work or research, pilots will typically require a Special Flight Operations Certificate (SFOC). This SFOC outlines the responsibilities of the pilot and any other party associated with the flight. It is used as a means for Transport Canada to track safe flight practices and to keep a record of each UAV flight. Once responsible flying has been demonstrated, the pilot can apply for a standing SFOC. This SFOC is completed on an annual basis instead of on a case-by-case basis.

A pilot can be exempt from the SFOC process if they meet all conditions for an exemption as outlined by Transport Canada. There are exemptions for UAVs that weigh 1 kg or less and exemptions for UAVs weighing 1 kg to 25 kg. Typically to be exempt from an SFOC, the pilot must confirm to Transport Canada that flights will only be conducted in Class G airspace at the required distance from all aerodromes and built-up areas. For UAVs weighing above 1 kg to 25 kg, the pilot must also present a record of training to prove the pilot understands:

i. airspace classification structure (Appendix A);
ii. weather and notice to airmen (NOTAM) reporting services;
iii. aeronautical charts and the Canada Flight Supplement; and
iv. relevant *CARs*.

In addition, the pilot needs a minimum of $100,000 of public liability insurance, and in most cases, proof of relevant knowledge as outlined in the CARs. This knowledge can typically be obtained through UAV ground schools.

Navigating the legislation surrounding UAV use is turbulent and occasionally vague. When coupled with the fact that most insurance policies do not cover public liability for UAV use and many populated areas are within airspace outside of Class G (Figure 3-1), this offers one of the greatest deterrents to adapting UAVs for archaeological use. However, as of the production of this paper, Transport Canada is attempting to amend the regulations to more clearly outline the requirements to legally fly UAVs (Transport Canada, 2017). In this clarification, they also aim to create definitions for multiple types of UAV operations dependent on anticipated risk and the size of the UAV.

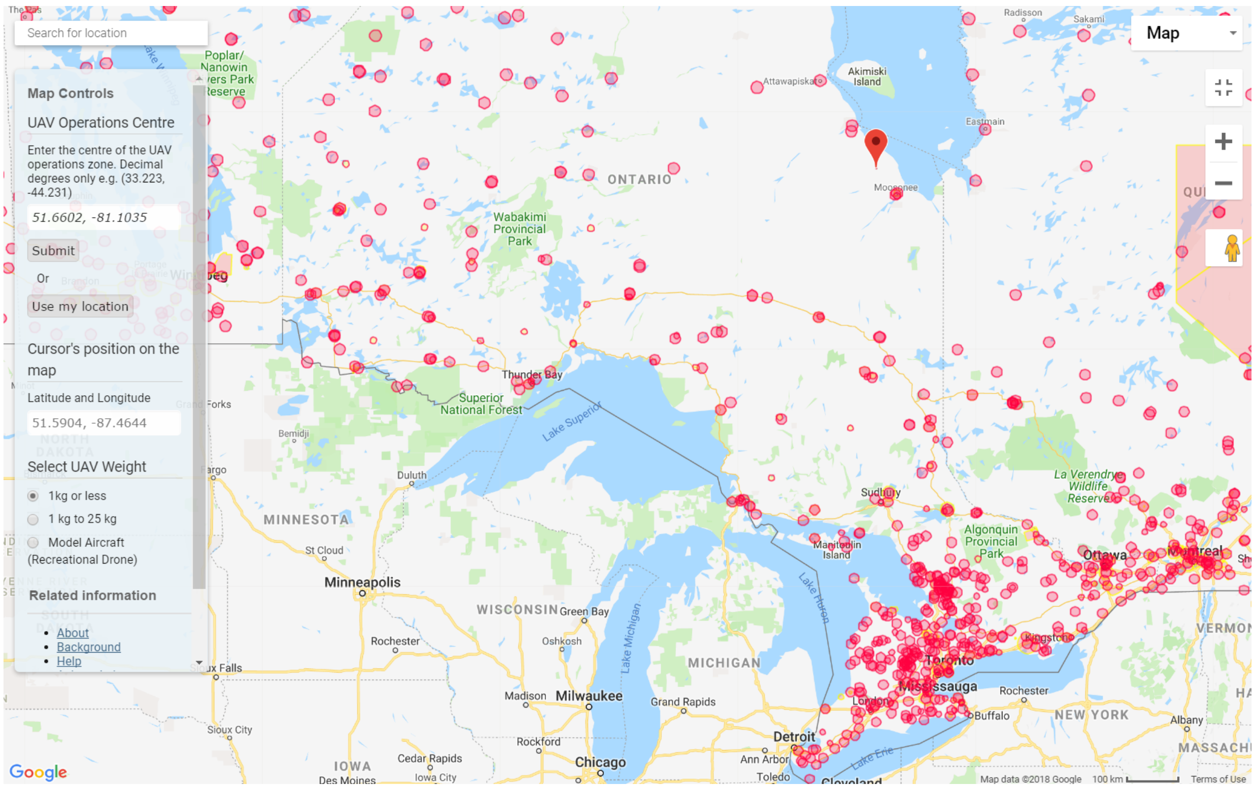


Figure 3-1 UAV 'no-fly zones' in Ontario, showing significant restrictions in southern Ontario (from NRCAN, n.d)

Multiple Canadian underwriters were contacted for quotes for public liability insurance regarding UAV (DJI Phantom 3) use for commercial purposes. Although most underwriters stated they did not have coverage for UAV operations, or simply did not respond, quotes were received for as little as $350 CAD annually. This is arguably a negligible cost for most consulting archaeologists in Ontario who already carry significant liability insurance coverage.

In addition to legislation and insurance, a UAV pilot is required by law to complete UAV ground school training. The course can typically be completed in three days, and costs approximately $300. It provides relevant information required for UAV use as outlined in the *CARs*. Though this may be perceived as a barrier to employing UAV survey, the associated costs are marginal in contrast to a UAV's potential utility in archaeological fieldwork.

3.3 Hardware

3.3.1 Unmanned Aerial Vehicle

During the 2014 investigations with the Blade 350QX by Hamilton and Stephenson, a DJI Phantom 3 and a Skywalker fixed-wing UAV were also considered as replacements to overcome the Blade's shortcomings. The fixed-wing UAV was desirable as it allowed for continuous flight-times around one hour and had the capacity to switch camera payloads to multispectral or NIR sensors. However, the Skywalker UAV, and by extension most fixed-wing UAVs, are ill-suited for most archaeological applications. First, the fixed-wing UAV is not portable when compared to a quadcopter. Second, the user-interface is not as accessible as those designed for the general consumer. Third, fixed-wing UAVs need to be constantly moving to sustain flight and cannot hover. Fourth, fixed wing UAVs require large open spaces for take-off and landing; space that is not always available in varied archaeological assessments across the province.

After the Blade 350QX crashed, Hamilton replaced it with a DJI Phantom 3 Advanced. This UAV was available at most major retailers for approximately the same cost as the Blade 350QX; however, it offered significant advantages over its counterpart. First and foremost, it features a 12MP, 94° FOV rectilinear camera on a 3-axis gimbal that takes photographs with no noticeable distortion. This lack of distortion enables the production of planimetrically correct and scaled site plans of archaeological sites without the margin of error that is introduced with fisheye lenses.

Second, the UAV features a suite of telemetric and safety systems that are displayed in a user-friendly, intuitive mobile app, DJI GO. The battery life is also reported in the app. The UAV provides telemetric data such as airspeed, flight direction, and elevation data through input from an inertial measurement unit (IMU), 6-axis gyroscope, and an accelerometer. Geospatial location information is derived from a GPS/GLONASS unit within the UAV. This unit boasts a ±1.5 m GPS accuracy in perfect conditions. In imperfect (i.e. real-world) conditions, the accuracy has a margin of error similar to that associated with modern hand-held GPS units. To assist the UAV's positional accuracy in both horizontal and vertical planes in GPS deprived environments, there is what DJI calls a "Vision Positioning System" (VPS). It features a downward-facing camera and ultrasonic sensors that are able to detect hard surfaces to maintain its elevation and horizontal position in real-time. The VPS is affixed to the bottom of the UAV and is constantly operational during the UAV's flight.

The Phantom 3 was employed for three of the four case studies within Chapter 4. The P1 (AlGs-486) case study is the notable exception, where a DJI Spark UAV was used instead of the Phantom 3. The Spark is lower in price and smaller in size and weight in comparison to the Phantom 3, but offers similar specifications in most other aspects. Though this UAV is intended as a hobby device for consumers, it still offers serious technical capacity. This is advantageous, as the Spark is affordable for most consultant archaeologists and can be easily implemented in typical field kits. However, a notable drawback is that most flight planning software does not support the Spark, so manual flights are required, making it difficult to replicate flights.

3.3.2 iPad

An iPad mini was purchased for use as a dedicated screen to operate the DJI GO and MapPilot (Section 3.4.1) apps. Using the iPad, flight plans can be created and the UAV's flight can be monitored in real-time during the mission. The tablet also displays telemetric and position information in real time. Although an iPad was used, these apps are available on all Apple iOS devices. MapPilot is not available on Android devices, but other software such as Pix4D can be used to the same effect on these devices. Most consultant archaeologists already utilize iPads for recording other data during field assessments. However, for those consultants who do not have iPads in their field kits, most smartphones will pair with the UAV for a similar effect.

3.3.3 Ground Control Equipment

To measure accuracy of the final products made through data processing, some rudimentary ground control equipment was used in the case studies. The areas of interest were delineated by at least four ground control points (GCPs). GCPs come in various forms, some of which display measurement points for increased precision. In the following case studies, small agility pylons were used as GCPs. The pylons' spatial positions were marked using a Garmin 64st handheld GPS unit and their positions relative to each other were measured using a fiberglass tape measure. In two of the case studies, 1 m scale bars were placed within the AOI to provide an additional means for assessing the accuracy of the final data products (Section 3.5.6).

More refined means to measure accuracy have already been established for photogrammetric processes (see Udin & Ahmad, 2014; Cramer et al., 2017; Yuan et al., 2013; Yanagi & Chikatsu, 2015), but are largely unaffordable for most Ontario consulting archaeologists. As such, all ground sampling equipment used in this research includes materials that most consultant archaeologists already own or are readily available for purchase and which require no further training to operate.

3.4 Software

3.4.1 Map Pilot

When DJI announced the Inspire 1 UAV in 2014, they also made software developer kits (SDK) available. This allowed third party software developers to access DJI's codecs, the codes and algorithms that control their UAVs. This has revolutionized the research and commercial application of UAVs. For example, one such developer (Maps Made Easy) created a mobile application called "Map Pilot" which is available on Apple iOS mobile devices. This application allows the user to easily create a flight plan that the UAV will automatically follow. The application is a crucial element to fast and effective data collection.

To use the application, the operator first selects the UAV's altitude and speed. The user creates the AOI by drawing a border over Google Earth imagery displayed in the application. Once the AOI is defined, the operator decides how much each photo will overlap with the previous, which is essential for the successful production of any structure from motion (SfM) products (Section 3.5.3). From there, the software will draw the flight transects reflecting the user-specified photo overlap percentage. After these parameters have been set and saved to the iPad, and the UAV is set to fly, the application will assume control of the UAV until the flight operation has been completed.

During the flight, MapPilot automatically triggers the camera to take photographs to ensure sufficient overlap. The application allows real-time tracking of the UAV's position according to the transect placements which is overlaid on top of satellite imagery within the app. When the camera has been triggered, a dot will appear showing the UAV's position at the time that photo was captured. A small window showing the UAV's video downlink is featured with very minimal video latency. This allows the user to view what the camera is capturing at that moment. It also displays necessary flight telemetry information such as speed, altitude, battery capacity, and GPS signal strength. Once the operation has been completed, Map Pilot logs the flight information and saves the metadata to be reviewed when appropriate. It also saves the flight path to be revisited with the UAV at any time (see the Boulevard Rock Ring Case Study, Section 4.2).

Automation software such as Map Pilot is an essential component for most UAV mapping operations as the flight parameters (e.g. altitude, photo overlap, flight speed) are clearly defined. This automation removes much of the user-error and potential data ambiguity derived from manual flights, affording a level of objective data that can be repeated during future research.

Various overlap spacing, flight speeds, and altitudes were used over the course of this study to determine the most suitable balance of flight times, flight plan complexity, and workflow accuracy. These variables are noted in each case study found in Section 4.

3.4.2 Maps Made Easy

Maps Made Easy, the developers of the Map Pilot app, provide an online orthophoto and 3D model generation service. The company offers a pay-as-you go service that allows a pilot to upload a maximum of 5000 photographs online to create orthophotos, 3D models, and digital elevation models (DEM). The process is completely online, which circumvents the need for the UAV pilot to purchase expensive computer hardware and photogrammetry software to generate similar products. This, and other online services such as Pix4D, provide an accessible means for consultant archaeologists to generate UAV-based data without the technical skills or hardware requirements normally involved. The service also provides analytic tools such as ground sampling distance (GSD) records and photo coverage maps. Files produced include: 3D model files (.jpeg, .mtl, .obj), geoTIFFs of DEM and colourized DEM, and .jpegs of the orthophoto maps. A .kmz file is also produced which includes a 3D model for use within Google Earth Pro (Section 3.4.3). Recent iterations of the software offer more output files including .txt and .las files for point cloud management.

Maps Made Easy was chosen over Pix4D for this research primarily because of cost. Pix4D is operated under a monthly subscription service that costs 350 USD for unlimited processing (Pix4D, n.d.). Maps Made Easy operates using a pay-as-you go system where the cost is reflected in the quality of dataset required. As an illustration: active consultant archaeologists who frequently employ UAVs in their assessments could process 545 hectares (1350 acres) of orthophotos, 3D models, and DEMs for 55 USD[7], or approximately 0.04 USD/acre (Maps Made Easy, n.d.).

3.4.3 Google Earth Pro

Google Earth Pro is a freely available, user friendly, albeit rudimentary geographic information system (GIS). The software allows the user to draw polygons, polylines, measure distances, and upload images that can be georeferenced over satellite imagery (typically Landsat,

[7] Assuming 60% overlap with a 2 inch/pixel GSD using a standard DJI camera.

NOAA, or Terrametrics). The satellite imagery resolution available in this software is inconsistent, and poor outside of built-up areas, which presents limited archaeological value for Ontario applications (see Section 2.4)

For consultant archaeologists with little capital, Google Earth Pro supports most UAV data products created by Maps Made Easy and allows for modest spatial distribution analysis of sites. It also provides a user-friendly platform to emphasize important site features through its annotation tools. It facilitates the production of cartographic materials using the high-resolution imagery collected in the field by the UAV. With this combination of software, the user can produce high-quality maps when robust GIS, such as ArcGIS, are cost-prohibitive. Little training is required to use this software and it enables a higher level of data recording that is accessible to most consultant archaeologists.

3.4.4 Agisoft PhotoScan

PhotoScan is computer software that uses multi-view stereopsis algorithms (Furukawa & Ponce, 2007) (see Section 3.5.3) to derive three-dimensional data from overlapping two-dimensional photographs. The software is available in two editions. The Standard Edition costs 179 USD and allows the licensee to generate dense point clouds to create high-resolution 3D models. The Professional Edition costs 3499 USD and allows for point cloud classification, DEM creation, georeferenced orthophoto export, ground control point support, and multispectral imagery processing.

For optimal results, Agisoft recommends running the software on desktop computers with 64GB of RAM and a dedicated graphics card. Computers with these specifications have become increasingly common and less expensive. Computers with less specifications are still capable of creating 3D models, but are less stable and processing time is drastically increased. In addition, processing with less-capable computers quickly becomes problematic when datasets are large and feature high percentage of image overlap.

The program has a mild learning-curve, but has a relatively straightforward workflow to create 3D models:

1) import all photos taken with the UAV;

2) command the program to align the photos – select quality of the alignment;

3) generate a sparse point-cloud – select quality of the point-cloud;

4) generate a dense point cloud – select quality; and,

5) build a mesh from the dense point cloud.

For large datasets, this workflow can be completed automatically in batches of photos to minimize the strain on the computer processor. From there, the 3D model can be exported into a series of 3D filetypes to be used in any 3D model post-processing software, such as MeshLab (Section 3.4.5) or ArcScene (Section 3.4.6). With the Professional Edition, all model georeferencing, measurements, and volumetrics can be completed within the PhotoScan software.

Photoscan was not used to create any outputs in this thesis, but was used to develop a working knowledge of SfM principles. Additionally, the program is likely what is used for Maps Made Easy processing.

3.4.5 MeshLab

In its simplest sense, MeshLab is an easy-to-use, free, open-source software to view, measure, and edit 3D models. It is available for Windows, Mac, and Linux platforms with limited Android and iOS apps available. The software has minimal computer hardware requirements, making it an ideal 3D model viewer. This research used the program at an elementary level to assess its utility in a consulting archaeology framework.

The program supports 3D models made from both PhotoScan and Maps Made Easy. During this research, this program was used in two ways. First, it was used at a high-level to assess relative accuracy within the 3D models by measuring the ground sampling equipment (Section 3.5.6.5). Second, the software was used to delete computer "artifacts" in the model, that is, spikes in the 3D model where the SfM software incorrectly interpolated elevation data due to vegetation or highly reflective surfaces.

3.4.6 ArcGIS

ArcGIS is an industry-leading GIS used by consultant archaeology firms with sufficient capital to sustain professional licenses. For this paper, ArcScene and ArcMap were used for manipulating and delineating 3D models. DEMs, delineated 3D models, and orthophotos were analyzed using ArcMap. Although valuable, this software requires specialized training for successful utilization, with professional licenses being quite expensive and inaccessible to low-capital archaeologists. However, similar, inexpensive or free software is also available, such as qGIS, Cartographica (Mac), or Google Earth Pro (as discussed in Section 3.4.3).

3.5 Methods

3.5.1 Preflight

Steps must be taken before a UAV flight to ensure quality data acquisition. Once the AOI is identified, a flight plan is created using the Map Pilot app on an iPad. The flight plan, which includes inputting the UAV's desired altitude, flight speed, transect spacing, and percentage of photo-overlap, is created in an office environment with Wi-Fi connectivity before fieldwork begins (Figure 3-2). The flight plan is then stored on the iPad and does not require internet functionality to operate in the field, giving flexibility to archaeological investigations that are removed from areas with Wi-Fi or cellular coverage. This lack of connectivity characterizes most of northern Ontario. The app will also provide details on how many photos will be taken during the flight, the duration of the planned flight, and how many UAV batteries are required, assuming a set battery life expectancy. In the case of flights discussed in this paper, battery life expectancy was assumed to be 15 minutes, representing 70% of the battery's capacity. Other information presented includes the total flight distance, the area covered by the UAV, and the photo resolution in cm/pixel (cm/px).

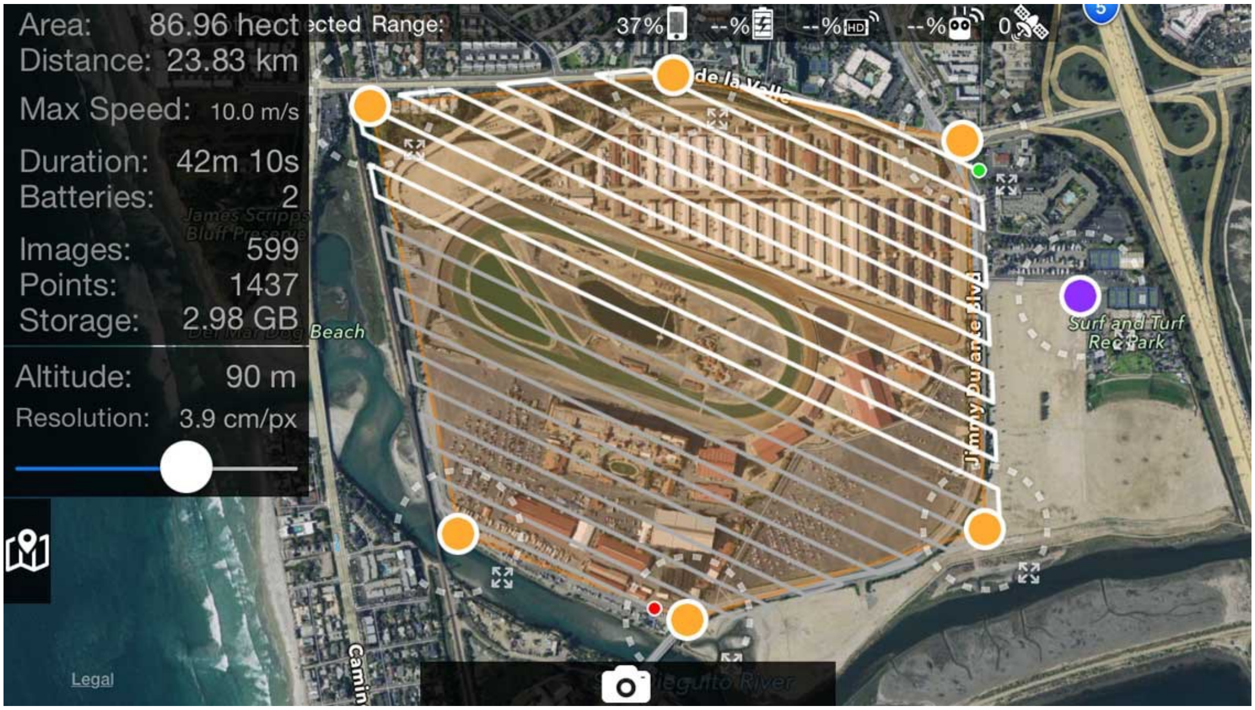


Figure 3-2 Example of Map Pilot user interface (Maps Made Easy, n.d.)

During the flight planning process, the app allows the user to define the cardinal direction of the transects. To minimize dishing and doming distortion errors in the final data products (Section 3.5.6.4), flight plans should anticipate the sun's position relative to the flight path. The app allows the flight transects to be rotated to avoid flying directly toward or away from the sun. Anticipating the sun's position relative to the flight transects is perhaps the most intensive process—before post-processing—as the transects cannot be rotated once outside of Wi-Fi or cellular service. If optimal lighting conditions are anticipated for the flight, the rotation of the flight transects does not need to be considered (Section 3.5.1.1).

Once the flight plan is created, the GCPs are laid out across the AOI. The GCP geospatial positions are then tagged using a handheld GPS unit, and their positions relative to each other are measured using a long fiberglass tape measure. For smaller AOIs (Boulevard Rock Ring, Dog Lake Effigy, and P1), four GCPs were placed around the perimeter of the AOI.

The UAV is then prepared in the following steps:

- Confirm software/firmware is up to date
- Ensure SD card with sufficient capacity is installed in the UAV camera
- Install camera filter (if using; Section 3.5.1.1)
- Check that batteries are sufficiently charged, including the remote control
- Inspect propellers for damage and confirm they are installed in the correct position
- Connect iPad to remote control and launch the DJI app
- Move the remote control's antennae into suitable position
- Turn on all devices and pair accordingly
- Calibrate the UAV compass
- Ensure UAV has connected to a sufficient number of satellites for GPS flight
- Safety-check the entire area for flight obstructions and to ensure bystanders or other non-participants are cleared from the operation
- Set a home-point and a return-to-home flight protocol elevation
- Hover the UAV 1-2 m above the ground for 30 seconds to confirm proper operation
- Land the UAV
- Quit the DJI app and launch the Map Pilot app
- Upload the flight plan to the UAV

Upon completion of the pre-flight protocol, the UAV is ready to begin the flight operation.

3.5.1.1 Camera Settings and Lighting Considerations

Relatively little photographic experience is necessary to successfully capture site data using UAVs. However, some basic settings ensure ease of use and sufficient data capture. Many camera settings on the Phantom 3 can be left in automatic mode with little to no adverse effects. However, while only a general understanding of exposure is required, exposure control is crucial for proper image capture. Generally, if an image is under-exposed, creating a darker image, image data loss is limited and can be rectified in post-processing if necessary. Conversely, if an image is over-exposed, creating bright images with blown-out highlights, much of the image's data is lost and is not recoverable in post-processing (see Boulevard Rock Ring case study, Section 4.2). Given this, it is always better to manually choose a lower exposure for image capture to ensure significant data retention, regardless of file format.

File format is hotly debated amongst photographers. DNG (RAW) format will create a "flat" image that lacks saturation but captures the most light-information available. It is the preference of most professional photographers because the images can be more easily manipulated in post-processing photography software. However, RAW images use more memory, resulting in larger file sizes that impact the process of transforming individual images into final orthophotos or 3D models. JPEGs use less memory but the image information is compressed and little true post-processing manipulation is possible. If the captured JPEG images prove unsatisfactory in UAV operations, another flight operation may be necessary. Conversely, if RAW images are unsatisfactory, the operator may be able to salvage the images and no secondary flight is needed. Both file formats have their advantages and disadvantages. Ultimately it is up to the operator's discretion or preferences. The majority of operations discussed in this thesis captured images in JPEG format.

Camera filters may also be considered to ensure acceptable data acquisition. As discussed throughout this paper, SfM processes are often compromised when dealing with highly reflective surfaces such as water or dried vegetation (Remondino, 2013). The process also cannot effectively discern elevation data in areas that are covered in tall shadows (although shadows are useful in some aerial photography applications in archaeology, see Wilson, 1975; Riley, 1987 p. 17-19). As such, overcast conditions would produce ideal lighting conducive to successful 3D modeling. The overcast clouds limit how much light reaches the ground, limiting the effects from reflective surfaces (except for water). The clouds also create a photography "lightbox" that minimizes shadows. However, it is often not feasible to wait for these optimal lighting conditions in consulting archaeology.

Instead, camera filters can mimic optimal lighting conditions to help reduce lighting-based errors in the 3D data. Although UAVs often have the capability of manually changing the exposure (as discussed at the beginning of this section), these changes are limited by the UAV's fixed camera aperture and can have a limited effect in especially bright lighting. Neutral density (ND) filters block certain amounts of light dependent on the filter's strength. In conditions where manually adjusting the exposure may still result in images that are too bright, an ND filter can be applied to reach the desired brightness.

Polarizing filters (Polarizers) are perhaps the most useful for aerial photography as polarizers reduce reflected light. These filters are crucial when photographing AOIs with highly reflective surfaces that would otherwise distort the datasets. Overall, the filters are inexpensive at around $50 for a set which includes a polarizer and two ND filters.

3.5.2 Flight

Once the preflight protocols are completed, the UAV flight mission can be initiated. The UAV begins its semi-autonomous flight at the desired altitude, flight speed, and transect spacing. Very little pilot input is required while the UAV is flying apart from ensuring the camera is in nadir position (the camera should move to nadir position automatically under normal conditions), maintaining visual-line-of-site (VLOS) with the UAV, and monitoring the UAV for any abnormalities in its flight or in its automatic photo capture. The pilot needs to remain vigilant to be competent to take manual control of the UAV if there are any signs of irregular operation.

During most of the case study flights, the UAV flew at either 40 or 60 m elevations with a 2 m/s flightspeed. The photos were automatically captured with an overlap between 60-90% with each photo in the transect and with a sidelap between 60-90% with the photos taken in adjacent transects (Figure 3-3). This allows adequate data capture to properly orthorectify the photo dataset and allows for 3D modeling using SfM.

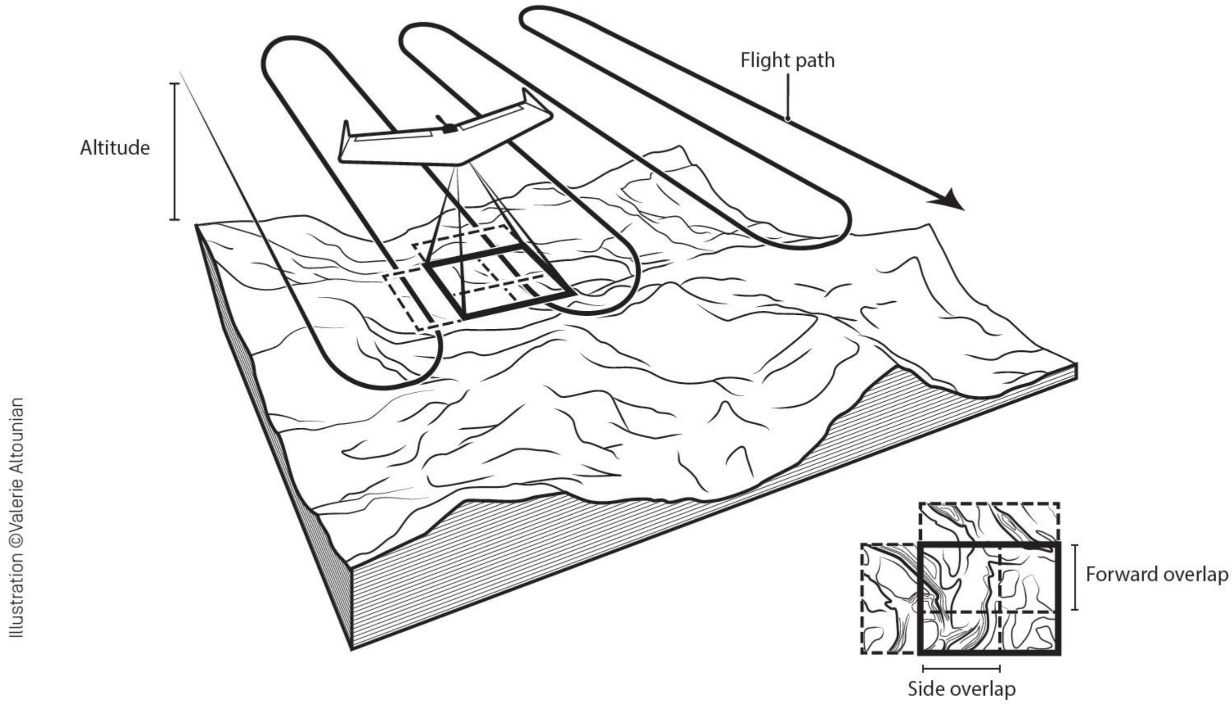


Figure 3-3 Visualization of UAV flight transects (Altounian, 2015)

3.5.3 Structure from Motion (SfM)

Structure from Motion (SfM) is a subset of Multi-View Stereo (MVS) principles to create 3D data (Fergus, 2012). MVS is typically derived from a subject with precise geometry, with measurable (typically solid) surfaces, which are photographed by a camera in a fixed and measured position from multiple prescribed locations or angles. SfM is where both the relative positional parameters and the motion are estimated for both the subject and the camera (Furukawa & Ponce, 2009). The rationale behind MVS and SfM is relatively straightforward. In essence, if a camera photographs the same subject from at least two slightly different perspectives, 3D views of the subject can be extracted from the photographs (Figure 3-4). Anaglyphs, stereoscopy, and human bifocal vision employ this same principle. It is the same principle that Frederick Laws began using for stereoscopic aerial photographs in WWII.

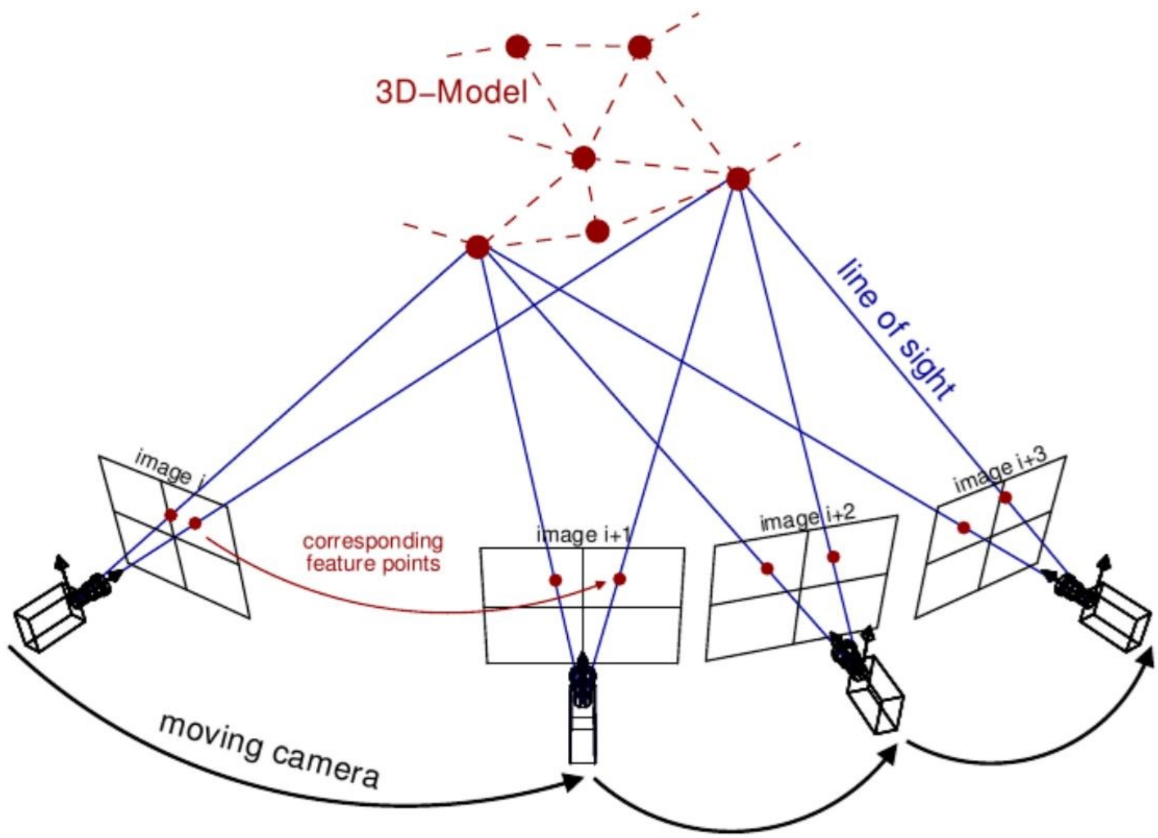


Figure 3-4 Rendition of Structure from Motion principles (van Riel, 2016)

The benefit of UAV-based SfM derives from the capacity of DJI's UAVs to measure and log their geospatial position using GPS, and their elevation using a telemetric sensor suite (stored in digital EXIF tags). This telemetric information is stored in the photograph data to assist the SfM program. Along with this positional data to assist the 3D model's drawing accuracy, most SfM software uses what is called "Bundle Adjustment" when creating the Z-axis. Bundle adjustment is enabled by taking more than two (stereo) photographs which allows the software to adjust points in the 3D model based on a bundle of overlapping photographs to minimize the sum of squared differences between points in the model and the real world (Verhoeven et al. 2013). This automated adjustment also means the subject and camera position points can be reconstructed without prior knowledge of camera positions and interior camera orientation

(Hartley and Zisserman, 2003; Szeliski, 2011), negating the need for calibrated cameras during image acquisition (Verhoeven et al., 2013; Quan, 2010). This also provides flexibility if the camera is not truly nadir. Even though perfect vertical position cannot be achieved, cameras pointed at an angle of $\leq 3°$ are considered nadir (Estes et al., 1983). By alternating the flight direction for every transect, the robust bundle adjustment will correct data taken by a camera positioned past the nadir threshold. This will still produce reasonably accurate orthophotos and 3D data products.

3.5.4 Data Processing

After the flight mission is completed there are two alternative approaches to data processing. The first is to upload the UAV images to the Maps Made Easy website for third party processing. The second is to directly create the products using Photoscan. Photoscan was used in its simplest form to create 3D models (outlined in Section 3.4.4). GCPs were not assigned in Photoscan or Maps Made Easy, but Maps Made Easy automatically assigns the model's geospatial parameters based on the GPS data logged by the UAV (EXIF tags).

3.5.5 Data Analysis and Manipulation

The data produced by Maps Made Easy were imported into MeshLab, Google Earth, and ArcMap for various analyses. MeshLab was primarily used for measurement and manipulation of 3D models. The program offers a simple way of measuring in XY and Z axes for analysis of archaeological features. However, the software is not a GIS and is isolated from information gained from geospatial analysis. Instead, Google Earth Pro and ArcMap were used for these considerations.

Although Google Earth Pro natively supports 3D models (.dae files), its utility is limited in that regard, because the software is more ideally suited for data presented in the XY planes. Therefore, while 3D models can be viewed in the free software, measurements could not be taken. Instead, orthophotos were overlaid in the program to measure XY values in the context of the AOI's surrounding areas. Z-axis measurements still require measurement in MeshLab or a more robust GIS.

ArcGIS is a more robust GIS that includes ArcScene, which is capable of manipulating 3D data, and ArcMap, that can display Z-axis values. This is especially valuable for managing data from the produced DEM. Maps Made Easy produces two elevation products aside from the 3D model: a DEM and a false-colour (computed) DEM. The false-colour DEM is a raster which severely limits the flexibility of manipulation and analysis. In contrast, the DEM is a vector which can be imported into ArcMap for a full range of data manipulation and geoprocessing of the interpolated elevation data.

The raster DEM maintains some utility despite its limitations. The false-colour DEM provides an initial view of the AOI's topography without prior data manipulation. Further, Maps Made Easy offers scaling and data manipulation of the raster DEM on their website, including volumetric measurement. These features are all based within the web-browser and require no additional software, making the scale and volumetric data available and accessible to consultant archaeologists who lack ArcGIS capabilities or have limited DEM experience. Pix4D offers similar features.

In addition to these 3D data products, planimetrically correct orthophotos are produced using SfM. These high-resolution orthophotos can be used in Google Earth Pro or ArcMap for high-resolution map production that can be annotated to capture archaeological sites or features for perseveration in the archaeological record.

3.5.6 Assessing Accuracy

3.5.6.1 Non-metric cameras and the survey-grade debate

Cameras are composed of multiple glass or plastic lens elements that allow light to pass through to reach the sensor. Because of the shape of the lens elements, and differing refractive indices of element materials and the space between them, the light reaching the sensor is ultimately not a true representation of the subject. Generally, these distortions are minuscule enough to go undetected when examining a photograph or video. But when a series of photographs are used to create 3D models using the SfM process, the distortion is amplified, causing inaccuracies in the model. These inaccuracies vary depending on the camera or lens being used, but will propagate throughout the process and will usually cause a dishing or doming effect in the model, in addition to increasing linear accuracy errors and surface noise (Carbonneau & Dietrich, 2017 p. 2). Dishing and doming effects in 3D models (Figure 3-5) are typically attributed to incorrect lens distortion corrections, or incorrect survey patterns (Cabonneau & Dietrich, 2017). Doming effects are illustrated in Figure 3-6. This resulted from a preliminary flight in which the UAV traveled directly to and from the sun's position during its mission[8] without regard for the impacts of direct sunlight and reflections on the final data products. Essentially, flying towards the sun will capture light at such an angle of incidence that will create 'sunspots' in individual photos. These sunspots inhibit the self-calibration in the SfM

[8] In reality the general topography of this example is somewhat domed. However, the doming is more dramatic in the UAV data.

workflow by introducing lens distortions that are not homogenous throughout the dataset. SfM cannot account for these varying distortions in an automated way and will produce a dishing or doming effect. (Carbonneau & Dietrich, 2017; Verma & Bourke, 2018). However, with proper flight planning and camera calibration, the inaccuracies can be identified and corrected for more accurate results.

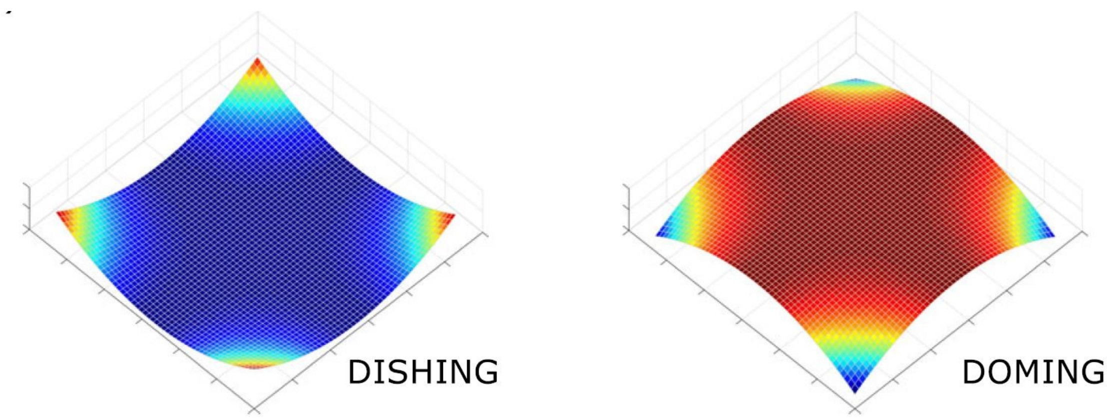


Figure 3-5 Rendition of dishing and doming errors (Carbonneau & Dietrich, 2017)

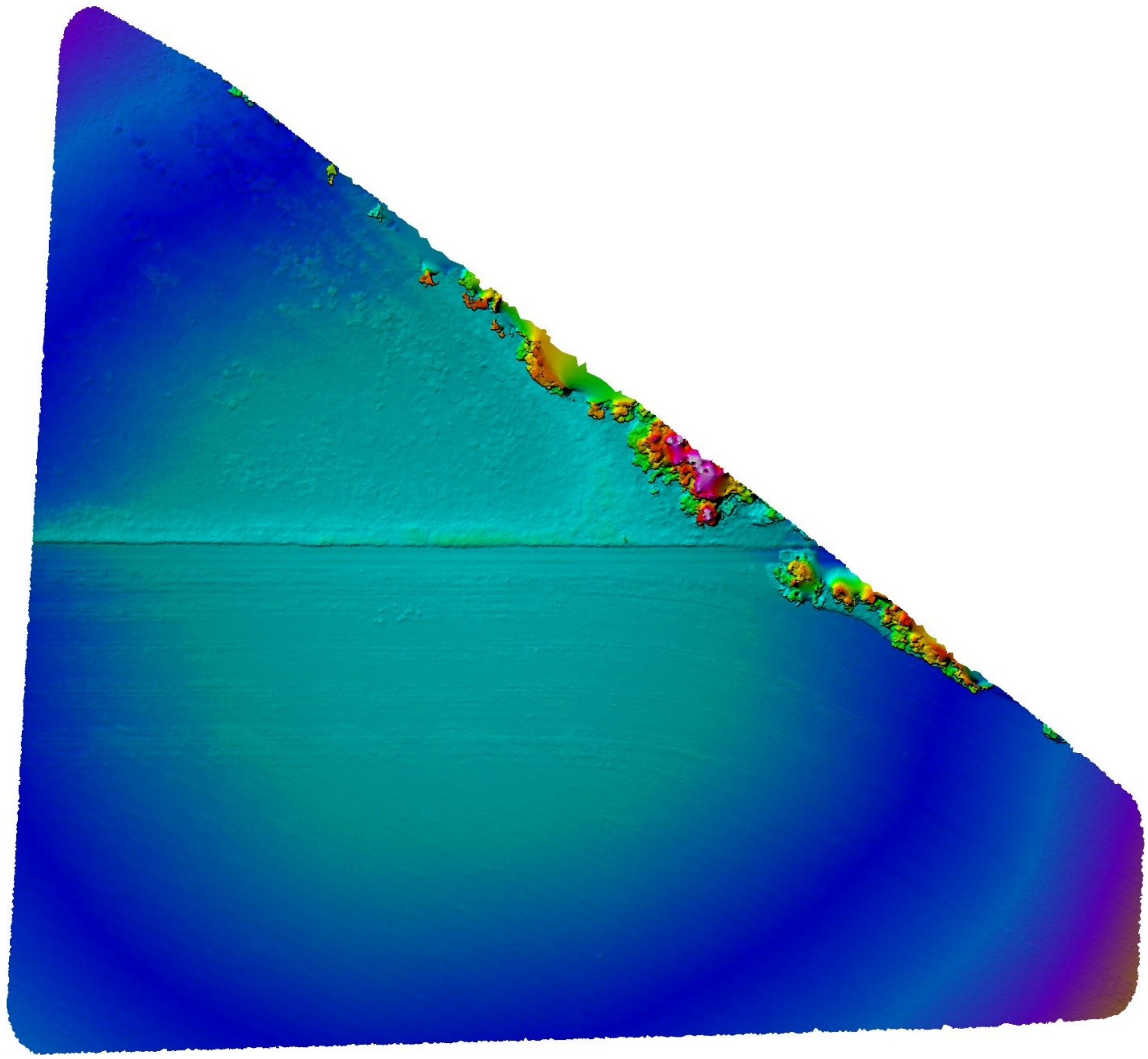


Figure 3-6 An example of doming perpetuated by flying into towards the sun

Conventional aerial photographs that are used for photogrammetric purposes use finely calibrated metric cameras that have stable, known, and repeatable interior orientations allowing for high obtainable accuracy. Fryer (1985) outlines metric camera features. Metric cameras usually have:

a. been specifically designed for photogrammetric purposes and take large format photographic images on stable-base film or glass plates (now stable digital sensors);

b. a stable interior orientation, that is the lens cone is rigid and the focusing distance pre-set at the factory. The optical axis is designed by fiducial marks fixed to the camera which are reproduced on each exposure as reference points; and,
c. a low distortion lens whose characteristics (focal length, radial lens distortions) are known from a manufacturer's calibration test.

Non-metric cameras, including consumer-grade UAVs, lack these qualities. However, steps can be taken to account for these shortcomings to achieve an accuracy level suitable for most needs. Without metric cameras, surveys and SfM products can never be the "survey-grade" that is a requirement in a geomatics/surveyor sense. However, survey-grade products far exceed the accuracy most archaeologists can achieve using conventional ground-based methods.

UAV cameras are not constructed uniformly, and there is a considerable variance in the accuracy they can achieve. Carbonneau & Dietrich (2017) tested the accuracy of two popular prosumer UAVs: the DJI Phantom 3 Professional and DJI Inspire 1. Both UAV cameras are 12MP resolution and have the same focal lengths, but have differing lens construction. They found that both UAVs are capable of producing high-quality topographic maps of sufficient quality for a limited number of applications.

Cramer et al. (2017) also compared the DJI Phantom 3 and Inspire 1. For their research, Cramer et al. used the DJI X5 camera on the Inspire 1 instead of the X3 camera that was utilized by Carbonneau & Dietrich (2017). The X5 camera has a higher resolution (20MP), a larger Micro Four-Thirds camera sensor, and lens interchangeability. Interestingly, the Phantom 3 camera, with its enclosed, fixed-focal length with entirely static elements reached an accuracy level close to what would be deemed as survey-grade in both articles. Its shortcoming was largely its onboard GPS unit, as it cannot reach the same precision as real-time kinematic (RTK) positioning used in most modern geomatic surveys. In contrast, Cramer et al. (2017) found that the Inspire 1 X5 camera had greater accuracy variations than the Phantom 3 despite the higher image quality of the X5. This is likely attributed to the interchangeability of the X5's lenses which introduces gradual changes in the camera's parameters, in contrast with the fixed Phantom 3 camera. Further, Carbonneau & Dietrich (2017) noted in their research that the Phantom 3 and the Inspire 1 X3 cameras produce similarly accurate products. Although the two cameras' exteriors are different, their interior organization is largely the same.

This is further discussed by Putch (2017) who assessed the linear accuracy of the Phantom 3, Phantom 4, and Inspire 1 (with both available cameras) at varying altitudes. The research shows cameras with greater resolution tend to have greater accuracy (such as the Inspire 1's Micro Four Thirds sensor) although the Phantom 3 still performed comparably well, especially at low altitudes (20-60 m). Putch (2017) found the average error for the Phantom 3 was 1.1% without any GCPs, which would not be suitable for documentation tasks requiring high accuracy.

While non-metric, consumer-grade UAVs cannot offer survey-grade precision, at issue is whether they provide acceptable data quality for archaeological mapping purposes. Scollar et al. (1990) addressed this concern in the context of airplane-based aerial photography:

> Photogrammetrists are upset by the rough and ready approach, but since archaeological sites are not precision features in the landscape like a railway line or highway, and since not all details available through excavation are visible from the air, the lack of precision in the imagery does not constitute a serious loss of information (p. 27).

UAVs offer significant improvements to archaeological map accuracy, despite not reaching survey-grade quality, as many contemporary site maps are drawn by hand using optical survey instruments and their precision is dependent on the skill of the archaeologist. Factors such as slopes, feature exposures, and calculation errors all impact the precision of contemporary site maps in an immeasurable way. The same sites or features drawn by different archaeologists will yield different results based on their interpretation whereas UAVs provide an objective view of the subject. Given this interpretation inaccuracy and that UAVs should still work in tandem with common archaeological provenience techniques, minor inaccuracies in the UAV data can be dismissed. Major inaccuracies will be detected with minimal air-photo interpretation training and can thus be identified as part of normal validity testing during archaeological site analysis.

3.5.6.2 Absolute and Relative Accuracy

In speaking on accuracy, it is important to note the distinction between absolute and relative positional accuracies. Absolute accuracy is concerned with a dataset's precision when projected within a larger geographic context. Put simply, absolute accuracy is how precise the UAV-derived dataset is within the *real world of published Cartesian space*. Relative accuracy is more introspective. It looks at the precision between features as they are within the *dataset*.

Absolute accuracy can typically be only as precise as the GPS used during data collection or the ground control points used to undertake the conventional map. As a baseline, if no GPS is used, including the GPS within most UAVs, the dataset created would have no absolute accuracy as it cannot be situated within a geospatial context. Sole reliance on the UAV's onboard GPS will result in the dataset's absolute accuracy being about the same as the precision of the handheld GPS. However, the accuracy can be increased by introducing ground control points (GCPs). These are physical points within the AOI that have been assigned a geospatial position by GPS, usually with a more accurate differentially corrected GPS (dGPS). The geospatial data can then be assigned to the GCPs within the post-processing software to refine the dataset's absolute accuracy. By increasing the quantity of GCPs, the absolute accuracy will also increase proportionately. Precision can also be increased by using RTK to mark the GCPs instead of GPS. However, as summarized by Scollar et al. (1990) (Section 3.5.6.1), hyper-precise absolute accuracy should not be a primary objective for archaeological applications. Instead, value lies in precise relative accuracy.

Modern, digital photogrammetric and SfM techniques produce datasets with highly precise relative accuracy with little effort. Relative accuracy is a direct function of the UAV's elevation, flight speed, and photo overlap. Higher altitudes, increased flight speeds, and more spatially dispersed photos (less % overlap) will result in poorer relative accuracy. Conversely, low-altitude, low-speed flights with significant photo overlap will ensure adequate data capture for SfM software to produce datasets with highly precise relative accuracy.

3.5.6.3 Z-Axis Accuracy

Photographs are 2D representations of a subject of interest. Therefore, single images only contain XY axes data, lacking depth created by the Z-axis. By using SfM software the triangulation of features in a series of overlapping 2D images derives Z-axis data from computer algorithms. This interpolation of the images to produce elevation data introduces an unknown error margin. To manually check the Z-axis accuracy, the elevation of GCPs can be recorded using precise RTK units. This is ultimately ideal, but is seldom available to consultant archaeologists. This again harkens back to relative vs absolute accuracy considerations and what margin of error can be considered acceptable in consulting archaeology.

Z-axis accuracy is directly affected by the same constraints imposed on XY axis accuracy (i.e. flightspeed, elevation, camera quality, photo spacing). However, because the Z values are interpolated from robust computer vision systems, the Z-axis typically reflects accuracy consistent to that of the X and Y axes. Fonstad et al. (2017) noted in the context of their research that the mean difference between Z values was 0.07 m with a standard deviation of 0.15, similar to the mean difference in X and Y values (-0.03 and 0.05 respectively).

As introduced in Section 3.5.6.1 and further discussed in Section 3.5.6.4, errors in data capture can propagate throughout the SfM process and inherently skew Z-axis values. However, these errors are easily detectable in the data products and the data ambiguity can be acknowledged in the analysis of the subject.

3.5.6.4 Common Errors

UAV-based survey and SfM processing are not without errors. The most common errors in the data products are detectable and will have different effects on the data ascertained by archaeologists. As noted previously, photographing reflective surfaces will usually lead to gaps or digital artifacts. This includes water, which is not only reflective but also frequently moving. These properties in photos will typically result in dramatic errors in elevation data (Figure 3-7). This can be remedied by avoiding reflective surfaces during photo capture, applying a polarizing filter to limit the reflection reaching the camera sensor, or applying a “mask” on reflective surfaces during data processing. The mask will essentially tell the software to exclude these surfaces during processing so the artifacts are not created.

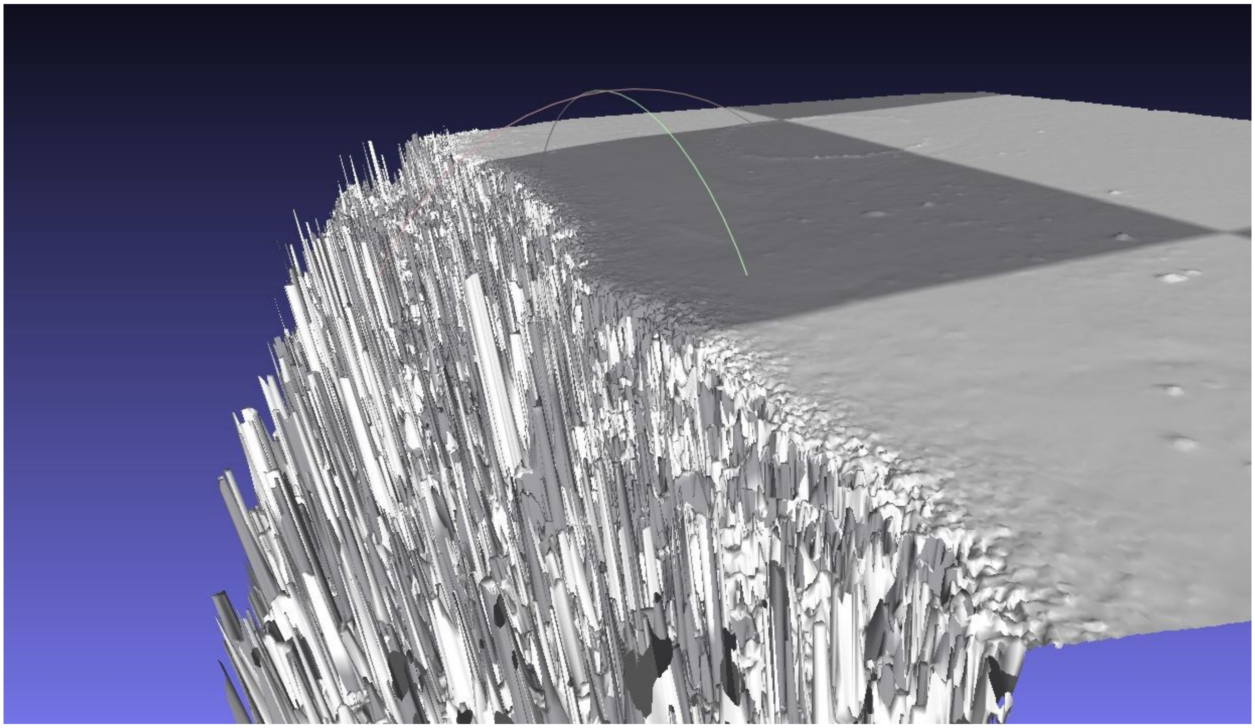


Figure 3-7 An example of "artifacts" caused by water reflections near the Boulevard rock ring

Similar artifacts will be created when photographing vegetation. Trees and grass are composed of fine details and typically have at least some motion that will lead to undesirable digital artifacts. This often makes it fruitless to photograph archaeological features through gaps in forest canopy. To partially mitigate these errors, vegetation can be masked during data processing, photo overlap can be increased, or the errors can be identified and omitted from analysis.

Shadows can also cause gaps in data as SfM cannot often detect any features in low-light areas. This is typically remedied by flying in optimal lighting conditions. If optimal lighting conditions cannot be achieved, then acceptable data capture lies with the quality of the camera sensor and photo file format. If the UAV supports RAW photos, and the colour mode is D-Log 10 or higher, the photos may have enough dynamic range to be edited to salvage information from shadows. However, this is not typical of most UAV cameras and may be considered extraneous work for the little data that could be extracted.

Jagged surfaces in DEM products are another error type propagated through SfM software. This is largely the result of insufficient photo overlap, mildly reflective surfaces, or repetitive features. However, the error is typically only noticeable and substantial when attempting to create contours from the DEM products and does not necessarily impact the overall data's accuracy.

As previously noted, dishing and doming are also common errors. However, data products with these listed errors are not necessarily unusable products. If the errors are acknowledged, other analytical value can still be derived from the products.

3.5.6.5 Means to Assess Accuracy

To evaluate the accuracy of the completed data products, multiple controls are placed before data acquisition. GCPs are placed, and their geospatial positions are marked with a handheld GPS unit. Once the final data products are created, their absolute accuracy is determined by comparing the differences between the GPS points taken in the field and the GCP geospatial position in the model. The differences are then averaged, resulting in the variance value and thus the precision of the model's placement within cartesian space. Absolute accuracy can be improved by generating averaged point values with the handheld GPS in the absence of high precision equipment.

The distances between each GCP were also measured in the field, and 1 m scale bars were placed around the AOI in some case studies. To measure the final data products' relative accuracy, the distances between the GCPs (and scale bars, when used) were calculated with the measure tool in either ArcGIS or MeshLab. The differences between the field measurements and the software measurements are then averaged, and the resulting variance can be assumed to be the data products' relative accuracy.

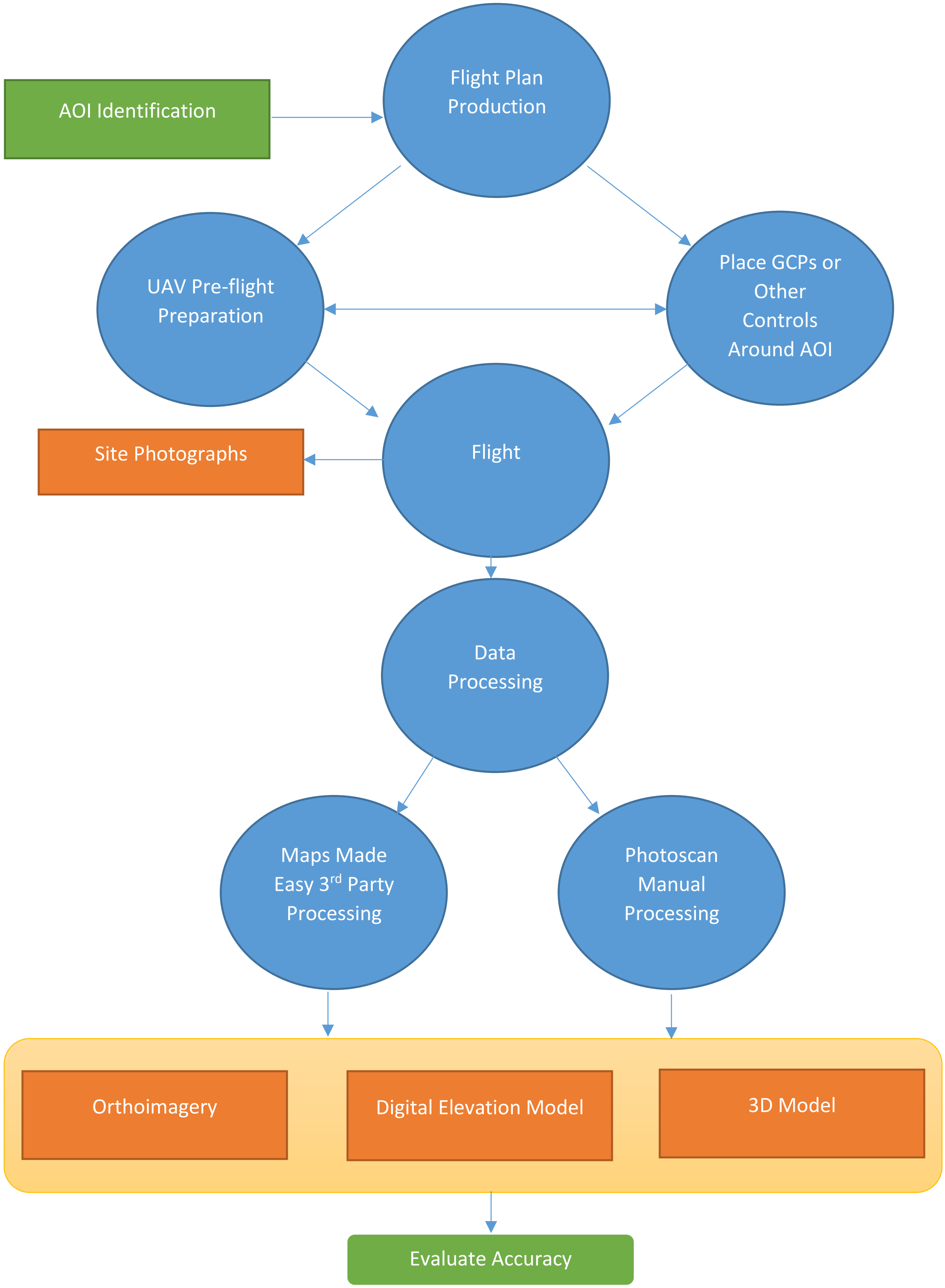
All of the following case studies feature landforms with elevation (Z-axis) values that would be difficult to measure in the field with an accuracy great enough to compare against the Z-axis derived from the UAV. Therefore, the Z-axis accuracy cannot be presented with a high degree of certainty, although it can be assumed to be somewhat equal to the relative accuracy as shown by Fonstad et al. (2017). Further, as discussed in Section 3.5.6.1, most archaeological surveys do not produce or require highly precise (survey-grade) data. Instead, generalizations on the Z-axis accuracy are made using field observations, previous archaeological survey data, and elevation data derived from LiDAR.

3.5.6.6 Interpretation Accuracy

Metric accuracy aside, air-photo interpretation is somewhat of an "art" when seeking to interpret features, functions, and site locations of archaeological interest. Certainly, as Scollar et al. (1990, p. 27) states "prolonged examination of other types of pictures usually leads to unwarranted fantasy which often cannot be confirmed by later excavation…it seems that if one stares long enough at a diffuse image, one's imagination will allow one to see almost anything." However, spurious air photo interpretation can often be mitigated by firstly acknowledging a level of uncertainty of the interpretations. Next, air photo interpretations should be compared to previous aerial archaeology investigations, if available. Lastly, the AOI should be ground-truthed through field inspection, which may include excavation. With these protocols, the subjectivity in air-photo interpretation can be embraced and major errors can be mediated.

3.5.7 Workflow Summary

The following flowchart provides a visual guide of the general process for UAV data acquisition and processing. This is the general workflow that was used for all of the case studies in Chapter 4, and is a summarization of what is discussed in Chapter 3.5.


AOI Identification
Flight Plan Production
UAV Pre-flight Preparation
Place GCPs or Other Controls Around AOI
Site Photographs
Flight
Data Processing
Maps Made Easy 3rd Party Processing
Photoscan Manual Processing
Orthoimagery
Digital Elevation Model
3D Model
Evaluate Accuracy

4 CASE STUDIES

4.1 INTRODUCTION

This chapter illustrates the general process of data acquisition in a variety of contexts in Ontario and Manitoba with consideration of the constraints that are imposed on Ontario consultant archaeologists. Background information, flight planning, conditions, data processing, accuracy, and analysis will be presented.

The following four case studies review the utility of UAVs in a number of scenarios that archaeologists may encounter. Variance from the methodologies outlined in Chapter 3 are discussed. The UAV's effectiveness and ease-of-use will be considered in each circumstance and the products derived from each mission will be assessed in order to provide examples of the potential data that can be captured. Metadata, and analysis of the product's accuracy is provided. In addition, history and previous archaeological assessments will inform the case studies. The Boulevard Rock Ring reflects preliminary flight attempts to determine the UAV's ease of use and accuracy. The Dog Lake Effigy and Hokanson case studies are of registered archaeological sites that were recorded over the past half century. The chapter concludes with a survey of P1 (AlGs-486) during the site's excavation in a consulting archaeology framework to synthesize the methods and analysis practices used in the other, more controlled case studies.

4.2 BOULEVARD ROCK RING

4.2.1 Introduction

Previous to this case study, the Boulevard Rock Ring had not been formally recorded by archaeologists. Many local Thunder Bay residents spoke of a rock feature submerged in

Boulevard Lake, but its precise whereabouts were unknown and it was never formally acknowledged. Boulevard Lake is an artificial lake that was created after the early 20th Century completion of a dam along the Current River in Thunder Bay, Ontario. In the spring of 2015, the City of Thunder Bay began an initiative to redevelop the recreational areas around the lake and to fix the dam that had long been in disrepair. This required lake drainage to facilitate remediation. Local archaeologists initially planned to find and document the rock feature during the summer, but the dam repair project was delayed until fall.

In October 2015, Thunder Bay municipal authorities unexpectedly drained the lake. George Kenny (a fellow archaeology graduate student at Lakehead University) informed Hamilton and Stephenson that the lakebed was recently exposed. Hamilton and Stephenson subsequently visited the site and proceeded with aerial survey using the Phantom 3 Advanced UAV. This flight also marked the initial test of semi-autonomous flight planning software to document a possible archaeological feature (Figure 4-1 and Figure 4-2).

Figure 4-1 Detail of the Boulevard Lake rock ring's composition and position from the ground

Figure 4-2 Hamilton walking around the ring showing scale and its position relative to the Current River

The flightplan for the mission was created using the Map Pilot app on-site by creating a personal Wi-Fi “hotspot” with a cellphone. The pylon GCPs were laid out around the AOI, with their positions marked using a Garmin GPSmap 64st handheld unit with an accuracy of ±3 m. The accuracy of these locations was maximized by collecting averaged values. The distance between these GCPs was then measured with a fiberglass measuring tape. The area was inspected before takeoff to ensure there were no bystanders.

4.2.2 Results

A total of three flights were completed over two days, all in overcast (optimal lighting) conditions. The first plan was flown at 4 m/s at a 40 m altitude. The flight speed proved to be too fast for adequate data capture, causing the photographs to be desaturated, and severely degrading their analytic value (Figure 4-3). The subsequent flights decreased the flight speed to 3 and 2 m/s, respectively and maintained the 40 m altitude. The quantity of photographs captured and the bearing of the flight transects were the only other differing variables between the two latter flights. The metadata of each flight is presented in Table 4-1 in Section 4.2.3. The resulting photographs were suitably saturated and were conducive for upload to the Maps Made Easy website (Figure 4-4).

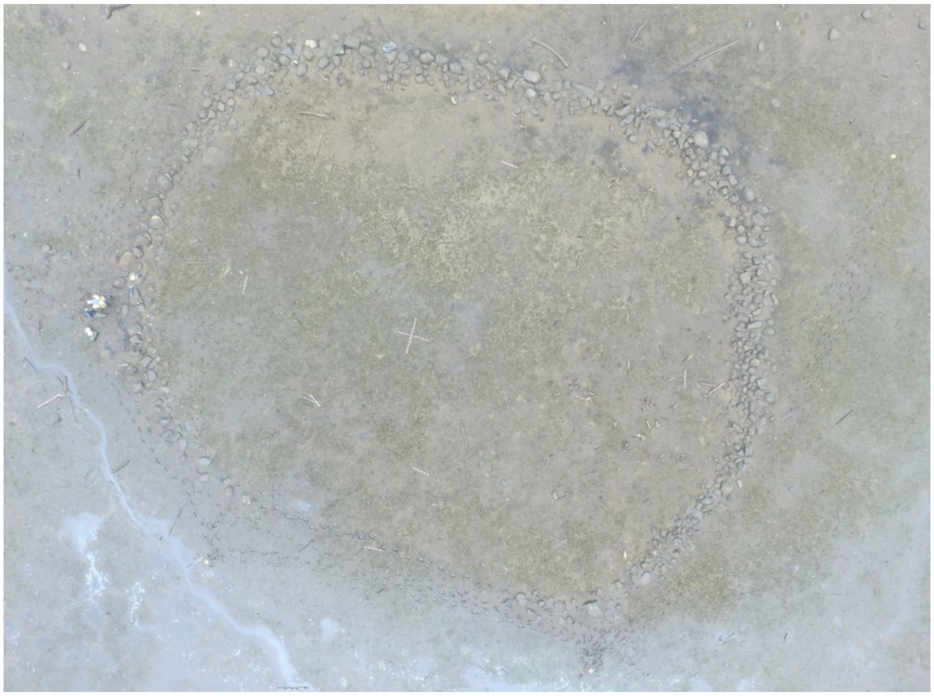


Figure 4-3 Desaturated photo of the rock ring from poor image capture

Figure 4-4 Higher quality photograph showing the rock ring

The Flight 3 dataset was selected to upload to Maps Made Easy. With modest internet speeds through an ethernet connection, the 313 images uploaded quickly to begin third-party processing. The overall costs associated with producing the data products was not recorded at the time, but the approximately 1.5 ha AOI likely cost less than 5 USD to process.

The total time spent preparing the AOI, creating the flight plan, and completing three flights is an estimated two hours. With this size dataset, Maps Made Easy delivered the final data products in 3-6 hours totaling 5-8 hours from initial survey to usable product. It is estimated that conventional mapping of the feature and its individual elements would have required at least two people working for about 5 to 7 days.

In addition to the UAV survey taking noticeably less time to complete than conventional methods, the survey produced high-resolution colour imagery with easily discernable individual elements making up the rock feature and surrounding geography. These components may not have been captured or adequately visualized using land-based survey methodology. For example, the Flight 3 orthophoto is 2.7 x 4.1 m at its full scale with 72 PPI print resolution, with the image itself being highly detailed (a very small-scale version is shown in Figure 4-5). This high-resolution imagery and large file size allows the dissemination of archaeological knowledge while retaining much of the value and information captured by aerial perspectives.

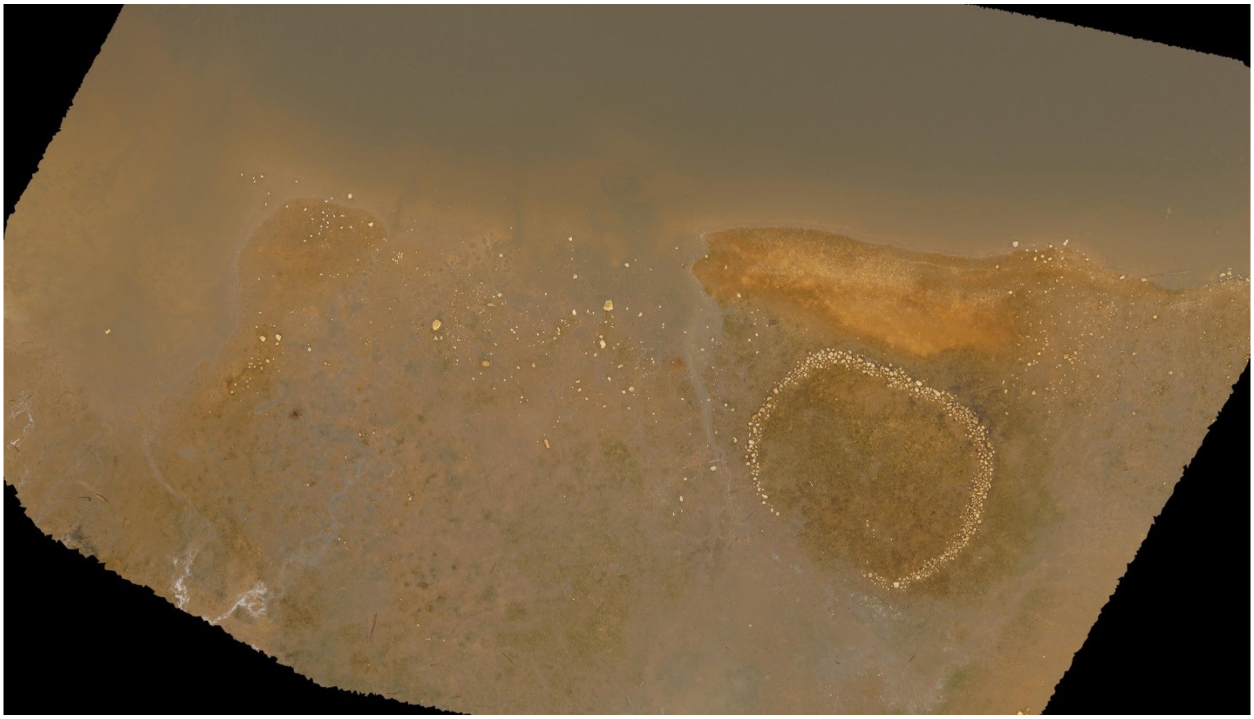


Figure 4-5 High quality orthophoto of the AOI, Boulevard Lake, Thunder Bay.

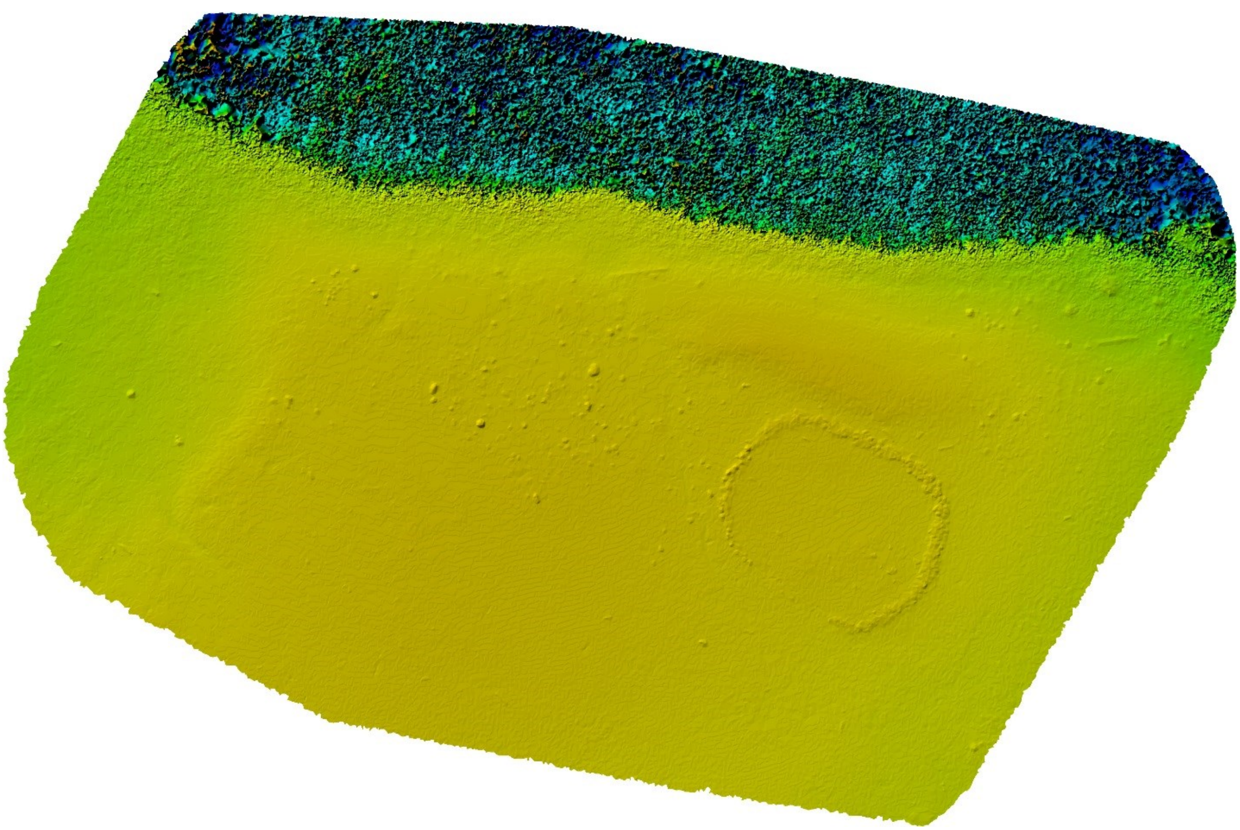


Figure 4-6 Initial raster DEM of the rock ring showing drastic unconformities in the water along the top of the image. The variance in elevation in the water skews the elevation scale in the rest of the model

The orthophoto data product, as shown in Figure 4-5, is immediately useful for analysis. However, the DEM and 3D model products were severely affected by water reflections that created digital artifacts defined by dramatic relief changes of approximately 80 m (Figure 4-6). If the models had been created by Hamilton and Stephenson (using Photoscan or another SfM program), the water could have been masked or removed before processing. However, since a service bureau was used to create these products, little editing was done, especially with the raster DEM. Upon realizing the magnitude of the data processing problem, the most appropriate images were selected to document the feature (discarding those with water surfaces) and the data resubmitted to Maps Made Easy for reprocessing. This resulted in a much more desirable product (Figure 4-7).

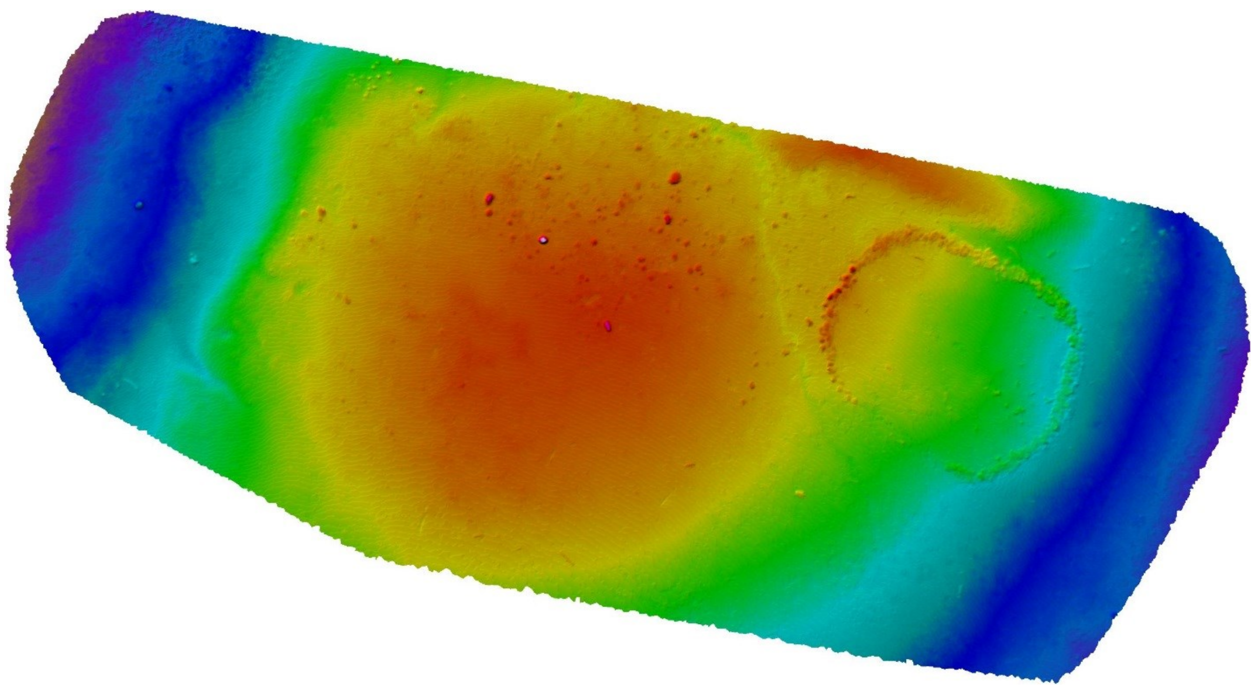


Figure 4-7 Re-processed DEM of the rock ring with an apparent "pseudo-dome"

4.2.3 Metadata

Table 4-1 Metadata of each UAV flight for the Boulevard Rock Ring

Flight 1	Values
Flight Speed	4 m/s
Altitude	40 m
Area	0.91 ha
Overlap	80%
Sidelap	80%
Images	126
Duration	8 min 41 sec
Batteries	1
Storage	0.63 GB
Resolution	1.7 cm/px
Filter	No
EV Comp	No

Flight 2	Values
Flight Speed	3 m/s
Altitude	40 m
Area	1.2 ha
Overlap	80%
Sidelap	80%
Images	149
Duration	13 min 23 sec
Batteries	1
Storage	0.78 GB
Resolution	1.7 cm/px
Filter	No
EV Comp	No

Flight 3	Values
Flight Speed	2 m/s
Altitude	40 m
Area	0.91 ha
Overlap	80%
Sidelap	80%
Images	313
Duration	15 min 39 sec
Batteries	1
Storage	1.71 GB
Resolution	1.7 cm/px
Filter	No
EV Comp	No

4.2.4 Analysis

At first glance, the raster DEM (Figure 4-7) appears to show doming in its centre, thus somewhat invalidating the Z-axis accuracy. However, when examining the orthophoto and recalling the field inspection, this "pseudo-dome" is a true reflection of a high point in the exposed lake bed (Figure 4-7). The orthophoto shows drier and more vegetated areas where the dome would appear in the raster DEM, and is not an error in the data processing.

However, a small error appears in the raster and vector DEMs. Both display a jagged surface throughout the data products. Although this does not affect the general analysis of these models, it hampers the geoprocessing when creating contours in ArcGIS (Figure 4-8). Further, the imagery is too low resolution to attempt to automatically delineate individual rocks in the C-shaped feature.

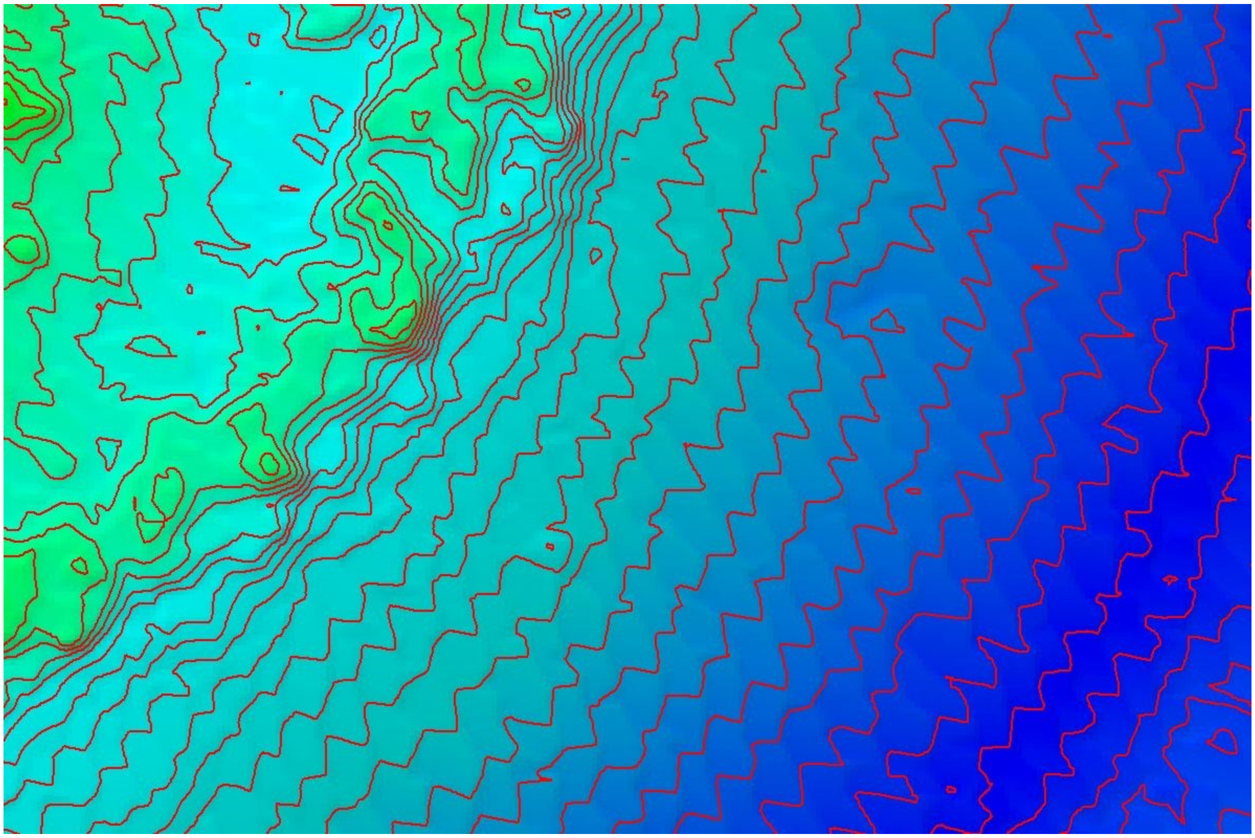


Figure 4-8 Jagged contours derived from the DEM of the Boulevard rock ring

Despite the minor limitation found in the data products, the data suite appears highly accurate. To determine the models' absolute accuracy, the GPS points taken during fieldwork were plotted in ArcGIS (using WGS 1984 UTM Zone 16N) and compared to where the pylon GCPs are situated within the orthophoto. The differences in distances between GCPs and the GPS points were measured and averaged to produce the absolute accuracy value (Table 4-2).

Table 4-2: Boulevard Rock Ring Absolute Accuracy

Points	*Variation Δ (m)*
GCP 1	4.05
GCP 2	5.35
GCP 3	4.20
GCP 4	2.20
Absolute Accuracy (Average)	±3.95

The distances between each GCP found in the orthophoto and their geospatial position recorded by a GPS were measured in ArcGIS and compared to the GCP measurements taken in the field to calculate relative accuracy (Table 4-3). Although the GPS points taken with the handheld unit do not technically correlate with the relative accuracy of the dataset, as they are not directly tied to the orthophoto, the points were measured as a secondary means to assess and illustrate the accuracy of the handheld device in this case study (Table 4-4). As the handheld unit and the UAV's onboard GPS systems are of similar precision, the accuracy outcome of the handheld GPS unit can be assumed to be similar to that of the UAV's onboard GPS, and subsequently the geospatial accuracy of each individual photograph's EXIF tag.

Table 4-3 Relative Accuracy of the Boulevard Rock Ring dataset

Line Segment	*Field Measurement*	*Model Measurement*	*Variance*
GCP 1-2	38.0	37.5	0.5
GCP 2-3	33.5	32.5	1
GCP 3-4	20.5	21.0	0.5
GCP 4-1	30.0	29.5	0.5
		Relative Accuracy	±0.6 m

Table 4-4 Relative Accuracy of the GPS Points taken around the rock ring

Line Segment	*Field Measurement*	*GPS Measurement*	*Variance*
GCP 1-2	38.0	38.5	0.5
GCP 2-3	33.5	41.0	7.5
GCP 3-4	20.5	20.5	0.0
GCP 4-1	30.0	33.0	3.0
		Relative Accuracy	±2.7 m

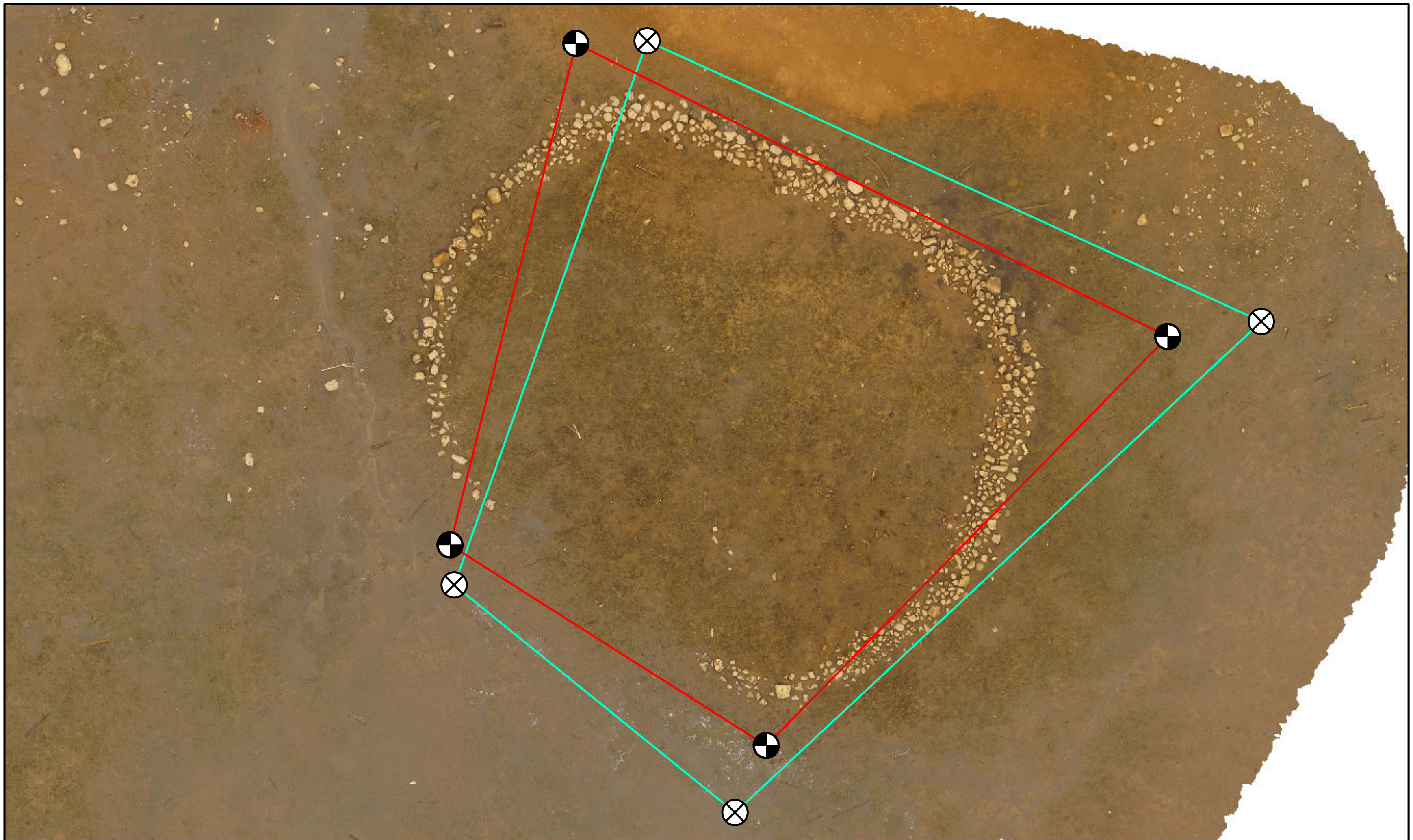
As can be seen in the tables above and in Figure 4-9, the relative accuracy of the model is sub-metre compared to the ±2.7 m accuracy of the four GPS points taken in the field. This illustrates the robustness of SfM software. The software may have produced a more accurate model than what the absolute accuracy suggests as each of the 100+ photographs have GPS locations attributed to them. The overall accuracy of the onboard GPS within the UAV would be mediated through the quantity of the photos compared to the four GPS points that were taken with a handheld unit. Essentially, the photo mosaicing process of finding common points (i.e.

bundle adjustment) results in geospatial data consolidation and refinement so that the georeferencing of the orthophoto and other data products is better than that represented by the EXIF tags of the individual images and of the GPS points taken from the handheld GPS unit.

The orthophoto and the geospatial position of the data products were the most valuable in the analysis of the feature. Using ArcGIS, individual rocks were manually delineated to assist in analysis. From this manual delineation, it is known that the feature is composed of approximately 1067 visible rocks ranging from small cobbles to large boulders, with the largest exposed portions of boulders being approximately 65 to 75 cm^2 in area. The sum of all of the exposed rocks is equal to approximately 82 m^2. The overall area of the feature, including its interior is 879 m^2 with a diameter of 35 m at its widest. The "entrance" to the feature is in the southwest portion of the ring facing away from the original riverbank, and is approximately 13 m wide (Figure 4-10).

By manually delineating the rocks in ArcGIS, the rock size and distribution can be quantified. The area of each individual rock within the shapefile was calculated by ArcGIS and quantitative symbology was applied. By classifying the shapefile attributes in 0.15 m^2 intervals, the rock distribution can be further visualized (Figure 4-10). Through this quantification, it can be distinguished that mid-size to large boulders (0.31 m^2 +) were placed closer to the exterior of the feature, with smaller rocks (0.00-0.30 m^2) generally scattered in between the large rocks and closer to the interior. Concentrations of large rocks are seen in the north and west portions of the feature while large clusters of small rocks are shown in the east. Rocks between 0.15 and 0.30 m^2 are found relatively consistently throughout the feature's shape and predominantly make up the west side of the entrance. Unfortunately, the UAV was flown over too large of an area and at too high of an altitude to make determination of the Z-axis values of the rocks analytically useful in the 3D model and DEMs.

The analysis described above could be completed using the freely available Google Earth Pro, though with limited functionality. The feature's total area, and size of the rocks could be calculated, although the latter would be more time-consuming when compared to delineating the rocks with ArcGIS. The major limitation of using Google Earth Pro is that classifying rocks by size would need to be completed manually for each individual rock, and would prove to be too time consuming.



Legend

GPS Point — GCP Measurement

GCP — GPS Measurements

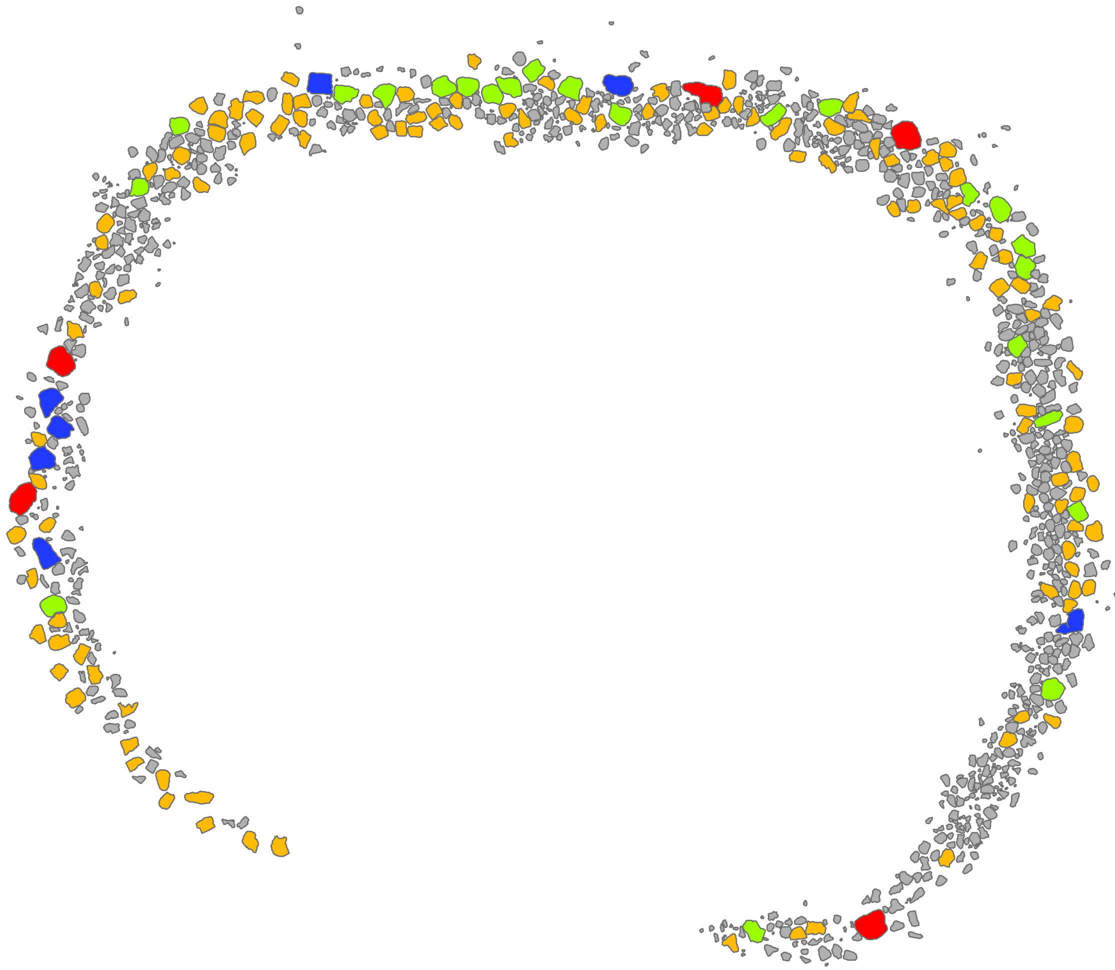
WGS 1984 UTM Zone 16N

N

Figure 4-9 : Boulevard Lake Ground Control Accuracy

Scale:
1:350

Meters
0 5 10



Legend

Area (Square Metres)

- 0.00 - 0.15
- 0.16 - 0.30
- 0.31 - 0.45
- 0.46 - 0.60
- 0.61 - 0.75

WGS 1984 UTM Zone 16N

N

Figure 4-10 : Rock Ring Boulder Measurement

Scale:
1:250

Meters
0 5 10

A key benefit of collecting UAV data is that the analysis presented above took place in 2018, three years after the UAV flight, and long after the feature was again inundated by the artificial lake. The speed and efficiency of UAV data collection enables information collection beyond the immediate needs of the investigators that can be subjected to continued analysis well after fieldwork has been completed. While other camera platforms (e.g. airplanes, balloons, kites, camera cranes) will provide similar results, UAVs are more advantageous in that they can be easily and quickly deployed.

The ring's cultural affiliation and function is not known, but by creating the georeferenced orthophoto using the UAV, researchers were able to quickly, efficiently and non-invasively collect information when the feature was briefly visible that permits more comprehensive analysis later. The ring is usually inundated by Boulevard Lake, but it is placed along the original Current River channel (Figure 4-11). Numerous Plano and Archaic period archaeological sites are situated along the Current River including registered sites and potential site leads only a few hundred metres away from the feature. Two initial hypotheses regarding ring function included a fish weir, or a ceremonial enclosure. However, the former is unlikely given the large gaps between the rocks that would allow fish to swim through freely. Additionally, the feature is situated south of a point bar that is of a higher elevation than the feature, and while upon a flood plain, the feature would only be infrequently flooded by the Current River prior to dam construction. Both points would indicate that the potential of capturing fish in this feature is low. The latter hypothesis is more preferred, although typical circular features found around Lake Superior are significantly smaller than this ring.

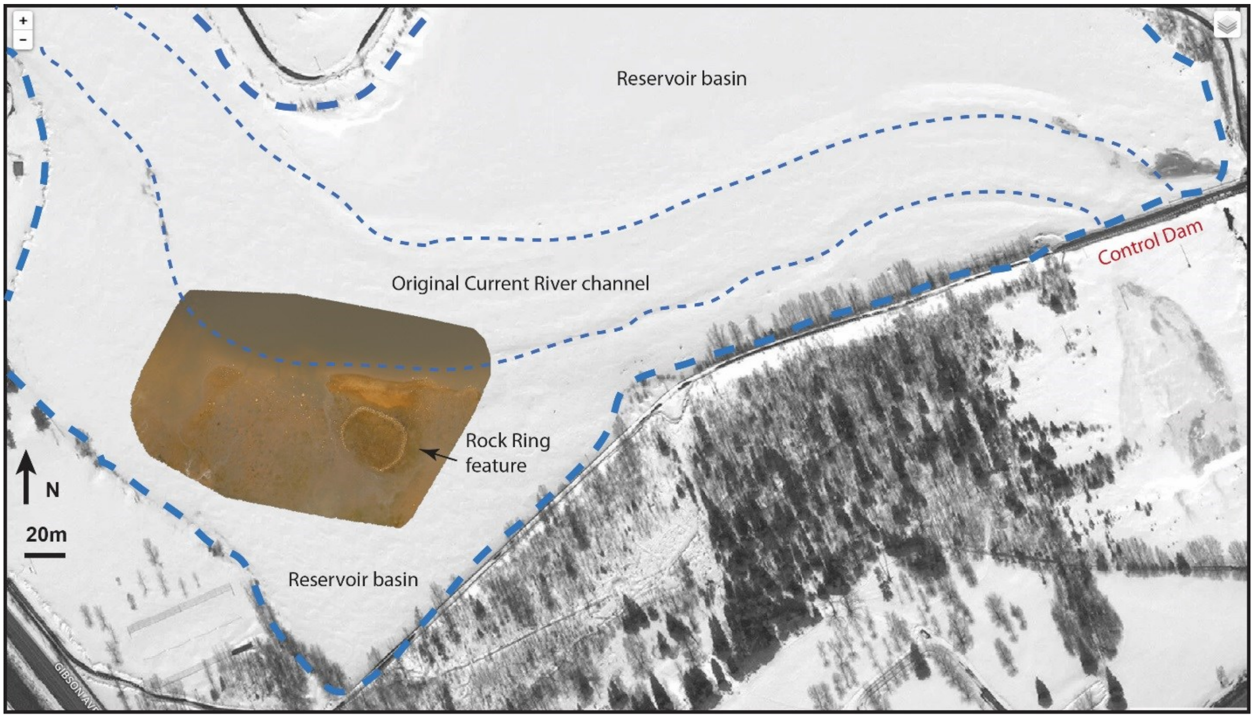


Figure 4-11 Rock ring feature relative to the original Current River channel (Courtesy of Hamilton)

The benefit of having a planimetric view of this feature is that it can be easily displayed and visualized in a public forum. Hamilton and Stephenson shared high-resolution colour images of the feature with the public in an attempt to solicit local information about the feature's origins and function.

4.2.5 Summary

The Boulevard Rock Ring is an example of a relatively successful, hurriedly planned UAV survey to record an archaeological feature that was briefly exposed during the unexpected draining of a reservoir. While wet conditions and widely spaced survey transects resulted in limited elevation information overall, the high-resolution orthophoto was fundamental in data analysis over the course of three years, and yielded suitably accurate XY data. Using ArcGIS to delineate and classify individual rocks in the feature was a useful initial attempt to determine the feature's spatial composition and distribution. Many of the same data analysis methods used in

ArcGIS could also be somewhat replicated in Google Earth Pro, but would require considerably more time and effort to achieve a similar product. This case study also showed the benefit of high-resolution imagery and DEMs in disseminating archaeological knowledge and providing materials in an open forum.

4.3 Dog Lake Effigy

4.3.1 Introduction

The Dog Lake Effigy is of particular interest in Thunder Bay as it is the only known effigy in the region and is one of only a few found in Ontario. Also known as the Kaministikwia [sic] Intaglio Dog Effigy Mound, writings about this archaeological feature appear as early as 1824 (Keating, 1824), yet little is known about its origin and cultural affiliation. In 1962, K.C.A Dawson (Dept. of Anthropology, Lakehead University), Kenneth E. Kidd (Dept of Anthropology, Trent University), and Trevor Page (Dept of Geology, Lakehead University), sought to locate and document the effigy after reviewing the scant literature (see Keating, 1824; Simpson, Hind and Kane; Piper, 1924; Denis, 1959; Bertrand, 1959) and hearing stories from local residents who occasionally frequented the area (Dawson, 1965).

Dawson and team located the effigy on Dog Mountain and recorded its features. The area had been impacted by soil test surveys completed a decade prior as part of a study for the now existing hydro-generating station along the Kaministiqua River. Three pits were dug within the effigy during this survey, but it otherwise remained relatively undisturbed. Dawson and team mapped the effigy and described it as an:

> …example of an intaglio type of zoomorphic mound. It has the generalized outline of a dog-like creature though it could easily be interpreted as a wolf, a

ground hog, or other beast. The tail is thick and could be mistaken for a second head changing the effigy to a Janus-like figure (Dawson, 1965 p. 5).

After its survey, and the subsequent passing of both Dawson and Kidd, the effigy once again faded into relative obscurity. In early winter 2015, Hamilton and Stephenson sought to resurvey the effigy using a UAV. This operation served several objectives: confirm the effigy's presence and condition; offer an archaeological update of the feature; and allow comparison of data collected by a UAV to previous survey results collected using conventional methods.

The 2015 survey posed an interesting challenge since there was little airspace to operate the UAV between the tree canopy and the ground (Figure 4-12). The tight space made flight automation impractical. Further adding to the challenges, the dense canopy cover surrounding the AOI severely impaired the UAV's GPS capabilities. In response to these challenges, the UAV was flown manually using the Phantom 3's VPS at low elevation and speed while attempting to trigger the camera shutter at regular intervals whilst attempting to fly in equally spaced transects. Further compounding issues were: the light cover of snow upon the ground at the time of survey; and the completion of the flight without the removal of the grass and shrubs that sparsely mantled the ground surface. In effect, an informal objective of this flight was to see how the poor conditions might degrade the quality of output.

Figure 4-12 View of the constrained airspace around Dog Lake Effigy

4.3.2 Results

It took Hamilton and Stephenson approximately an hour to drive to the site, and another 30 minutes to hike along the portage to reach the effigy. Once the location was reached, 10 minutes were used to lay out and measure the GCPs and to place 1 m scale bars throughout the AOI. The total flight time to collect the data was no more than 7 minutes, with only a few hours required to process the results.

One flight was completed with an altitude between approximately 5–8 m. The VPS ensured the UAV hovered in place, but course and altitude corrections were made to avoid the nearby trees. The flight speed was around 1 m/s. A total of 40 photographs were taken to cover an area approximately 40 m^2. Metadata details are presented in Table 4-5 in Section 4.3.3. Since there were so few photographs in the dataset, Maps Made Easy processed the imagery at no charge.

Unfortunately, there was not enough photo coverage over the southern portion of the feature for the SfM software to include the “head” because of the nearby thick coniferous canopy. In addition, two of the GCPs were not adequately captured in the photographs and were therefore excluded by the SfM processing software. As such, the two GCPs were not available to be used as accuracy sample points (Figure 4-13). However, the remainder of the feature is well represented, even with the presence of snow within the AOI. Some digital artifacts appear in the 3D data caused by the wild grass, fireweed, and conifers.

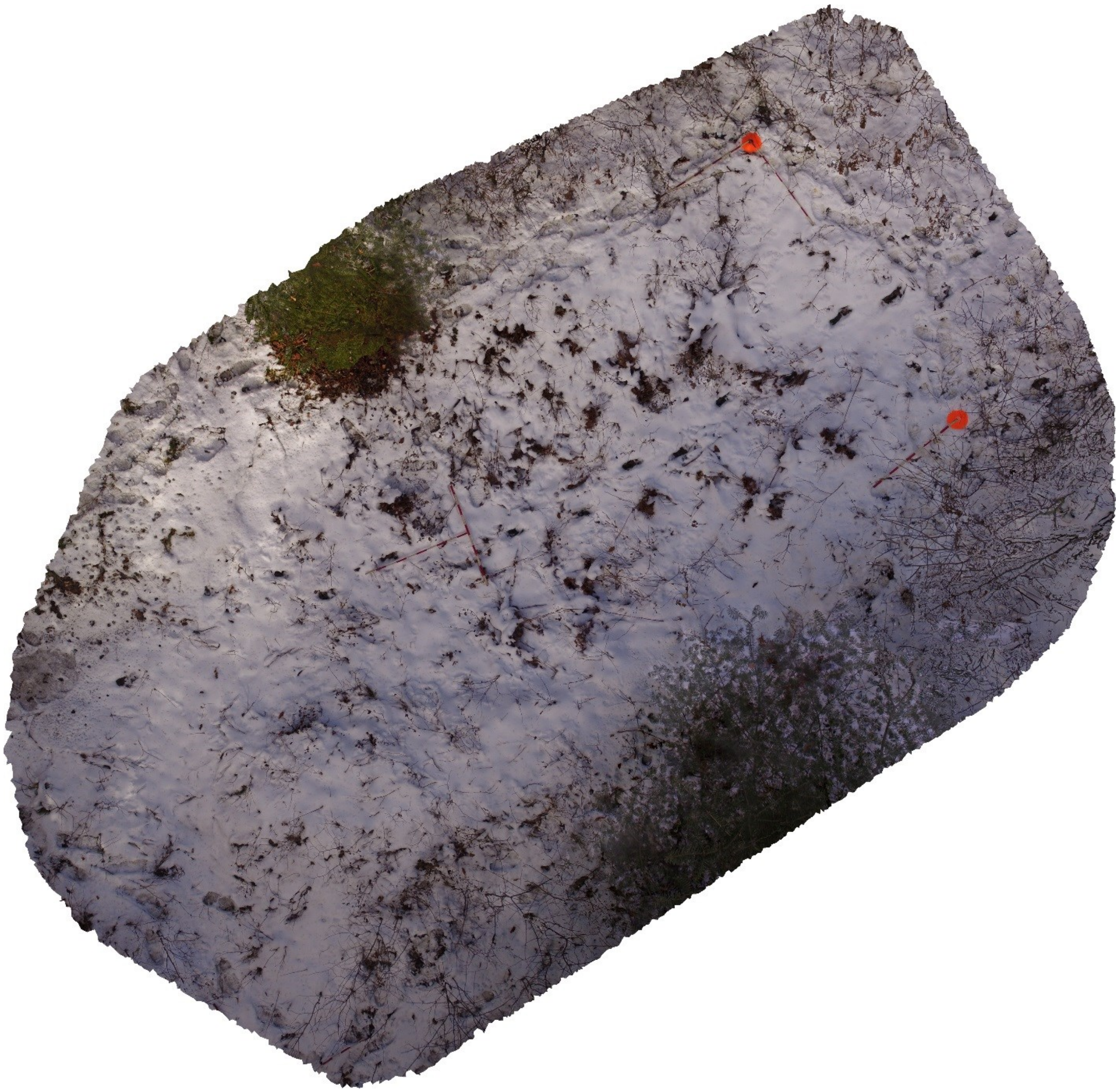


Figure 4-13 Dog Lake Effigy orthophoto at scaled and compressed resolution

4.3.3 Metadata

Table 4-5 Metadata for Dog Lake Effigy flight

Flight 1	*Values*
Flight Speed	~1 m/s
Altitude	5-8 m
Area	40 m^2
Overlap	~90%
Sidelap	~70%
Images	40
Duration	7 min
Batteries	1
Storage	0.19 GB
Resolution	unknown
Filter	No
EV Comp	No

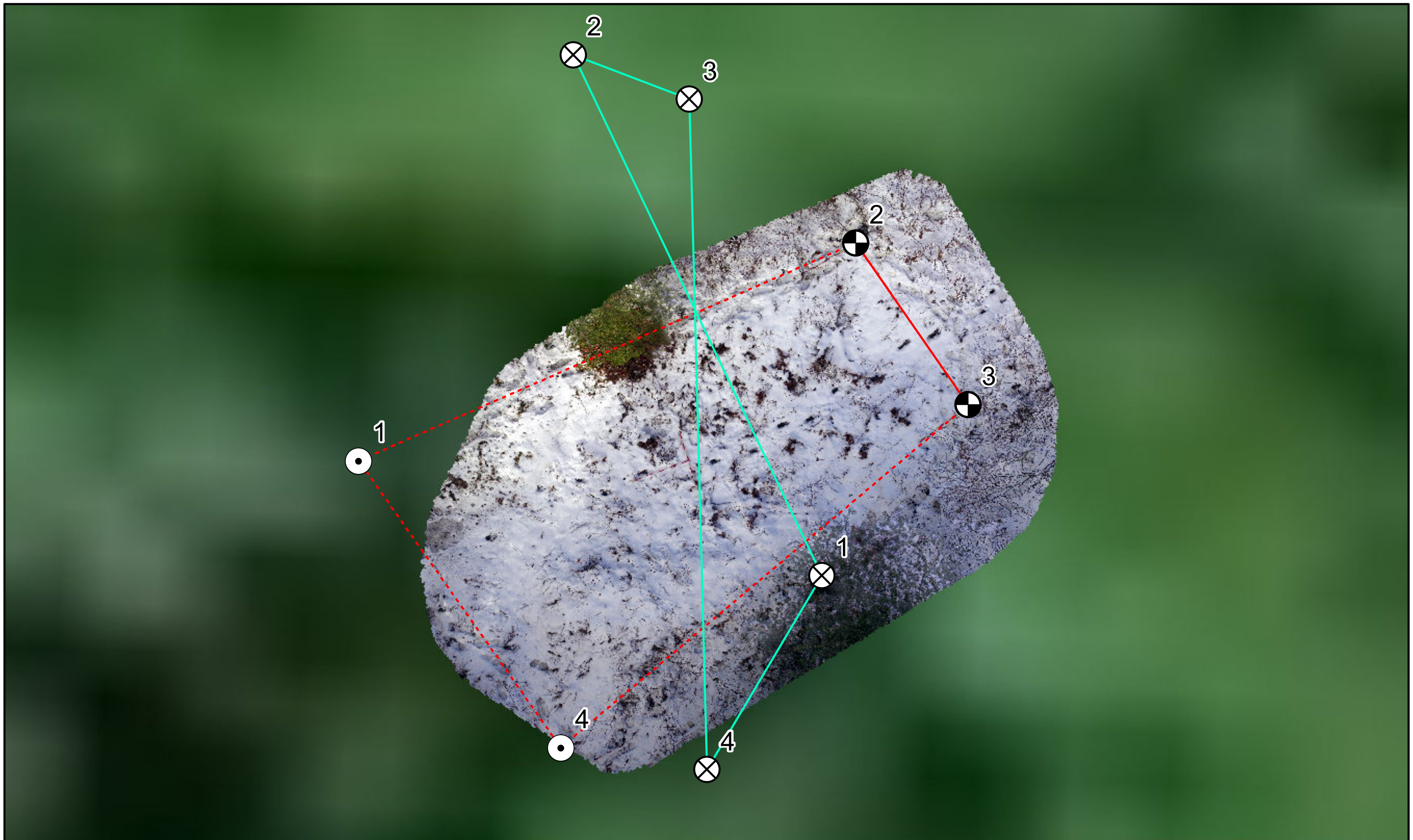
4.3.4 Analysis

The effigy is not clearly represented in the orthophoto as the snow cover obscures the already subtle relief changes of the feature. However, this reflects reality, as the effigy is difficult to distinguish during ground inspection under optimal conditions (Figure 4-14) or using satellite imagery available on Google Earth (Figure 4-15). Figure 4-16 shows the high-resolution orthophoto situated on top of the low-resolution satellite imagery basemap available in ArcGIS. In comparison, the orthophoto provides a significant improvement over the freely available satellite imagery (Figure 4-15).

Despite not adequately displaying the feature, the orthophoto was still used to calculate the data set's accuracy. However, since two of the GCPs are not visible in the model, calculating the absolute accuracy of the data product is difficult. Figure 4-16 shows the points taken of the GCPs with the handheld GPS in contrast to where the GCPs appear in the orthophoto. There is a significant disparity in the GCPs' positions according to the GPS, which is likely a result of poor satellite reception during the survey. This disparity is quantified in Tables 4-6 and 4-7, showing the variance of the XY axes between the GPS points, GCP positions in the orthophoto, and GCP field measurements. As there are only two GCPs to measure in the model, the five 1 m range poles that were placed around the effigy were also measured and presented in Table 4-6 to determine the relative accuracy of the data products.

Figure 4-14 View of the Dog Lake Effigy from the ground

Figure 4-15 Satellite imagery showing the Dog Lake Effigy (located in the clearing in the centre of the image)



Legend

GPS Point — GPS Measurement
GCP — GCP Measurement
GCP (Approx) — GCP Measurement (Approx)

WGS 1984 UTM Zone 16N

N

Service Layer Credits: PDEM Ontario Open Data License, Esri, DigitalGlobe

Figure 4-16: Dog Lake Effigy accuracy

Scale 1:100

Meters
0 0.5 1 2

Table 4-6 Relative accuracy calculations of the Dog Lake Effigy products

Line Segment	*Field Measurement*	*Model Measurement*	*Variance*
GCP 2-3	3.3	3.2	0.1
Range Pole 1	1.0	1.0	0.0
Range Pole 2	1.0	1.0	0.0
Range Pole 3	1.0	1.0	0.0
Range Pole 4	1.0	1.0	0.0
Range Pole 5	1.0	1.0	0.0
		Relative Accuracy	0.1 m

Table 4-7 Relative accuracy of the GPS points taken during the Dog Lake Effigy survey

Line Segment	*Field Measurement*	*GPS Measurement*	*Variance*
GCP 1-2	8.8	9.4	0.6
GCP 2-3	3.2	2.0	1.2
GCP 3-4	8.6	10.9	2.3
GCP 4-1	5.6	3.6	2.0
		Relative Accuracy	1.5 m

As demonstrated in the tables above, the model has a high relative accuracy. This is likely attributed to the high number of photos (40) taken in a relatively small area (40 m^2), which equaled one photo every square metre, and allowed for significant photo overlap. However, this accuracy could not be measured using Google Earth, as the software encountered issues with scaling the Z-axis of the Dog Lake effigy .kmz model. Essentially, the .kmz file is not "clamped to the ground" and floats in space in the software. Therefore, while Google Earth can be used as a geospatial viewing tool, the model has an indeterminant accuracy as it is not directly tied to cartesian space.

The most significant analytic outputs derived from the UAV data are the 3D model and DEMs. The 3D model allows the user to manipulate the view of the effigy to begin understanding the feature's overall shape, perhaps better than can be achieved in the field. The DEMs clearly delimit the effigy's shape (Figure 4-17), and since the feature was previously mapped using ground survey methods, the UAV output can be directly compared to cartographic materials collected nearly 50 years ago.

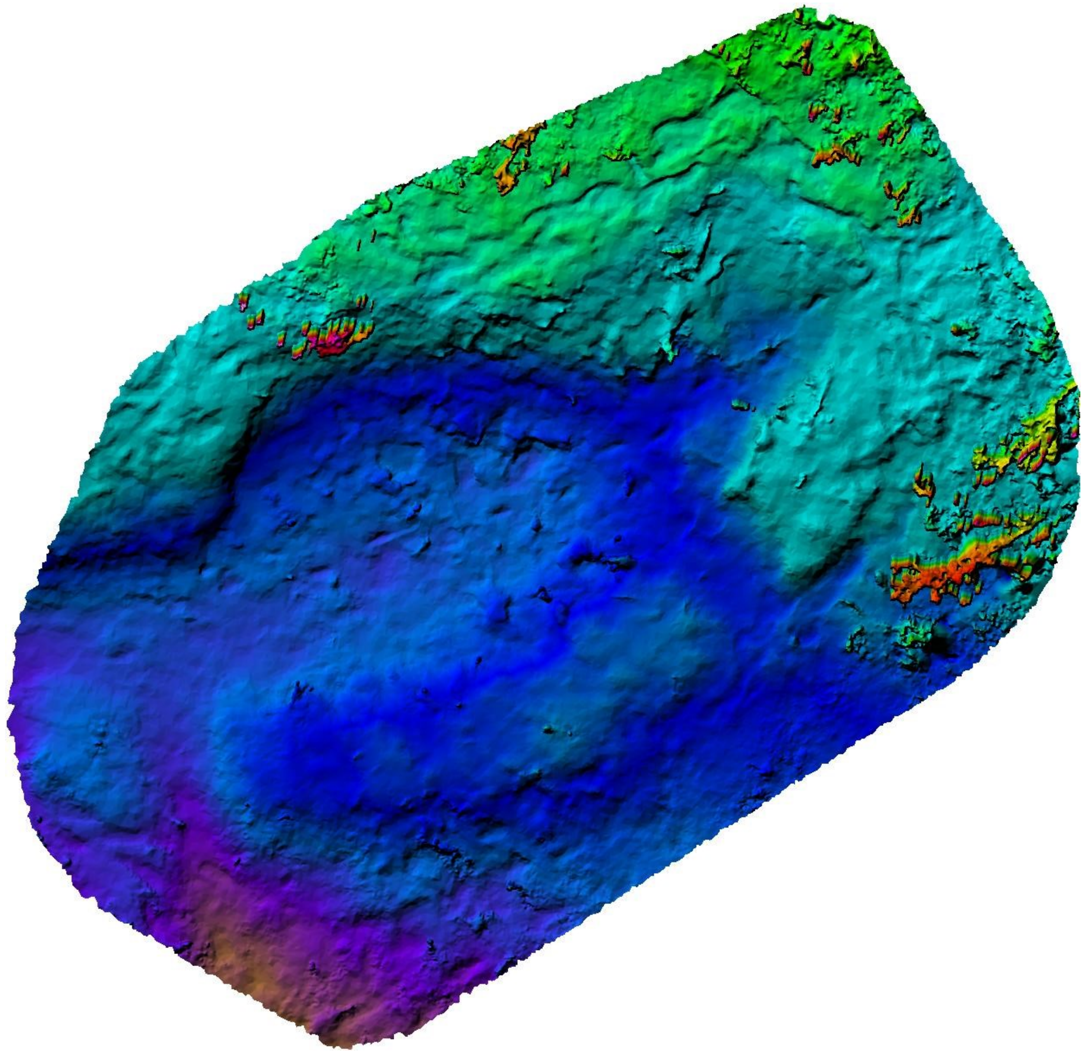


Figure 4-17 Raster DEM of the Dog Lake Effigy

Dawson's investigation of the site resulted in a sketch map with relief represented at a 6-inch contour interval (Figure 4-18). The UAV-derived raster and vector DEMs can then be used to compare accuracy and efficiency in both surveys. Using the contour tool in ArcGIS, contours at 10 cm intervals were created using the vector DEM. The contours, raster DEM, and Dawson's survey were then composited together to compare (Figure 4-19). The 2015 UAV data and the 1965 manually surveyed data do not correlate well, though neither dataset can be assumed to represent an absolute reality, and both provide similar general relief trends. While the contours are generally similar, the shape of the effigy presented does not match. This is not and should not discredit Dawson's original survey –having been to the effigy on multiple occasions, Stephenson acknowledges the difficulty in interpreting the feature's shape *in situ*— but the shape discrepancy illustrates the subjective nature sometimes presented when surveying in the field. Surveys can often be directed by personnel's subjective interpretation of the site. Instead, through the SfM UAV survey, objective data can be collected and interpretations from this data can be made after the fact.

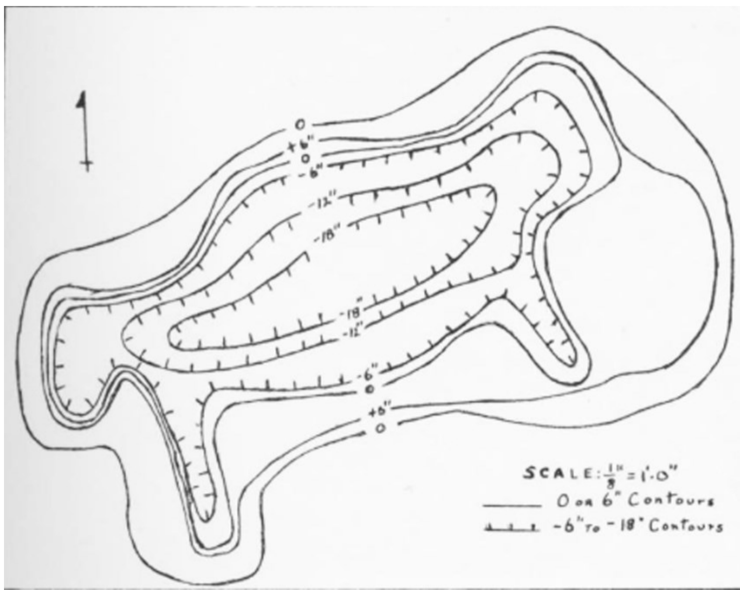


Figure 4-18 Dawson's isocline survey of the Dog Lake Effigy (Dawson, 1965)

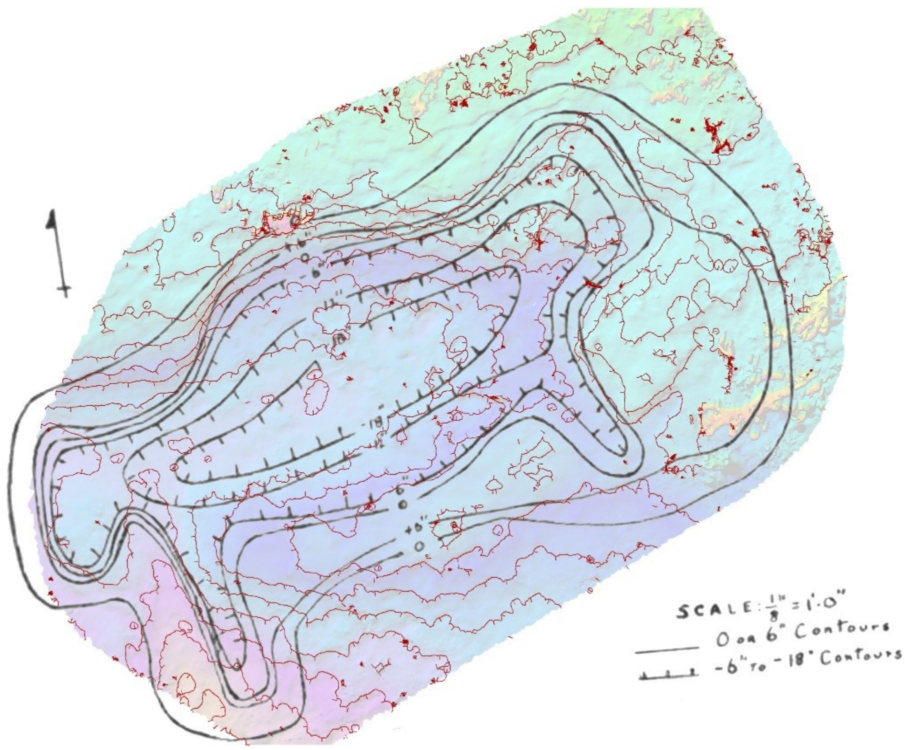


Figure 4-19 Contour composite of the 1965 and 2015 surveys

The most noticeable shape discrepancies are the effigy's legs. Where the 1965 survey depicts the legs as relatively straight, the DEMs and 3D model show their mild curvature towards each other. The 1965 survey also included an aerial photograph that shows the effigy's shape more accurately (Figure 4-20). This is perhaps the only time aerial photography was employed specifically for archaeological application in northwestern Ontario's boreal forest.

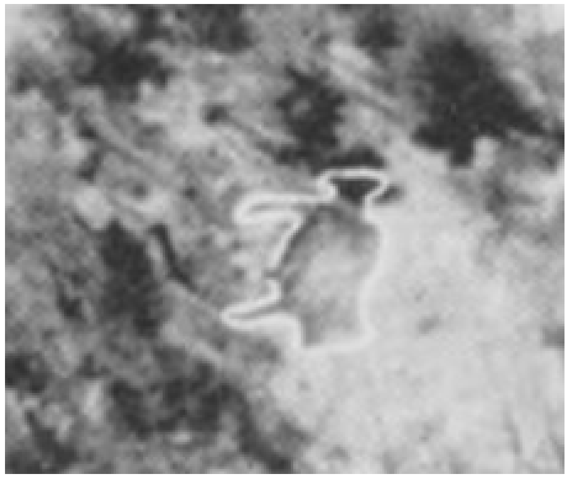


Figure 4-20 Dog Lake Effigy outlined in flour during previous historic aerial survey

The most interesting analytic output from the UAV-based DEM is the appearance of a "tail" on the eastern end of the effigy. The tail was not recorded during Dawson's survey nor was it apparent during the 2015 field inspection. However, the presence of a tail supports one of the hypotheses surrounding the effigy's cultural affiliation. Keating (1959) and local Ojibwe (Dawson, 1965) state the effigy was created by a Sioux war party during a conflict between the Sioux and Ojibwe near Dog Lake. At the conclusion of the skirmish, the Ojibwe vandalized the effigy by digging a second head, thus destroying its supernatural powers.

Landscape Considerations

During the previous case study, the surrounding landscape's context was not strongly considered as the Boulevard Rock Ring's affiliation and function are unknown. Therefore, the context is ambiguous and cannot be confirmed by UAV survey without other field investigation methods. Dog Lake Effigy, however, is a defined, registered archaeological site that has been excavated and documented by numerous accounts. Thus, it was decided to employ a UAV to capture oblique photographs of the effigy and surrounding landscape to supplement the effigy's narrative.

The effigy is strategically positioned at the crest of Dog Mountain along a portage route between Little Dog Lake and Great Dog Lake (now known as Dog Lake) (Figure 4-21). The portage along the Kam-Dog-Maligne Canoe Route (or Kaministiqua Route) was originally used by the Ojibwe before European contact (Dawson, 1965), and was later used by fur traders beginning in 1688, and after 1803 when the USA began to exercise its right to tariff goods transported through USA territory via Grand Portage (Morse, 1969 pp. 80-82). The Great Dog Portage was one of the steepest portages along this canoe route (Brown, n.d.). Figure 4-22 was created using the open-license Ontario Provincial Digital Elevation Model (PDEM) to illustrate the steep incline along the portage. Morse (1969) believes the route is too steep for any voyageur and they would have likely taken another route slightly east to reach Dog Lake, and would take the Great Dog Portage when travelling south. Morse does not provide an explicit rationale for the alternative routes. As part of this case study, a viewshed analysis was performed using the PDEM to attempt to ascertain why this portage was chosen. The UAV data was used to accurately pinpoint the effigy's location to select the point in which the viewshed was conducted (Figure 4-23). From the effigy at the crest of Dog Mountain, the entirety of Little Dog Lake can be seen, including the portage trailhead and much of the portage route[9]. This is exemplified by Figure 4-24 taken with the UAV, albeit at an approximately 20 m elevation off the ground.

[9] Assuming minimal or sparse tree coverage.

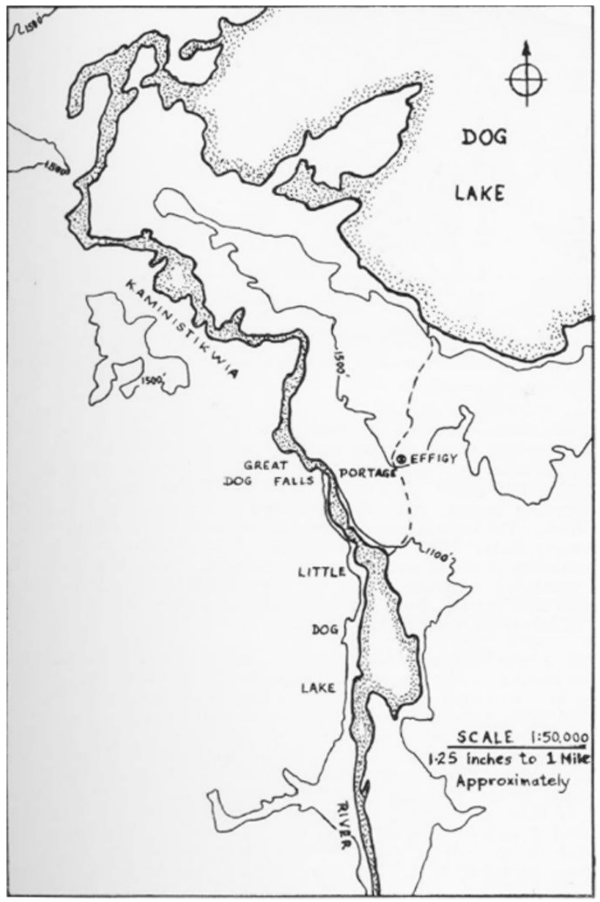


Figure 4-21 Approximate Dog Mountain portage route (Dawson, 1965)

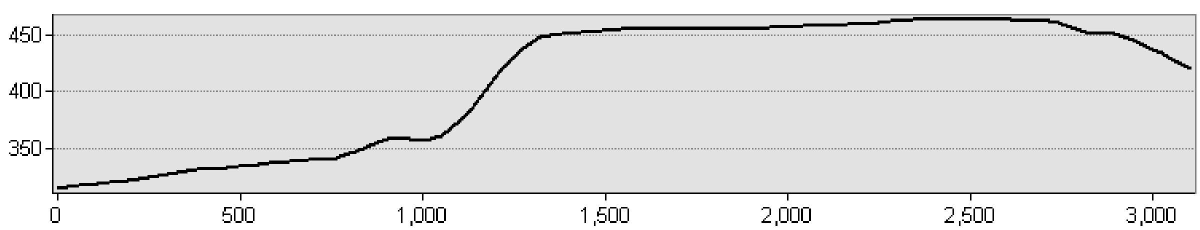


Figure 4-22 Elevation profile of the portage route

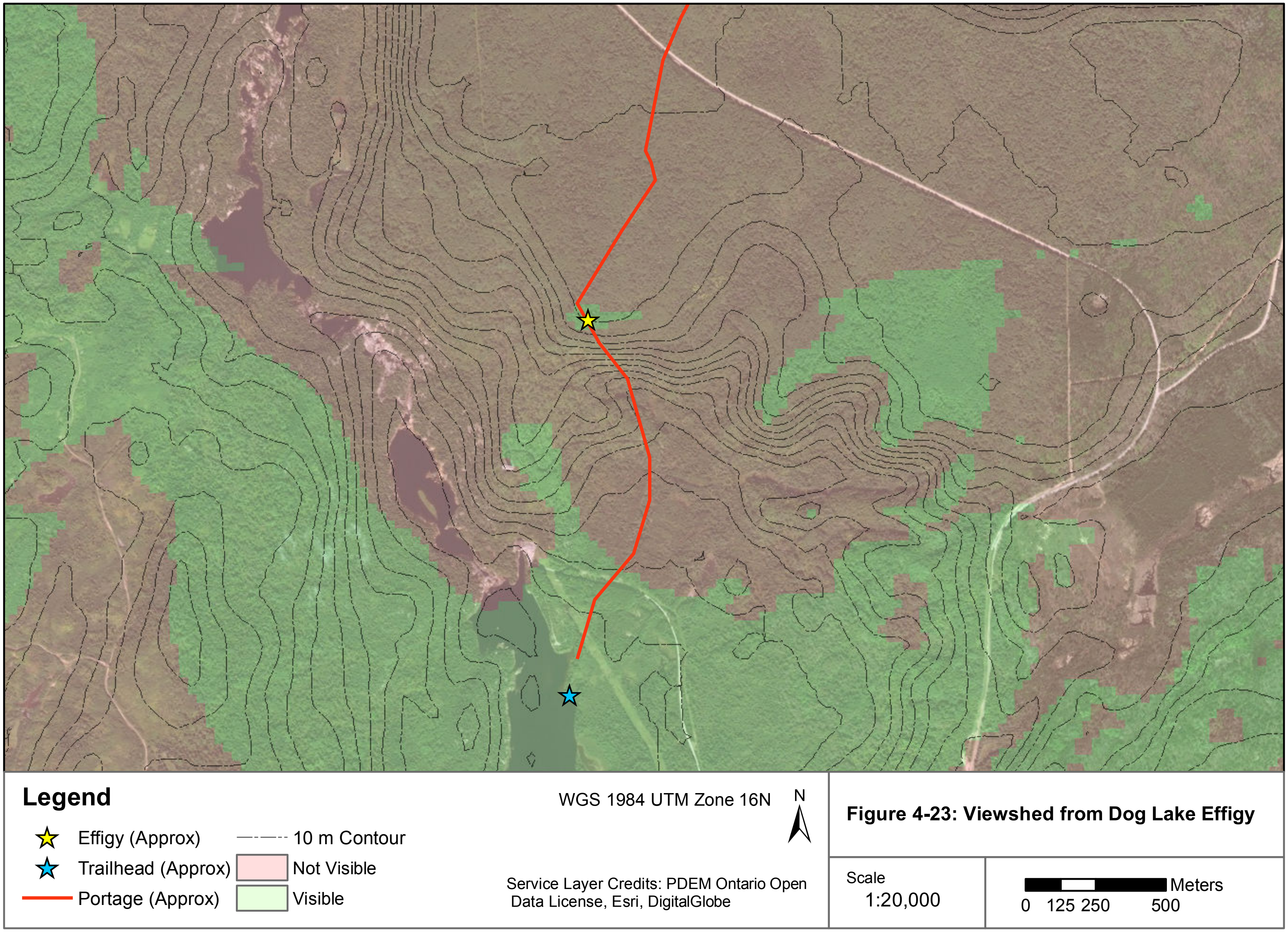
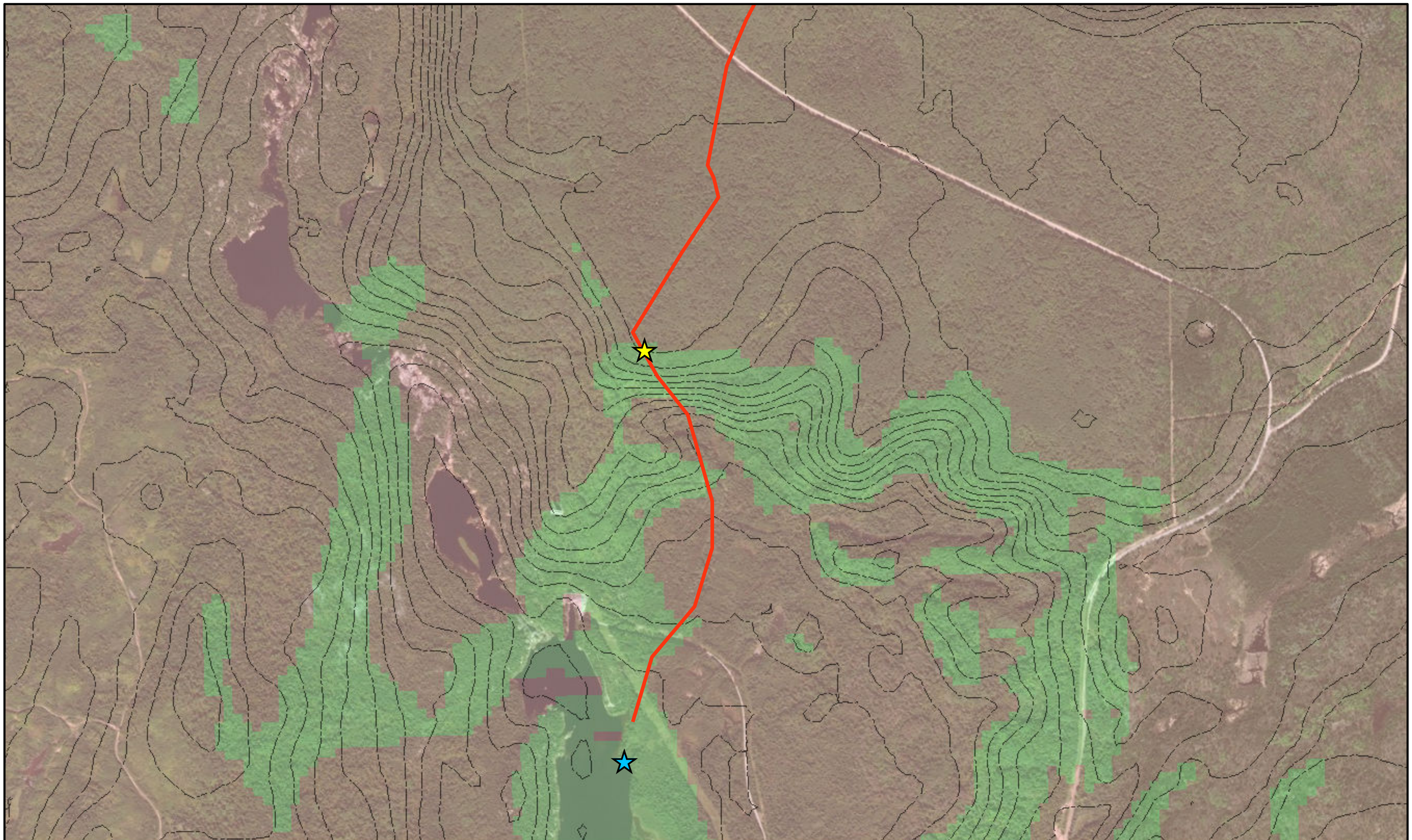


Figure 4-23: Viewshed from Dog Lake Effigy

Figure 4-24 View of the Kaministiqua River valley with the Dog Lake Effigy in the foreground



Legend

Effigy (Approx)
Trailhead (Approx)
Portage (Approx)
10 m Contour
Not Visible
Visible

WGS 1984 UTM Zone 16N

N

Service Layer Credits: PDEM Ontario Open Data License, Esri, DigitalGlobe

Figure 4-25: Viewshed from portage trailhead

Scale 1:20,000

0 125 250 500 Meters

A second viewshed analysis was completed which reversed the observer point to the portage trailhead instead of the effigy. As illustrated in Figure 4-25, much of the portage route leading up to the Dog Mountain crest (where the effigy is located) is visible, whereas Morse's proposed eastern portage is largely obstructed. This may be a factor in the previous determination of both the effigy and portage's placement, although this will likely never be confirmed.

Although this viewshed exercise is largely based on publicly available elevation data as opposed to UAV-derived data, the UAV aided in the visualization and contextualization of the otherwise planimetric viewsheds. The question as to the effigy's placement was posed during the field survey, and the viewshed analysis was completed years later. Without the oblique aerial photographs taken by the UAV, it may have been more difficult to show the effigy's placement in relation to the portage by viewshed alone.

4.3.5 Summary

This case study demonstrates the UAV's efficiency in collecting small high-resolution datasets. The UAV was flown in a GPS-deprived environment but was still capable of producing high-resolution data products with high relative accuracy. It also showcases the value of 3D data by sufficiently illustrating the effigy while true-colour photographs have difficulty representing it. The accuracy and objectivity of UAV-based interpretation is also demonstrated, while offering a direct comparison to a previous survey of the feature completed by conventional, land-based methods. Further, preliminary attempts at using the UAV to ascertain the context surrounding the feature was explored to aid in the visualization of the landscape.

4.4 HOKANSON

4.4.1 Introduction

Hokanson Site (DiLv-29) is a Late Pre-contact bison kill and processing site in the Tiger Hills in southern Manitoba. Bison kill sites are not commonplace in Ontario; however, this archaeological site is rich in data to be used as a comparative dataset. This previously collected data can be used to contrast UAV-based information against other methods of spatial data extraction to evaluate the UAV's efficacy.

The site was initially reported to Hamilton in 2000, and excavations occurred across the site from 2000 to 2002 (Norris & Hamilton, 2004). The site is interpreted as having two activity areas: a bison kill zone along the edge of an internally draining "slough" wetland (Area A), and a processing/camp zone in a forested area south of the wetland (Area B) (Norris & Hamilton, 2004). It has been theorized that bison would be driven from the northeast over a low ridge, and then downslope into a pound within the wetland where they were killed and processed. The topographical changes between the ridge and Area A are not dramatic—with an incline of approximately 10 degrees—but it is hypothesized that the bison were unable to see the pound in the lowlands until they were at the crest of the ridge (Dechaine et al*.,* 2002; Norris & Hamilton, 2004; Hamilton et al*.,* 2007; Playford, 2015). This was further explored by using differential GPS (dGPS) and optical survey to create isoclines at 25 cm contour levels. The dGPS elevation data was then used to create a DEM (Figure 4-26) of the site along with an exaggerated wireframe (Figure 4-27) model as an early attempt at 3D computer visioning. This allowed for rudimentary visualization of a 'bison-eye view' of the ridge and kill zone. However, computer visioning at the time was not at a resolution to successfully illustrate a bison's viewshed during a kill event. Another method to visualize the 'bison-eye view' was proposed by Hamilton by using a still camera to represent the proposed viewshed from various locations approaching the kill zone (Hamilton, per comm).

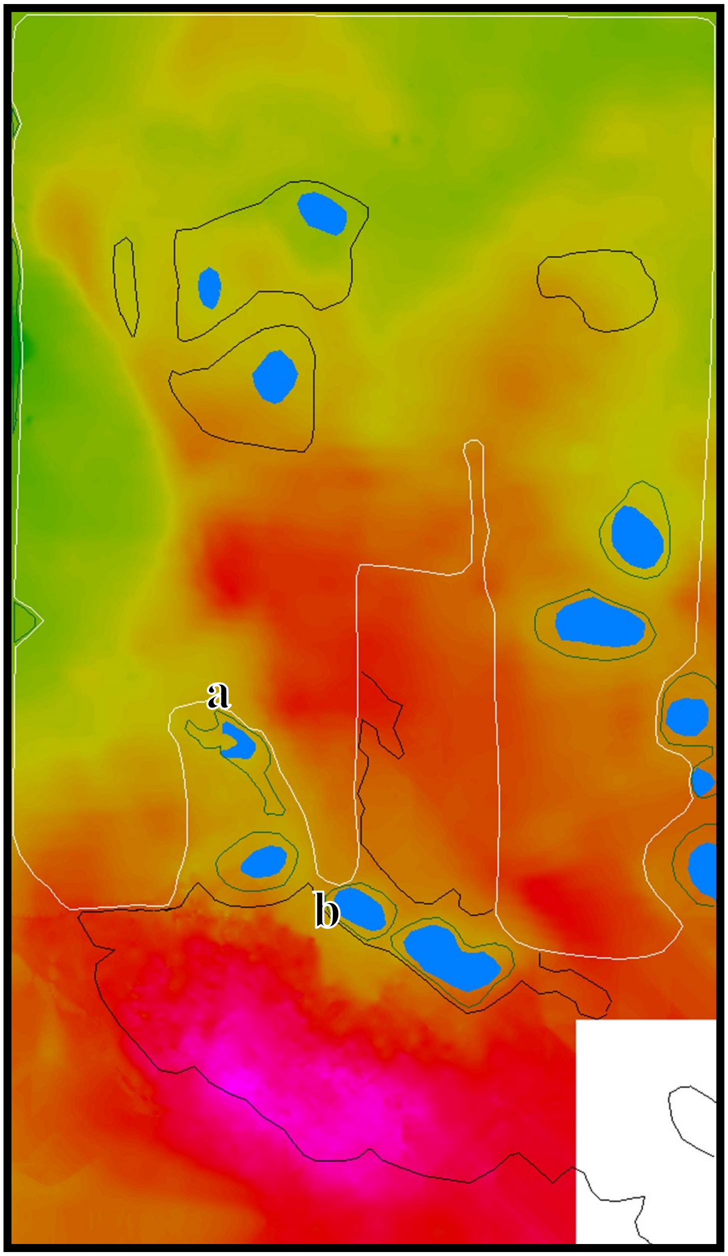


Figure 4-26 Digital relief map created by Hamilton from dGPS elevation data in 2000-2001

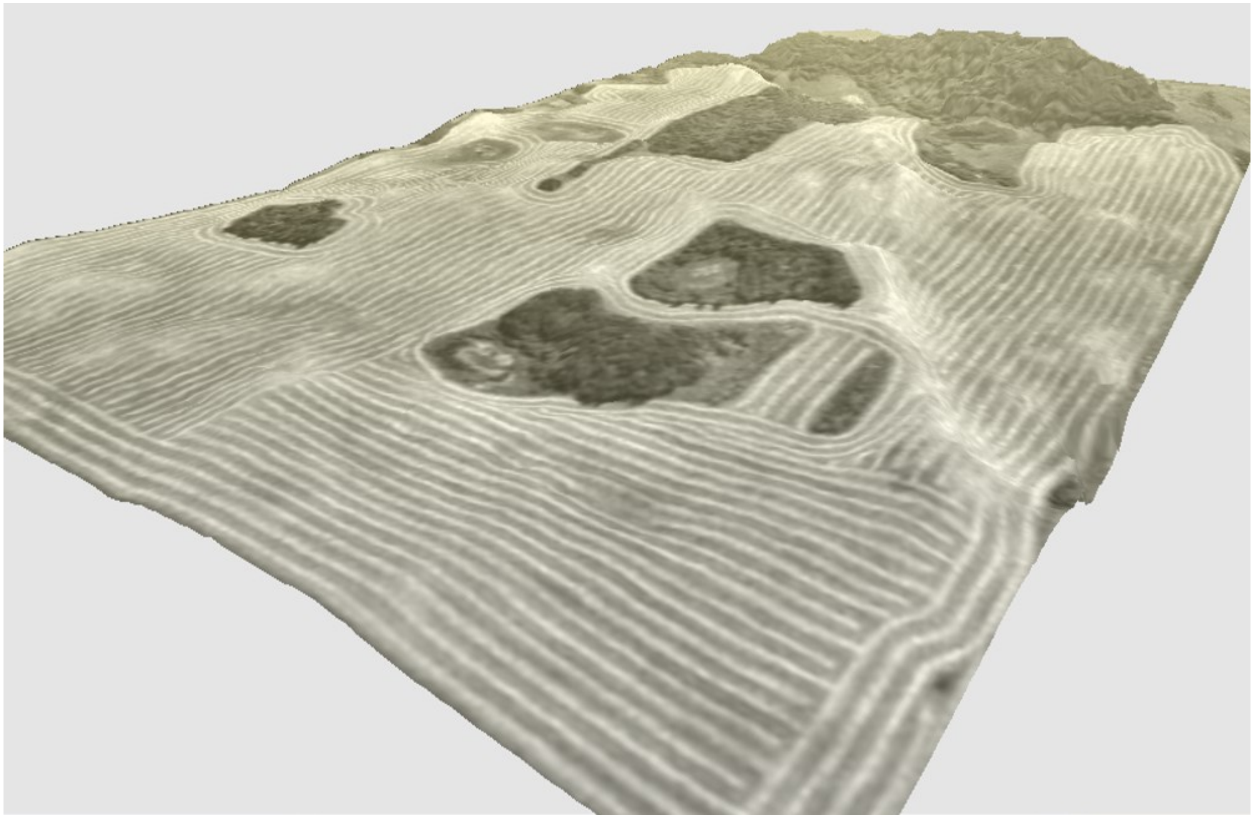


Figure 4-27 Digital model of Hokanson created by Hamilton in 2000-2001 by overlaying an orthophoto over an exaggerated wireframe

Manitoba's publicly available LiDAR data further adds to the rich information surrounding this archaeological site. The raster DEM for the Souris Watershed was released in 2015, having been derived from LiDAR data collected over three days. The DEM was interpolated from the data at 1 m absolute horizontal Cartesian accuracy with data resolution of 1 m^2. This provides an opportunity to compare UAV-based data over larger AOIs against high-accuracy, LiDAR-acquired elevation information.

Three UAV flights were completed for the Hokanson Site: the first was a quick overview completed June 2016 to capture a few oblique photographs of the site; the second was conducted in September 2016 after harvest; and the third was completed in April 2017 before the agricultural field was planted. The timing for the latter two flights allowed for photography of the field's bare-surface, avoiding elevation and processing complications that arise once crops begin to grow. While the Phantom 3 was completing its third mission, another Phantom 3 loaned by Kevin Brownlee (Manitoba Museum) was flown in order to visualize a 'bison-eye view' of the site.

4.4.2 Results

The first flight in June 2016 sought to only capture oblique photographs of the landscape. Little to no metric output can be extrapolated from the oblique photo, but like the Dog Lake Effigy oblique photo, the image provides context and offers another perspective to help articulate the site. Figure 4-28 shows the site, with Area A being the approximate kill zone and Area B being the processing/camp zone. The photo also illustrates how little of the topographic relief is visible in planimetric and oblique aerial photographs, as the ridge in the centre of the photo is barely discernable. This subtle relief was effectively utilized for bison hunting in the Late Pre-Contact Period.

Figure 4-28 Oblique photo of Hokanson

The second flight was composed of three separate flight plans with varying transect bearings for each plan. The mission captured a total of 182 images and a usable dataset was produced by Maps Made Easy in only a few hours. The imagery fits well within its geospatial position despite not using GCPs during processing, and the resolution is markedly better than the satellite imagery readily available in Google Earth or ArcGIS for the area (Figure 4-29). However, the image overlap report created by Maps Made Easy shows less-than optimal photo coverage for the AOI (Figure 4-30). This was caused by the sparse transect spacing and photo overlap. While not necessarily crippling for effective data analysis, the lack in overlap may introduce gaps in the data or cause incorrect elevation interpolation. Thus, Hamilton and

Stephenson sought to revisit the site with a flight mission that ensured sufficient overlap to compare the effects of this undesirable overlap report.

Figure 4-29 Resolution comparison between UAV orthophoto and satellite imagery available on Google Earth (1:60 scale)

The third flight was composed of one flight plan with a tighter photo overlap. The resulting data products were made from 384 photos covering a slightly larger AOI. The overlap report shows more than sufficient overlap as compared to the second flight (Figure 4-31). Metadata from the latter two flights is presented in Table 4-8 in Section 4.4.3.

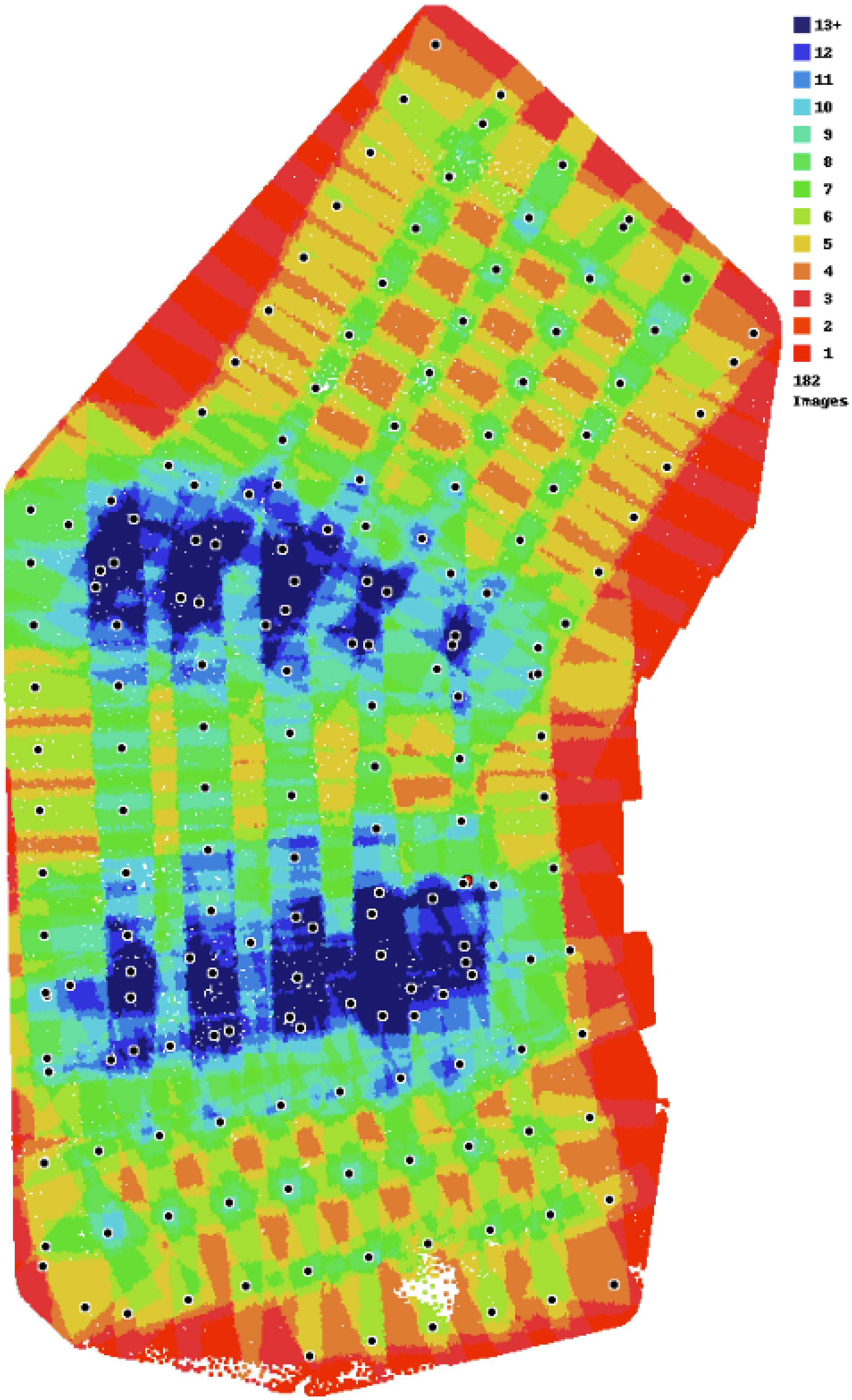


Figure 4-30 Subpar aerial image overlap report from Flight 2

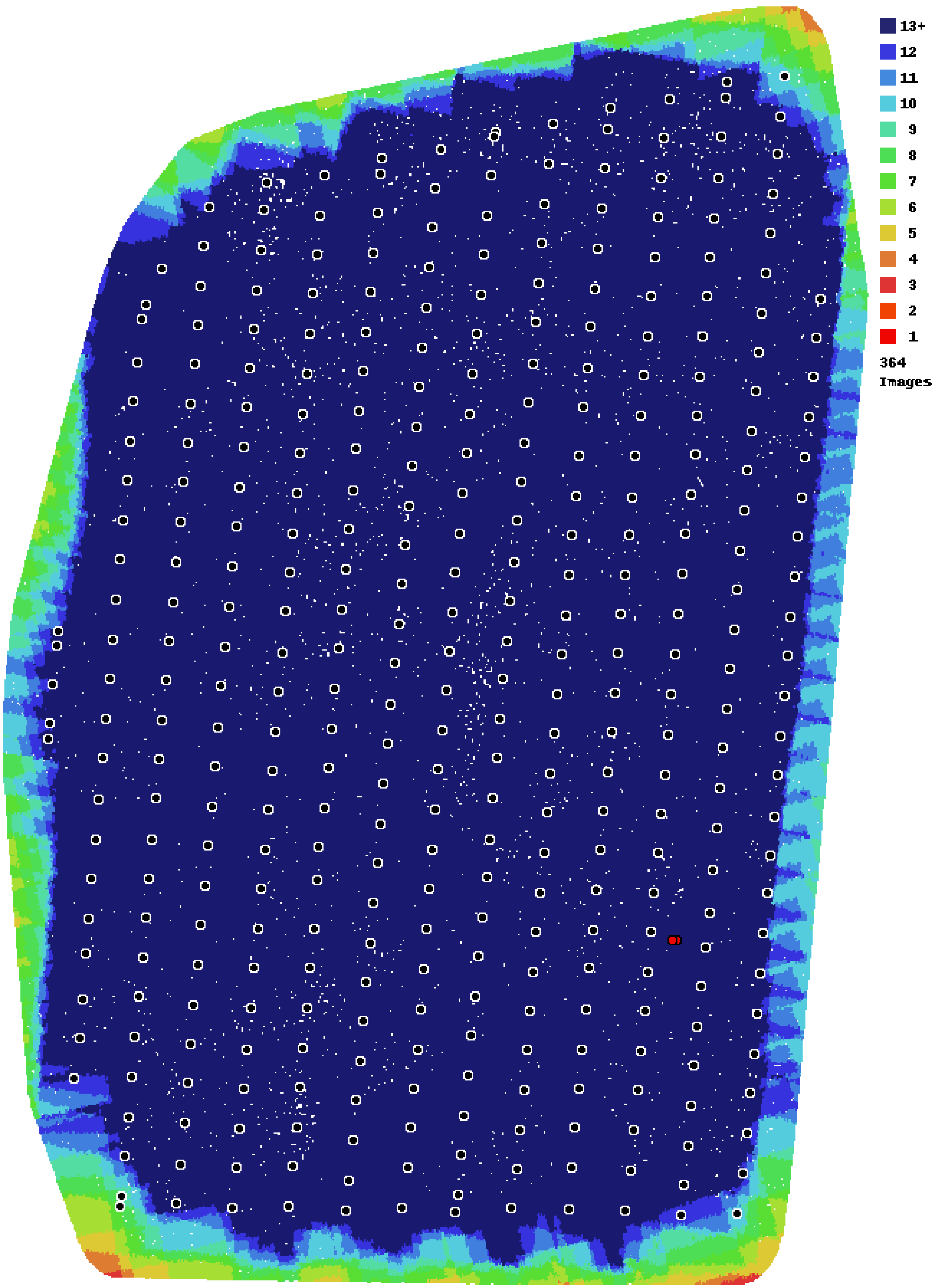


Figure 4-31 Improved aerial image overlap report from Flight 3

4.4.3 Metadata

Table 4-8 Metadata of the Hokanson flights

Flight 2	Values
Flight Speed	2 m/s
Altitude	40 m
Area	8.45 ha
Overlap	60%
Sidelap	60%
Images	182
Duration	41 min
Batteries	3
Storage	1.02 GB
Resolution	1.7 cm/px
Filter	No
EV Comp	No

Flight 3	Values
Flight Speed	2 m/s
Altitude	60 m
Area	10.41 ha
Overlap	80%
Sidelap	80%
Images	364
Duration	59min 58s
Batteries	3
Storage	1.96 GB
Resolution	2.6 cm/px
Filter	Polarizing
EV Comp	No

4.4.4 Analysis

After Flight 3 was completed, the two datasets were compared to determine whether the sparse images in Flight 2 negatively affected the relative and Z-axis precision of the orthophoto and DEM. The dataset from Flight 2 appears highly accurate and comparable to Flight 3 despite the undesirable overlap report created by Maps Made Easy. Both flights' orthophotos show the wetland/slough in the field where the kill zone is located and provide a high-resolution basemap for annotation and description of the archaeological site (Figure 4-32). Annotation can also be achieved with either of the 3D models that were produced during Flights 2 and 3, although the topography is so subtle that it may be difficult to effectively illustrate (Figure 4-33). Instead, the DEM products may offer the most analytic value out of the data suite.

Figure 4-32: Orthophotos from the Hokanson Site

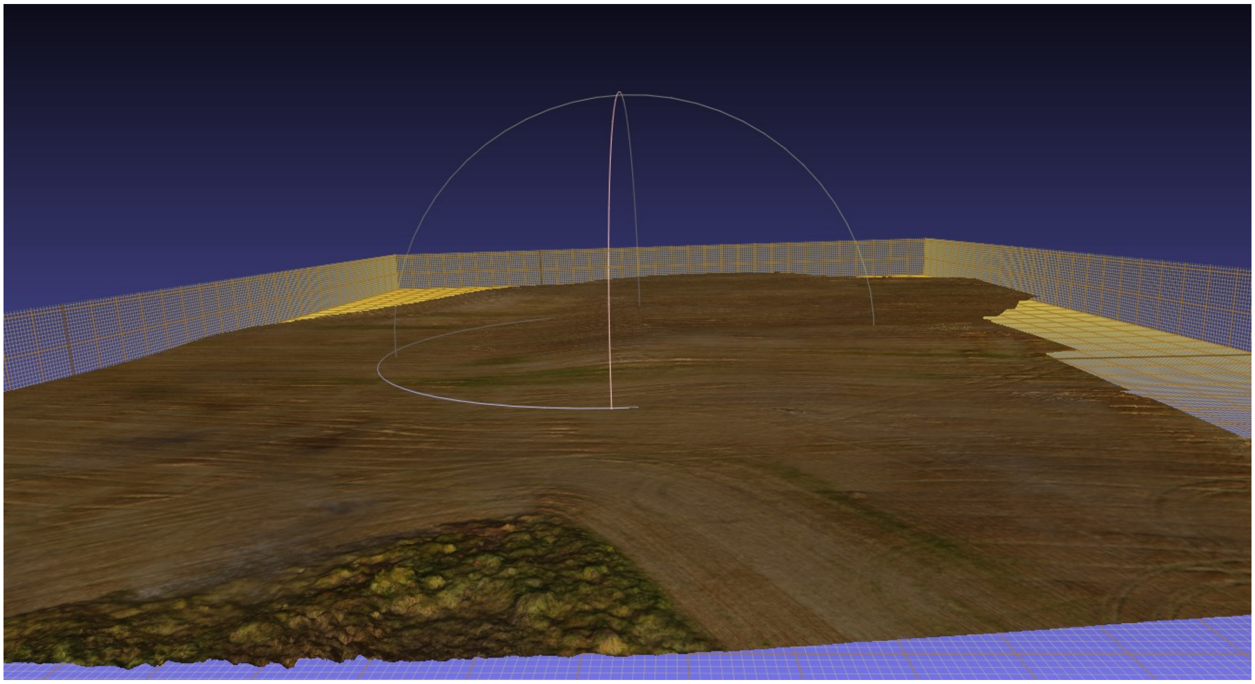
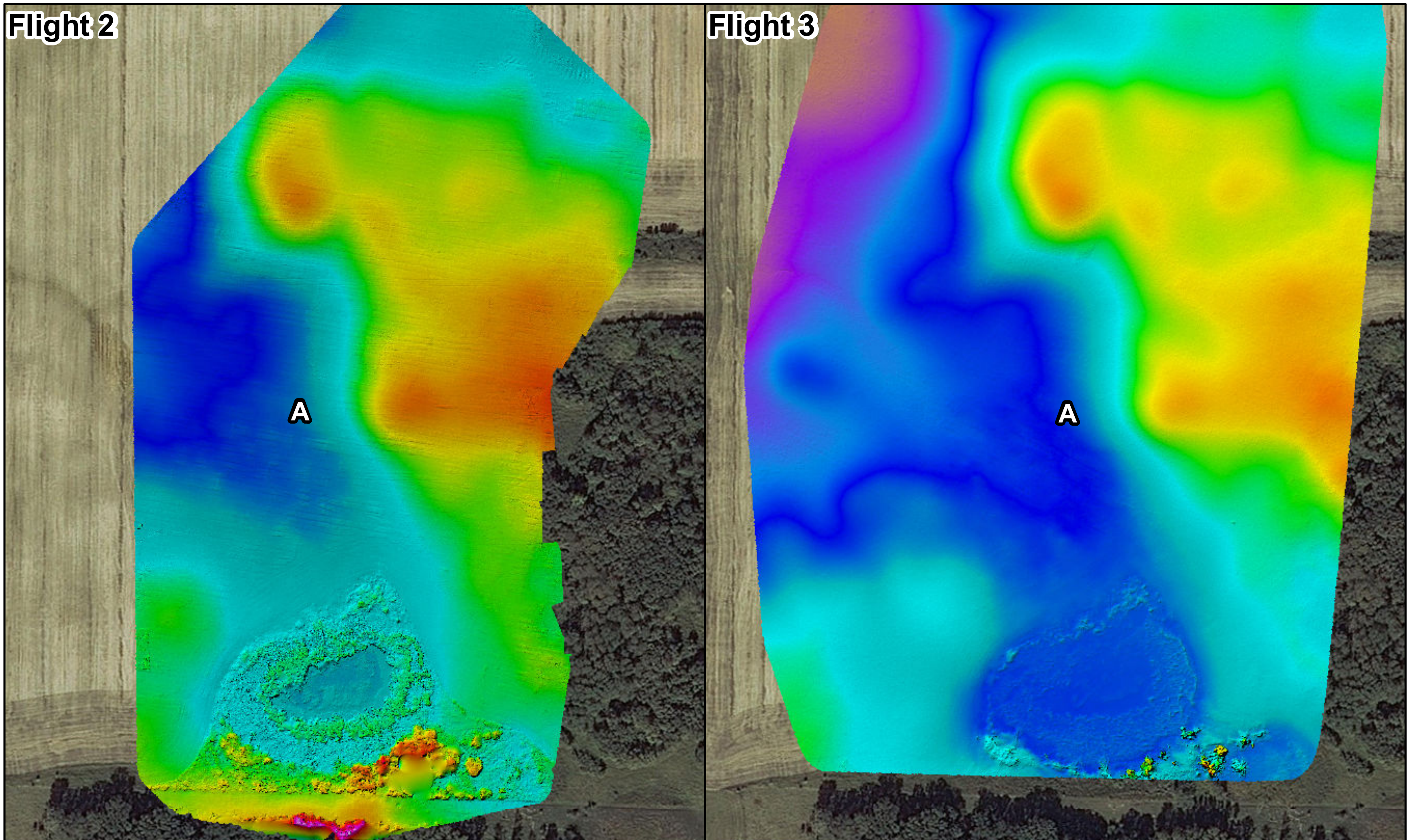


Figure 4-33 3D model showing subtle topographic relief across the Hokanson AOI

The raster DEM provides an initial and simple visualization of the site's topography, displaying its indistinct geographical relief. Interestingly, Flight 2 most effectively illustrates the subtle relief changes of the site in comparison to Flight 3 (Figure 4-34). This is simply a product of the smaller project footprint captured by Flight 2, which excludes relief changes outside of the AOI that may skew the DEM's elevation range. However, both rasters effectively display the high ridge to the northeast of the kill zone with the low, slough area shown southwest of the base of the slope where bison remains were found during excavation.



Legend

Value

High : 8.5

Low : 0.0

WGS 1984 UTM 14 U

N

Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User

Figure 4-34: Raster DEMs

Scale 1:3,000

0 15 30 60 Metres

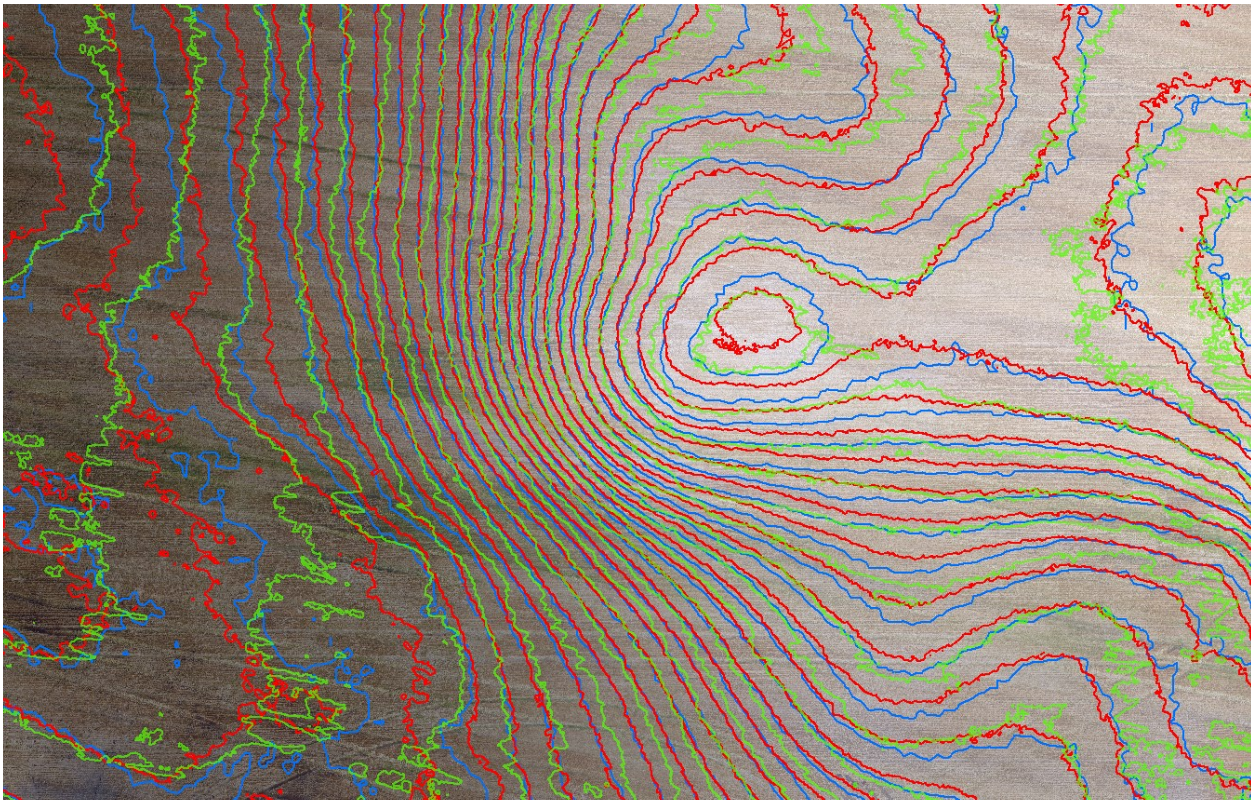


Figure 4-35 Contours at 25 cm intervals derived from Flight 2 DEM (green), Flight 3 DEM (red), and public LiDAR data (blue)

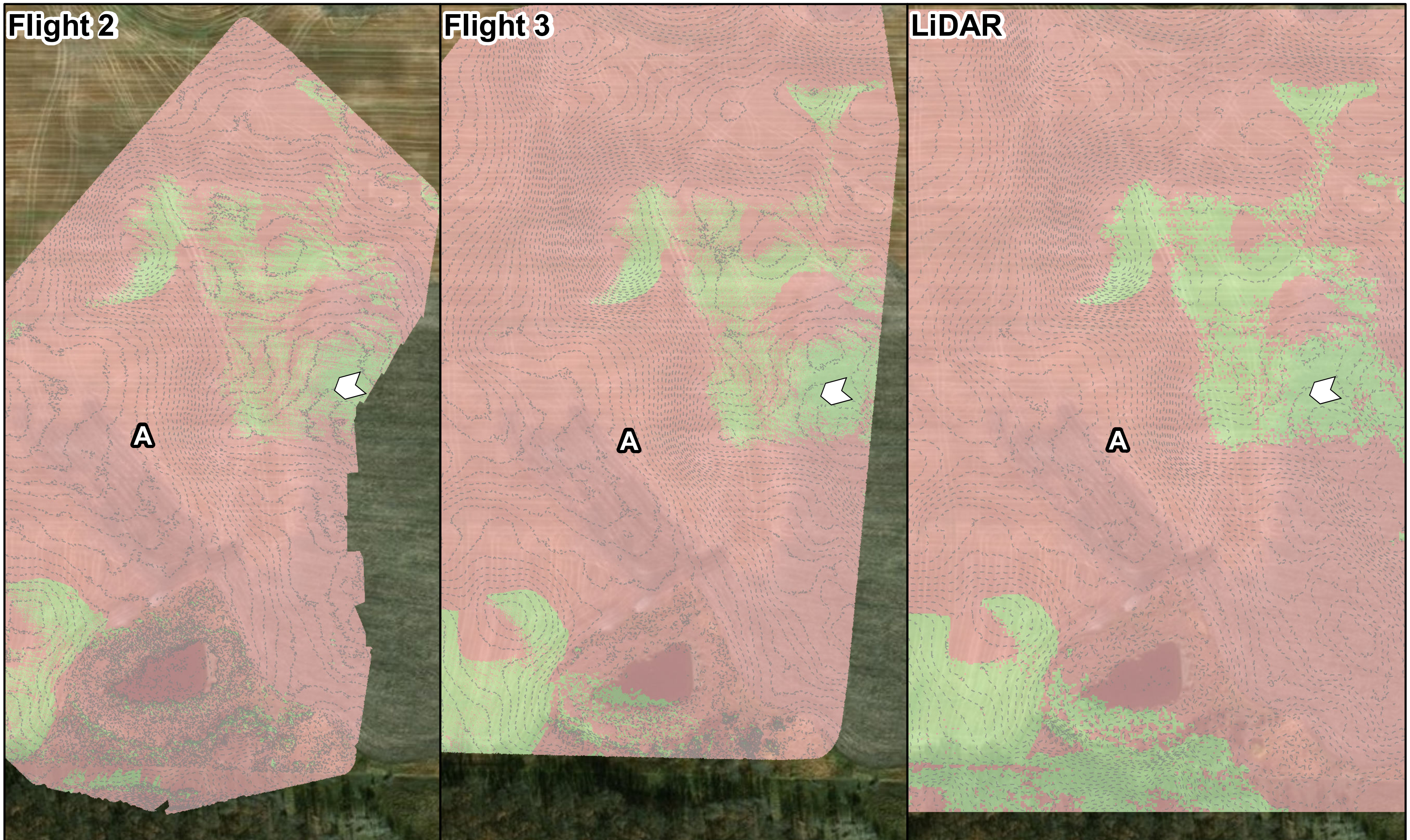
The vector DEM allowed for further site analysis. Contours were created in ArcMap at varying intervals using the vector DEMs from Flight 2 and Flight 3. LiDAR elevation data of the Souris River Watershed was then imported into ArcMap to compare the accuracy of the UAV-based elevation data. The ArcMap contour tool was applied to all three datasets at 25 cm intervals (Figure 4-35). Slight unconformities are to be expected using the contour tool and is largely a product of differing elevation values attributed to each dataset. The LiDAR data is measured in elevation above sea level (ASL) whereas the UAV-derived DEMs only measure elevation relative to the UAV's elevation upon takeoff. For example, the LiDAR elevation range of the AOI is 463.8 to 477.16 m ASL whereas Flight 2 and 3's elevation ranges are 5.2 to 15.0 m and 0.8 to 8.2 m above takeoff elevation, respectively. Further, the UAV's takeoff benchmarks differ between each flight, with Flight 2 taking off at an elevation lower than the AOI, and Flight

3 taking off within the AOI and therefore at the AOI's base elevation. Varying conditions also affect the isoclines: Flight 2 was completed after recent cultivations, causing the ploughed furrows to be more pronounced; and Flight 3, was flown before cultivation so the ground had been weathered over the winter, softening the furrows.

The variations in the contour positions as seen in Figure 4-35 do not devalue the elevation data collected by the UAV. These variations are largely a result of differing elevation benchmarks and soil conditions at the time of data capture. Flight 2's contours are the most divergent of the isoclines given the elevation benchmark below that of the AOI and the pronounced furrows across the site. However, each dataset still produced reasonably similar contours. As the elevation benchmark varies in each flight (i.e. based on the two launch points as opposed to measuring in ASL) there are little means to measure absolute accuracy in the model's Z-axis, but the relative accuracy of all three data sets is remarkably high and all models consistently represent the topography of the site. It is also important to note that the high relative accuracy of the UAV models is more useful than a high absolute accuracy, since the site's position ASL is seldom recorded in conventional archaeological surveys. Further, these results were produced in a timely manner that is exponentially quicker than conventional survey with a transit or dGPS, and conveys similar elevation information to supplement archaeological analysis. The contours provide a visual illustration of Hokanson's topography to support the communal bison hunting hypothesis.

Viewshed analysis further supplements the site's narrative. Using both DEMs and the LiDAR data, the viewshed tool was run in ArcGIS using its default parameters (i.e. 1 m elevation) to emulate a bison's view when approaching the ridge towards the pound situated below (Area A). The tool was run from two points east of the ridge and one point north of the ridge (Figure 4-36, Figure 4-37, Figure 4-38). The results are generally homogeneous across all three datasets and all three points. Area A is completely obscured by the subtle ridge in all scenarios (Figure 4-36, Figure 4-37, Figure 4-38), demonstrating how the landscape can be an effective tool for communal bison hunting in Manitoba. The results also prove the UAV to be an effective tool for landscape recording that produces elevation data similar to that collected by more expensive LiDAR units.

Figure 4-36: Hokanson Viewshed (Point 1)



Legend

Viewshed Point & Direction

Not Visible

Visible

Contour (25cm Interval)

WGS 1984 UTM 14 U

N

Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User

Figure 4-37: Hokanson Viewshed (Point 2)

Scale 1:3,500

0 20 40 80 Metres

Figure 4-38: Hokanson Viewshed (Point 3)

4.4.5 Summary

The Hokanson case study illustrates that the precision of the Z-axis interpolated by SfM software from data captured by UAVs is acceptable for archaeological purposes. This is supported by the minimal variance of the elevation data collected by the UAV in comparison to the highly accurate LiDAR-based data. It also demonstrates the value of the variety of UAV-derived data products, offering multiple types of visual information to supplement the site's analysis and to support the bison kill site hypothesis. The case study also strengthens and reaffirms the importance of recording and accounting for landscapes surrounding archaeological sites as it is often a determining factor in where a site is situated.

4.5 P1 (AlGs-486)

4.5.1 Introduction

P1 (AlGs-486) is a Late Woodland period archaeological site located in southern Ontario. The site is of unknown function but has yielded early-Late Woodland ceramics attributed to Pickering and Glen Meyer pottery wares and contains diverse archaeological features and lithic debitage. The site was undergoing full excavation within an Ontario consulting framework in 2018, allowing for the methods described throughout this paper to be synthesized to evaluate UAV-based aerial photography applications in a setting which consultant archaeologists often encounter.

The site was discovered by WSP[10] in 2017 through prospecting-type test pit survey on the periphery of an agricultural field. Within a 250 m radius, a cluster of four Woodland Period

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[10] WSP is a global professional services firm with archaeology teams across North America, South America, and Europe.

archaeological sites were found during the 2017 survey. Winnifred (AlGs-103), another registered site, is located in an adjacent field approximately 250 m away from this cluster (Spittal, 1978; Ambrose, 1981). Although Winnifred's original site report seems to have been misplaced, the site record on the MTCS's online database indicates the site is a village attributed to the Pickering techno tradition. Given their proximity to each other, it can be inferred that all five archaeological sites are closely related.

UAV survey took place in November 2018. P1's topsoil was stripped using a mechanical excavator to expose a series of archaeological features indicated by a sharply contrasting change in sediment coloration. As the rapid drop in temperature threatened freezing sediments and subsequent shut down of the excavation, a rapid but accurate survey map was crucial. The objectives of the planned UAV flights were twofold: the first objective was to produce a high resolution orthophoto floorplan of the exposed features; the second was to produce high-resolution imagery of the entire area that encapsulates the five sites.

The Phantom 3 that was used for all the other case studies was not available during the excavations. Instead, a DJI Spark (approximately $700) was used for the survey. Map Pilot and other similar flight planning software does not support the Spark, so the UAV required a manual flight that emulated consistent transects.

4.5.2 Results

Weather and lighting conditions were poor on the day of the scheduled flight. The temperature was -10°C and gusts of wind were between 30-40 km/h which severely affected the UAV's hardware. In addition, there was very little cloud cover to soften the light from the low sun that cast tall shadows across the site, and snow accumulation had partially covered the ground. Further, as the temperature had been steadily declining over the past month, preventative measures were taken to ensure the exposed archaeological features would not freeze. Specifically, loose straw was placed over each feature and covered with insulated tarps when not under excavation. Upon removal of the tarps and most of the straw, features were still left partially obscured.

Despite the poor conditions, a flight was still attempted. The wind posed a considerable challenge for the Spark which weighs 300 grams. While it somewhat maintained a straight flight path, the UAV flew on a tilt, and was severely affected by strong gusts of wind, making continuous flight transects impossible. Further, the UAV's elevation was kept at around 3 m above the ground to prevent any gusts from blowing the UAV into the nearby hydroelectric power lines. The flight conditions during this attempted survey illustrate a worst-case-scenario where a UAV flight becomes suboptimal and high-risk. Metadata from the flight is presented in Table 4-9 in Section 4.5.3.

Only a small number of photos were captured by the UAV that offer analytic output as few of the archaeological features were adequately uncovered (Figure 4-39). Overall, the wind inhibited the UAV from maintaining consistent flight transects, and strong gusts caused many of the photos to be blurry (Figure 4-40). Further, the photo overlap was not sufficient for image-based modelling. Other photos simply contained too much straw that obscured any features that would otherwise be visible. As the first flight was proving ineffective, the second objective of photographing the surrounding area was not initiated.

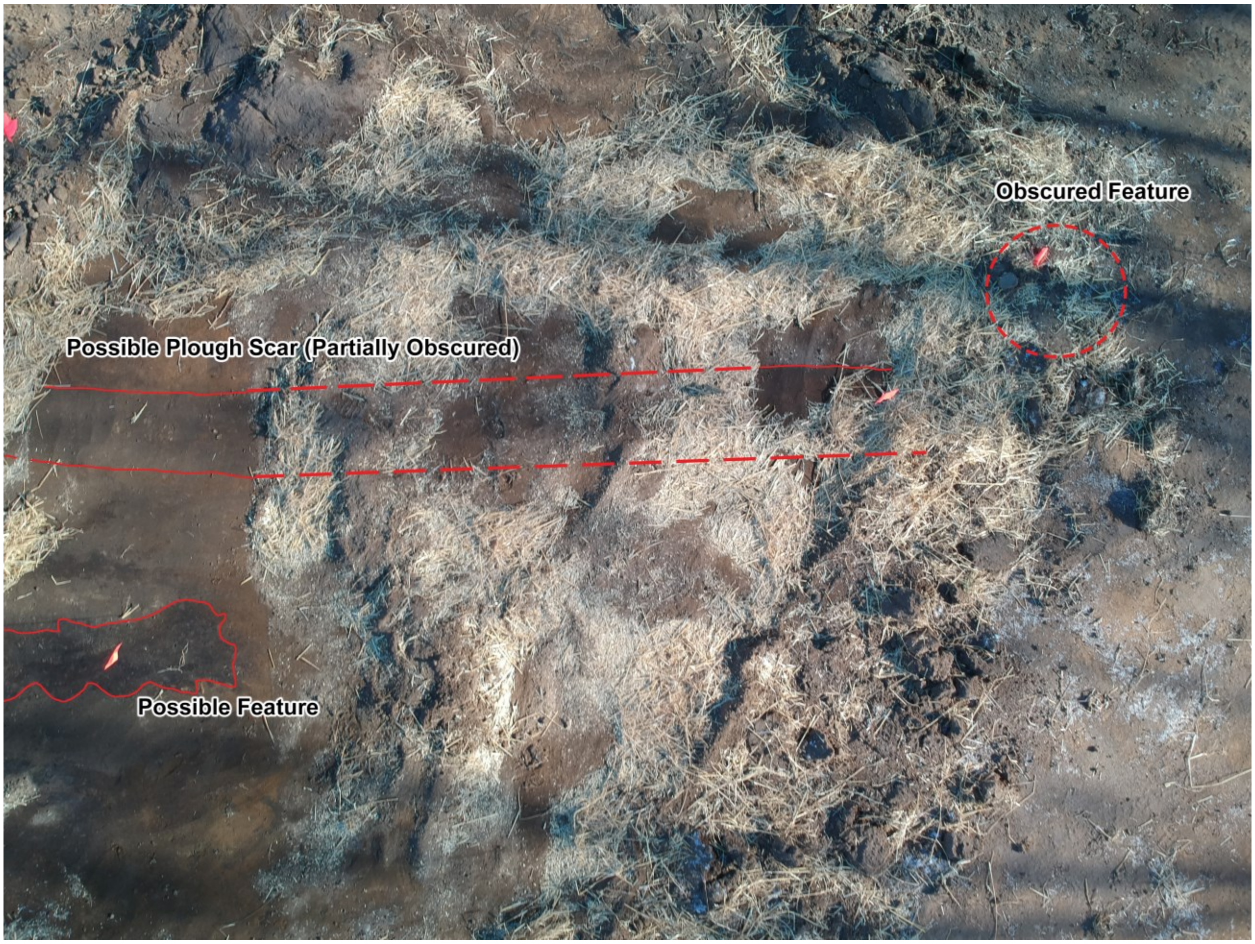

Figure 4-39 UAV image showing a feature in P1

Figure 4-40 Blurry photo from strong wind gust during photo capture

A total of 64 photographs were captured during the flight. Despite the majority of the photographs being negatively affected by poor weather conditions, the photos were uploaded to Maps Made Easy in an attempt to salvage the data. Uploading the photos took approximately 5 minutes, and the data products took 30 minutes to process. As the AOI was so small, the processing was gratis. The resulting data products are highly distorted and offer no analytic value (Figure 4-41).

Figure 4-41 Orthoimage result from poor data capture conditions

4.5.3 Metadata

Table 4-9 Metadata of the P1 manual flight

Flight 1	*Values*
Flight Speed	~1 m/s
Altitude	3 m
Area	40 m^2
Overlap	Variable
Sidelap	Variable
Images	64
Duration	7 min
Batteries	1
Storage	0.04 GB
Resolution	unknown
Filter	ND4 Polarizing
EV Comp	No

4.5.4 Analysis

Though the final data products offer no analytic value, some of the photographs illustrate the UAV's utility within a consulting framework. This case study illustrates the temporal flexibility and high-resolution imagery a UAV can provide, even a small, inexpensive UAV like the Spark. Had conditions been better, a UAV could have captured data like that presented in the former three case studies to be used for spatial analysis of the many features contained within the site. The high-resolution imagery could then be used as a basemap instead of the relatively low-resolution satellite imagery that is freely available (Figure 4-42 and Figure 4-43).

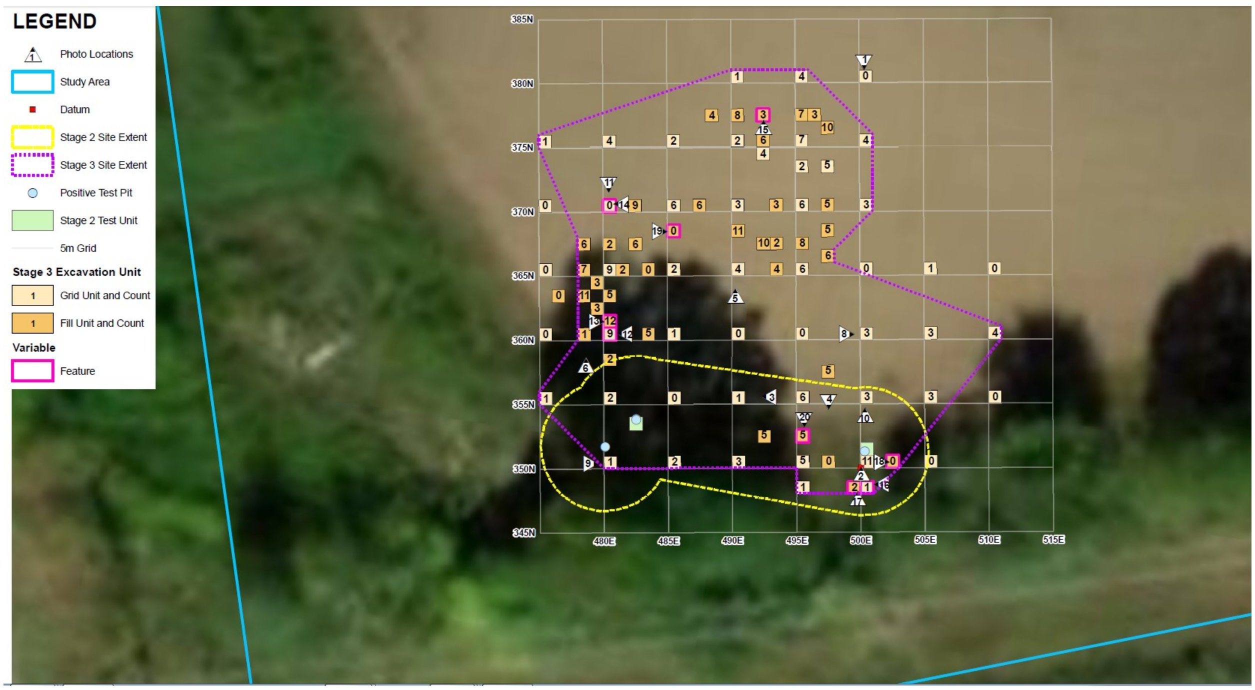

Figure 4-42 Example of the basemap that was used for an archaeological report for P1 (WSP, 2018)

Figure 4-43 Satellite imagery freely available on Google Earth showing the preliminary stages of excavations of P1

4.5.5 Summary

Although the flight operation was unsuccessful, this case study illustrates the ease of use of high-resolution, UAV-based data capture in a consulting archaeology setting. As UAVs become increasingly compact, they become increasingly unobtrusive for storage in a field kit or vehicle. This allows for the rapid capture of high quality data for cartographic or spatial analysis purposes when flying conditions and site condition are optimal without hindering daily field activities. This case study's flight was completed in approximately 7 minutes. In favourable conditions, an archaeological site similar in size (approximately 100m^2) may only require 15 minutes to ensure optimal data capture. This is a marginal additional cost to a tight budget for the quality of data the UAV produces and the "value-added" the UAV can provide for clients and required archaeological reports.

5 Discussion

5.1 Applicability

When this research began, the Phantom 3 was purchased because of its ubiquity and advanced technology, but multiple UAV iterations have since been released within the past three years. However, even with the rapid advancements in UAV technology, the materials and methods used in the thesis, including SfM and other photogrammetric processes, are still relevant and applicable.

Over the last three years, DJI has released nine consumer-grade UAVs, including three new iterations in the Phantom series. The sheer quantity of new UAVs implies that the Phantom 3 used in this research is obsolete, with the evaluative results becoming irrelevant. However, the technology in the new UAVs has only been marginally improved. The most important advances have been the introduction of obstacle avoidance sensors, increased flight-times, and in the case of the Phantom series, an increased camera sensor size. The increased sensor size would translate to more accurate datasets, but otherwise these developments offer little change to the overall process described in this paper. The most important transformation has been the decrease in size of most consumer-grade UAVs. Since Transport Canada's requirements vary depending on the size of the UAV, having a significantly reduced UAV size and weight, while maintaining similar or better onboard technology is ideal. Further, small form-factors and less weight are easier to integrate into conventional field kits routinely used by archaeologists, thereby minimizing any logistical impediments that may usually be caused by the addition of a new tool or device. Conversely, UAVs similar in size to the Phantom 3 require cumbersome protective cases that would not integrate well into conventional field kits. As UAVs decrease in size, archaeologists can more easily introduce the devices into their daily workflow without noticeable encumbrances.

5.2 Future Advancements

Although its value has been discussed in this paper, 3D image-based modeling using UAV-based data remains imperfect. 3D data extraction is hampered by highly reflective surfaces, shadows, and vegetation. LiDAR can collect data in these environments but is not readily available for all consultant archaeologists. Is there another technology that can act as an alternative for LiDAR in these environments? Ultrasonic sensors are a potential technology to act as a LiDAR alternative to supplement 3D image-based modeling, and are available on most prosumer UAVs today. DJI's VPS and most optical flow positioning systems use a combination of cameras and ultrasonic sensors to create 3D depth-maps for stable flights. Essentially, the UAV is using a form of echolocation to create a 3D map of the ground to increase its flight and hovering stability. There is potential to advance this technology to be extracted for use to fill in the data gaps produced by image-based modeling in non-conducive environments. Where 3D imaging artifacts are generated by a highly reflective or vegetated surface, the ultrasonic depth map could correct these inaccuracies. A pitfall is that the ultrasonic data used by UAVs is not accessible to the average consumer, although research regarding this technology has already begun (see Deris et al, 2017; Yuncheng, et al, 2018; Ramon et al*,* 2016) and opportunities to utilize this sensor's data will likely be available within the next decade.

5.3 Cost/Benefits

As the target consumers for UAV applications discussed in this paper are archaeological consultants, financial considerations are a major determinant in whether UAVs will be adopted by businesses. Table 5-1 breaks down the initial overhead costs to begin UAV survey, and continual operational costs are considered. For the purposes of this outline, it is assumed that the newest DJI Mavic Pro would be selected for its small form factor and upgraded technology, although other, less expensive models, such as the DJI original Mavic Pro or a Spark would suffice. Taxes are not included in the cost breakdown.

Table 5-1 Initial Overhead Costs for UAV Use

Item	*Cost ($)*
UAV	2029
Batteries (each)	120
Camera Filters	100
iPad (or similar)	300
Semi-Autonomous Flight App	15
Ground Control Equipment (e.g. pylons, tape)	60
UAV Ground School	300
Public Liability Insurance for UAV Use	350/year
Total	**3274**

Estimated initial overhead costs would be around $3500, with a recurring annual cost of $350 for insurance. Other costs would include the rates for a pilot to pre-plan the flight and a visual observer to watch the pilot during the flight's execution. In addition, third-party processing costs are roughly $5/ha. Although fees related to UAV survey could not be directly billed to the client (unless agreed upon in the contract), these additional operational costs would largely be recovered within a year of work by offering a more efficient means of map production. Also, the high-quality datasets produced by the UAV supplement analysis and allow for the creation of exemplary cartographic materials that provide a "value-added" in the project deliverables. As demands grow for greater inclusion of landscape analysis (Section 5.4), archaeology firms may increasingly adopt UAVs for such applications. The early adopters can advertise industry leadership and innovations, and as more firms adopt this practice, others will need to follow suit in order to preserve their reputation with the shifting status quo.

5.4 Implications in Ontario Archaeology

Perhaps the most valuable component of employing UAV survey of archaeological sites and features is that high-resolution digital files are created. These digital files do not occupy any physical space, and they can also be easily and electronically shared with researchers globally. This easy dissemination and retention of raw data adds more information to the archaeological record that can be studied indefinitely by researchers anywhere. While sometimes the value of information derived from UAV-based data is not evident to those who collected it, conclusions can be made *post hoc* once new technology and data manipulation methods are created. This is especially important given the rapid pace of fieldwork conducted by Ontario consultant archaeologists.

Even for archaeologists without access to a robust GIS, UAV-derived orthophotos, 3D models, and raster DEMs can be viewed and manipulated through rudimentary software such as Google Earth Pro to allow for limited analysis. Advanced analytic inputs, such as viewsheds or drawing contours, may not be widely available in rudimentary GIS, but the UAV data can be easily shared with other archaeologists who have the appropriate GIS software and training. This allows for a preservation of finite site data and a digital means to disseminate archaeological data to other researchers. This is especially pertinent given that the provincial standards will continue to be improved upon to more adequately capture site information. If the MTCS updates the standards for archaeological research, UAV data captured within the current *S&Gs* framework will allow archaeologists to revisit and expand upon archaeological sites that are currently being excavated to elevate them to these new standards.

Currently, detailed landscape analysis is not a requirement of the MTCS' *S&Gs* apart from specific landscape elements identified in their predictive model of archaeological potential. In fact, Section 7.8.2 of the *S&Gs* state "do not document non-archaeological cultural heritage features (e.g. built heritage, cultural heritage landscapes) unless those features are part of or relevant to the archaeological record." This language somewhat deters landscape analysis and does not offer definitions of what is deemed relevant to the Ministry outside of their indicators of archaeological potential (Appendix B).

Further, as concerns of Indigenous groups are better integrated into Ontario consulting archaeology, considerations in how archaeological sites are situated within a landscape will become a more prominent focus. Already, First Nations communities, such as Saugeen Ojibway Nation (SON) and MNCFN have criticized the MTCS' *S&Gs*, including the way any major landscape analysis is dismissed. A growing number of First Nations communities are calling for more action to be taken to better preserve and respect their cultural heritage (SON, 2010; MNCFN, 2018). This speaks to a greater and more complex issue, of which UAVs are certainly not the solution. Instead, as archaeologists continue to engage with First Nations communities, UAVs, the data they produce, and the subsequent analysis of the data can become a key instrument to supplement the growing need to encapsulate landscapes and First Nations perspectives outside of the immediate area surrounding archaeological sites.

6 CONCLUSION

High-quality data recording in Ontario consulting archaeology is inhibited by competitive budgets, and few incentives to exceed the minimum methodological benchmark are offered by the *S&Gs* (2011). The methodology employed within time- and budget-sensitive archaeological fieldwork presents a great risk of data loss in an inherently destructive scientific field. Therefore, technological and methodological efficiencies must be sought in order to capture more information in a cost-effective way that can easily supplement consulting archaeology's shortcomings.

This thesis explored inexpensive, consumer-grade UAVs as a potential tool to improve technological and methodological efficiencies in field recording and landscape analysis. Through four case studies, the UAV's accessibility, cost, and possible data outputs were evaluated. The Boulevard Rock Ring demonstrated the speed in which a UAV survey can be planned and executed. It also illustrated how the high-resolution digital files could be analyzed to great effect, well after the UAV survey was completed, and the information captured by the UAV can easily be disseminated to other archaeologists, Indigenous groups, and the general public. The Dog Lake Effigy investigation demonstrated the precision of UAV-derived three-dimensional representation of archaeological features compared to that collected by conventional means. The case study also illustrated the value of three-dimensional data while offering preliminary insights in landscape analysis. The placement of the nearby portage route could be modelled, and subsequently the placement of the effigy itself, supported by aerial images captured by the UAV. The Hokanson case study demonstrated the reasonably accurate Z-axis created by UAV image-based modelling. It also provided an example of how landscapes are a key factor when investigating archaeological sites, and that UAVs can be employed to easily collect details about its overall geography. P1 illustrated the ease of adopting a UAV into an archaeological toolkit to be used with ease whenever an aerial perspective will benefit an archaeological investigation, despite the case study not yielding analytically useful results.

Aerial imagery's value in archaeological applications is undeniable, and has been used globally for the past century for many landmark archaeological surveys. Although airplane-based aerial imagery was not widely adopted in North America because of cost and a perceived lack of suitable subjects, the addition of satellite imagery has become commonplace. However, freely available satellite imagery cannot match the quality of aerial photography, and often offers limited geographical information and no temporal flexibility to capture archaeological data during excavation. Consumer-grade UAVs fill this data gap by providing high-resolution aerial imagery that can be captured cost-effectively and at any time the archaeologist finds necessary and suitable.

Though a UAV has clear advantages over satellite imagery or airplane-based aerial photography, it may not be suitable for every archaeological investigation in Ontario. Restrictions outlined in the *CARs* impact the accessibility of UAV applications in built-up areas and airspace outside of Class G. Moreover, archaeological features such as crop marks, ruins, monumental architecture, or earthworks that are well-suited for UAV survey are not frequently found in Ontario. Historically, this was a similar reason as to why airplane-based aerial photography was not actively employed in North America.

Nevertheless, UAVs allow consultant archaeologists to easily gain new perspectives of landscapes that cannot be easily discerned from the ground. Landscape considerations are a key component of the archaeological record, especially in Pre-contact or Indigenous contexts, as the landscape shaped and was shaped by the past occupants in Ontario.

Ultimately, consumer-grade UAVs are cost-effective, highly accurate, and collect high-resolution geospatial or geographical data that are an invaluable tool for consultant archaeologists. The devices are easy to use and can greatly supplement the data collected in current consulting practices.

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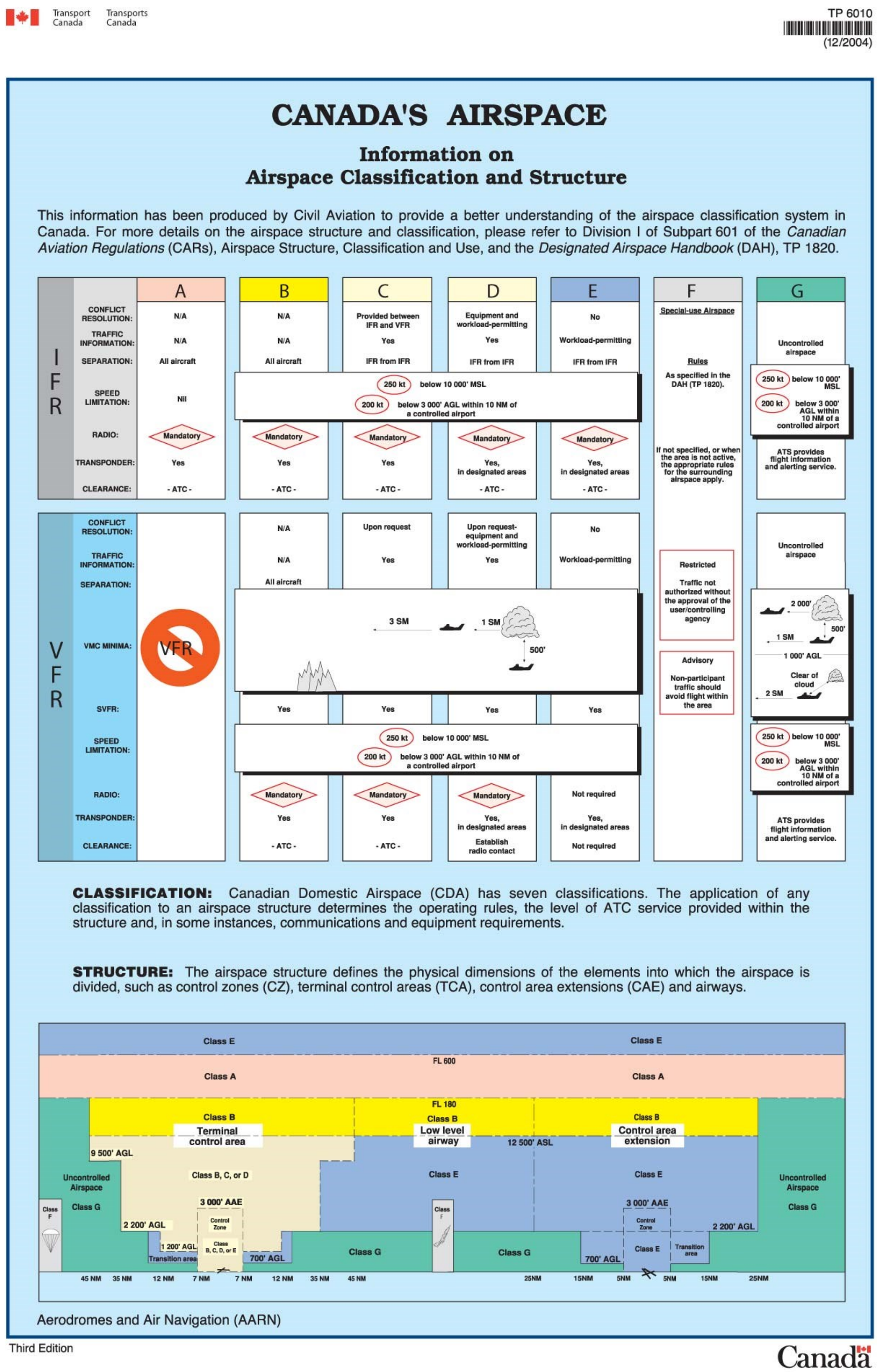
APPENDIX A: AIRSPACE CLASSIFICATION STRUCTURE



APPENDIX B: INDICATORS OF ARCHAEOLOGICAL POTENTIAL (MTCS, 2011)

The following are features or characteristics that indicate archaeological potential:

- Previously identified archaeological sites.
- Water sources:
  - Primary water sources (lakes, rivers, streams, creeks).
  - Secondary water sources (intermittent streams and creeks, springs, marshes, swamps).
  - Features indicating past water sources (e.g. glacial lake shorelines, relic river or stream channels, shorelines of drained lakes or marshes, cobble beaches).
  - Accessible or inaccessible shoreline (e.g. high bluffs, swamp or marsh fields by the edge of a lake, sandbars stretching into marsh).
- Elevated topography (e.g. eskers, drumlins, large knolls, plateaux).
- Pockets of well-drained sandy soil, especially near areas of heavy soil or rocky ground.
- Distinctive land formations that might have been special or spiritual places, such as waterfalls, rock outcrops, caverns, mounds, and promontories and their bases.
- Resource areas, including:
  - Food or medicinal plants (e.g. migratory routes, spawning areas, prairie).
  - Scarce raw materials (e.g. quartz, copper, ochre, or outcrops of chert).
  - Early Euro-Canadian industry (e.g. fur trade, logging, prospecting, mining).
- Areas of early Euro-Canadian settlement. These include places of early military or pioneer settlement (e.g. pioneer homesteads, isolated cabins, farmstead complexes), early wharf or dock complexes, pioneer churches and early cemeteries.
- Early historical transportation routes (e.g. trails, passes, roads, railways, portage routes).
- Property listed on a municipal register or designated under the Ontario Heritage Act or that is federal, provincial or municipal historic landmark or site.
- Property that local histories or informants have identified with possible archaeological sites, historic events, activities, or occupations