Drone and Photogrammetry Use in the Spatial Analysis of Fortress Archaeological Sites, Western Colorado

Submitted to Northern Arizona University

Graduate faculty of Geography, Planning and Recreation
In partial fulfillment of the requirements for

Masters of Applied Geospatial Sciences
Geospatial Technologies Emphasis

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Abstract

Use of mapping in archaeology has been a standard practice since the conception of archaeology as a science. The recording, measuring, and analyzing of site data has provided much of what we know about archaeological sites. In the new world of data analysis aided by unmanned aerial systems, understanding site placement, orientation, and construction are now convenient to record in a way that was not previously possible. This study will investigate ancient fortress sites in Western Colorado and the Colorado Plateau to explore opportunities available to record and analyze these archaeological sites. Using 3D modeling software, and automated flight ability to capture data at each site, the resulting models are a repeatable product of the site captured in time. The sites are easier to assess for their overall structure, environmental building conditions, and provide further insight into how these fortresses were constructed, and why.

Problem Statement

In archaeology sites are destroyed through most conventional methods, though new technology has created ways to observe and record sites without damage. This study will contribute to the field geospatial sciences, as well as archaeology, in the search for methods that cause the least harmful impact on historic sites. Many of the sites I look at occupy steep terrain, adorn cliff tops, or are harder to access with conventional methods.

Research Objectives

This research aims to establish an understanding of the destructive methods of excavation and provide solutions through Geospatial Analysis. The study of the fortress sites will offer a platform for establishing these best practices in a real world setting to understand the extent of information that can be provided by non-invasive means.

Timeline

January - May 2022 - Literature research into cultural aspects of ancient puebloan structures.

June - August 2022 - Visit fortress sights in Colorado Plateau for field work. Additional literature at the forefront of field research and technologies available. Recertify FAA part 107.

September - November 2022 - Processing digital information. Meeting with the advisory committee. Revisit any sites if needed. Write up results of analysis.

January - April 2023 - Meet with the advisory committee. Finalize research and present at the Colorado Council of Professional Archaeologists conference. Defend electronically for Northern Arizona University.

May 2023 - Graduate MS in Applied Geospatial Sci from NAU.

Literature Review

Introduction

In the investigation of culture, the exploration of archaeological sites provides the closest ability to step back in time, to see a lifestyle through its few material remains. Archaeology, notoriously, is destructive in nature by means of excavation, object removal from sites, and disruption simply due to the presence of the archaeologist presence at the site. The use of superposition has been the basis of much archaeological interpretations. John Frere's understanding of the first deposited materials being the oldest at the lowest level (Feder, 2010) resulted in the race to the bottom-layer, where archaeologists found greater significance to the items at the bottom of the excavation than consideration for the top layers, and is the longest earliest used method. The use of geospatial technologies is becoming more popular in the archaeological field. The advancements at such a rapid rate have provided archaeologists ways to record sites that were previously inaccessible (Gonzalez-Tennant, 2016). Using this cartographical approach with the stratigraphical methods, a timeline can be created to learn more about how humans have interacted with their landscapes (Haciguezeller, et al. 2019).

Aerial Photography

Aerial archaeology has a long standing historic value to the study, with earliest forms coming from hot air balloons in the late 19th century (The-Past, 2012). The ability to photograph from the sky provided a perspective to see a bigger picture of how the landscape was altered over time.

Using an aerial perspective in looking at archaeological sites provides the ability to assess the spatial context of features. This process has long existed in the use of site maps providing an illustrated layout of a site. As many archaeologists can attest, site map creation becomes a lengthy process where the timeliness is inversely affected by the accuracy of the map. An overview of an archaeological site, combined with other spatial data of the locality to other sites provides information about larger aspects of a site's importance, any astronomical significance, trade relations within the surrounding area, and contextual landscape contributors.

This ‘footprint’ left by humans over time can be better understood when looked at on a larger scale (Goodchild 2010). This is seen in multiple sources where the use of large scale GIS has produced a revelation in the expanse of a civilizations reach. Most notably Friedman (2017) looks at aerial imagery between Chacoan sites in the American South West and establishes that roads, trails and paths can be seen and used in understanding the trade and migration patterns.

The use of spectral photography and the use of satellite images for the assessment of vegetation has produced variations in the vegetation which can be indicators of soil type and depth (Stow, 2010). As the sites primarily visited in this study were rock outcrops, the use of infrared provided little information. The sites, which included masonry walls, and post hole drill sites (Conner, 2022), would need another form of visual manipulation for the analysis of the site. This comes in the form of DStretch which is discussed in the Methodology section.
Historic England delved into a large-scale project of recording the country's multiple sites to extra pre-Roman era using aerial photographs. This project took archaeology of the British isles by storm and increased interest in cultural preservation by allowing patrons to visit the sites via the aerial recordings (Sherwood, BBC News, and Historic England, 2021).

Advancement in Technology

The newest technologies can oftentimes be costly and their application to an archaeological site reduces their access during field work. Even the most basic of drones were cost prohibitive until recent advancements in technology has progressed drones to the status of widespread hobby and nearly a household object.

GIS systems are seen as a potential speed bump in the archaeological method due to the accessibility for proprietary GIS software. Cattari and Clutterbuck (2011) explored these barriers as it pertained to Irish Archaeology, deciding that Geospatial knowledge of sites was crucial enough that open source options still provided valuable resources when recording sites.

Lidar, which has had an advantage in accessibility for the last decade (at the time of writing this,) has become the standard idea for what drone technology can do. In the Netherlands, lidar was combined with citizen science for the mass assessment of Lidar data, which resulted in over 1,000 burial mounds being discovered (Chen, 2023).

In drone archaeology, advancements include Ground Penetrating Radar affixed to the drone. This analysis allows for up to 15 feet (approx 5m) depth beneath the surface of the soil with accuracy for as little as 3 cm, with some projects allowing detection as much as 100m below surface (UgCS integrated Systems), though this technology can still be cost prohibitive, with equipment costing around $40,000 USD.

Thermal spectral analysis has also recently become an option in the use of drones for archaeological sites. A study conducted by Colorado State University’s Drone Program revealed that the foundation of a mid-19th century structure that had burned down retained heat differently than the surrounding soil. By using a thermal infrared drone at dawn or dusk, when temperatures change the most rapidly, the outline of the foundation buried just below the apparent top soil allowed archaeologists to pinpoint the location of the structure (CCUAS, 2011).

In flying a drone for non-profit, research, or on behalf of an organization, the same legislation applies as flying for a business. Because of this, in the United States, to fly the sites used in this project, I was required to hold an active FAA Part 107 Certification. Considerations include permitted access to fly at the location, proximity to any airfields or heliports, time of year, bird activity and topography. While this requirement reduces the accessibility to drones to fly the site, it has increased the interest in archaeologists in obtaining Part 107 certifications.

3D Modeling

Landscape topography has been known to impact the location of cultural remnants. The erosion from ongoing human activity, like that of travel, or the creation of terraced farming, causing the displacement of cultural indicators are prevalent in a 3 dimensional model as opposed to a 2 dimensional map. This can then give archaeologists additional information on the wear of the site for a better prediction of habitation at the higher contours of the site (Brandt, Groenewoudt, abd Kvamme, 1992).

We have seen digitally remastered renderings of long buried cities, helping to inspire the curiosity for what was in an ancient landscape. The 3D renderings of Badillo and Aldrich (2023) which creates a model of the city of Pompeii has allowed for an indepth look into other geospatial information of the city. Further examples of 3D modeling in the cartographic analysis of archaeological sites are seen in studies by Fry et al. (2015) and Rejangam and Rajani (2017) of Peru and India, respectively. In both landscapes, the use of modeling resulted in the discovery of how the long-term occupation impacted the terrain and the implications on local resources from the cultural terraformation (Friedman 2017).

Culturally modified landscapes can present themselves as terraforming, waypoint and navigation alterations, and habitation alterations. When looking at these traces of humans in their environment, they present a deeper understanding into the environmental resources and potential struggles the earlier inhabitants encountered (Schein 2010).

Potential errors from Web based photogrammetry include the image overlap ability, and the accuracy of GPS positioning. Use of ground control points for georeferencing work best with low vegetation, high GPS accuracy and stability of the drone. The points are compiled through multiple images overlapped, and do require a high number of ground control points, or coordinates, which are referenced throughout the model using the drones position and how that interrelates with the images (Guan, Zuh, and Wang, 2022). Additionally, this can be a limitation when working with the final model, as there could be discrepancies in the data compiled if there were not enough samples taken in the initial survey. This is seen in the use of photogrammetry at archaeological sites from a ground based collection. In close range photogrammetry, doing repeatability tests is often the standard for assuring accuracy (Sapirstein, 2016). Sapirstein, and Guan, et al both detail that errors in the readings can stem from motion. where Sapirstein, considers human movement resulting in camera blur, this translates to Guan, Zuh and Wang focusing specifically on unmanned aerial systems. These limitations can be mitigated by the presence of multiple images that contain additional information of the area where images overlap. Simply put, greater overlap and higher resolution means increased accuracy. In many cases, small drone cameras cannot be calibrated for photogrammetry, and in the research by Sanz-Ablanedo et al, (2020) the best way to overcome dome errors would be the use of ground control points. In that same research, a DJI Phantom 4 was used, which has a comparable CMOS sensor size to the Mavic 2 Pro of 1” with 20MP, and found that the greatest dome errors came from vertical images at high altitudes, where “Near Vertical and Convergent imagery in the same direction (E-W) achieved the optimum absolute result” (p.14).

During my research, (as described later in my methodology,) there was evidence of this where the drones launch point and the effect it had on the programmed flight for % overlap did have an effect on the resulting point cloud. The method of collecting images, either by camera or by drone, each have additional considerations. Where the camera can provide higher image accuracy due to the ability to get closer to the site, it often needs additional reference points for georeferencing, and takes much longer to record a full site (Sapirstein, 2016). A drone flying over the site will provide a faster compilation of images, and is preferable to recording sites that would otherwise be difficult to get to in person (Guan, Zuh, and Wang, 2022). This project would be an example of how accessibility would be applicable in the planning of site compilation.

A Revolution in Sitemaps

The excavation of archaeological sites is inherently a destructive method. Wadsworth et al. assessed the bias and ethical issue in the excavation of sites pertaining to Native Americans, with many western colonial sites being the forefront of newer technology use (2021). By applying an objective lens through geospatial science, there is an attempt to remove cultural bias of ‘the other’. The further advancement in the ability to include environmental and landscape factors in cultural use, GIS provides a way to be beneficial to the archaeological lens (Egbert, 2004). This is a further step in creating complete data which contributes to a complete result when looking at an archaeological site (Dixon 2010).

With the ability to create high resolution maps using precision imaging, the products with substantially small measurement uncertainty are becoming more common. Furthermore, an overlap of area reduces this uncertainty further (Kwion & Kanade 1992). This method is used in this project in the photogrammetry of the sites, with multiple photos creating more accurate depictions of the site.

Hand-drawn User created maps, which would apply to archaeological maps created by and for archaeologists, “may contain errors that come from distortions in the map representations, such as exaggerations, simplifications, embellishments, etc” (Lu & Arikawa 2015). Some site maps in this project appeared to have embellishments that were intended to help in the locating of sites. Using programmed flights with GPS capability, combined with GIS cartography methods, the resulting maps are more accurate and a true representation of the site.

Fortress Sites Study Area

The area studied contains the Canyon Pintado National Historic District. This area is significant because of its ongoing habitation by multiple cultural groups. This is determined by the extensive diversity of staples of cultural rock media located throughout the region (Conner, 2021). The fortress sites themselves have some similarity to the man made impressions created at the top of Mesa Verde, which similarly could have been used as a lookout, or possibly an astronomical observatory (Malvale and Munson, 1998).
Using this rock media, including petroglyphs at sites, the structure's purpose is sometimes revealed. For example, there is rock art at one of the fortress sites that represent warriors with shields and spears, adding to the consensus that the site was used as fortifications (Conner 2019). A map of the study sites can be seen in the Methodology: Site Maps section.

Methodology

Introduction to Fortress site recording

During the first two weeks of August 2022, I conducted field research alongside Carl Conner, Archaeologist for the Dominquez Archaeological Research Group (DARG). The project, funded through a grant from the History Colorado State Historical Fund, aimed to update and supplement records of known and sites suspected to have been built as fortresses by the Puebloans. Over the course of this study, we visited 19 sites throughout Northwest Colorado. Due to the sensitive nature of these sites, and the requirements of the Bureau of Land Management, exact locations of these sites will not be discussed in this thesis, but will be referred to by their site identifiers to append the information already in existence.

Drone Imagery

Equipment

The field work to fly, photograph, and save nearly 10,000 images for multiple sites required initial planning. For this project, my qualifications included a FAA Part 107 certification, Wilderness First Aid certification, and a background in Archaeology. These were required well in advance of the kickoff of this project. As the project approached, my experience with flying other sites for DARG gave me additional insight to the requirements we may encounter in the field.

The drone used over the course of the 2 weeks was primarily a DJI Mavic 2 Pro that had been altered by Kolari, a visual equipment specialist, who removed the built in filters for a Full

Spectrum modification. With this, the drone would be flown 3 times per a site; first with a 'Hot Mirror' which would allow the drone to photograph with visible light, and next with an Infrared filter that would allow for two different bands of Infrared light Blue Green Neutral (BGN) and Red Green Neutral (RGN). The purpose of these multiple flights was to assess the ability for the drone to photograph vegetation for the purpose of finding trails, worn areas, and other indications of use at the archaeological site. In addition to the 'ready to fly' drone, I also used a 'fly more combo' from DJI that had two additional batteries, an extra set of propellers, and a car charging unit for the batteries. The drone itself folds up and is a light 1.6 lbs with the battery installed, making it ideal for transporting into the field (Picture 1).

Picture 1. Posing with the field equipment after hiking to launch point.

Each pre-charged battery would allow for 27 minutes of flight, with the last 5 being the emergency amount that would allow the drone to make it back to the 'home point', or the location of the launch. With only 22 minutes of flying, or 66 minutes per a set of three batteries, flight plans, locations of sites from the starting point (usually dictated by the ability to traverse the landscape), wind conditions, bird activity, and many more factors could infringe on the amount of flight that would be required at each site. Because of this, before August I acquired a Solar Charging Station that doubles as a large electric battery and solar inverter. This allowed for the re-charging of batteries between flights, making it possible to fly three to four sites comfortably without much waiting on recharge times. This unit could be recharged by either the car charging cable that came with it, or the solar panel (purchased separately). As inclement weather days were anticipated, we would not field two days over the duration of the project, and in such conditions, lack of sun for charging was not a concern. Ultimately, the charging was through a DC charger in the vehicle, and even lack of sun was not a concern by the time we fielded.

An issue that did arise was the overheating of the batteries from constant rotation. We would recharge the batteries and use them after it was within the temperature allowance, and would occasionally require ‘down time’ in the field. I would have added an extra battery if I had known, so that there would be additional ‘cool down time’ for the batteries.

Picture 2 a & b, the charging station set-up that provided power while in the field, and the charging set up with 100w SolarSaga solar panel.

In the field, an iPhone 11 and ipad mini were both used in the process of connecting to the drone for flight.

Software

Using DJI GO, initial flights of a site would be free flown for confirmation of proper flight altitude to be put into the programmed flight.

In-field transect imaging was completed using Pix4D photogrammetry software. This application is mobile iOS and Android based and completes flight patterns as programmed by the user. Variables include the size of the transects, the altitude reach, the angle of the camera, and the overlap of the images. This provided a way for me to be sure that the images would overlap enough for the processing software to create a 3D Model (discussed in the next section.)

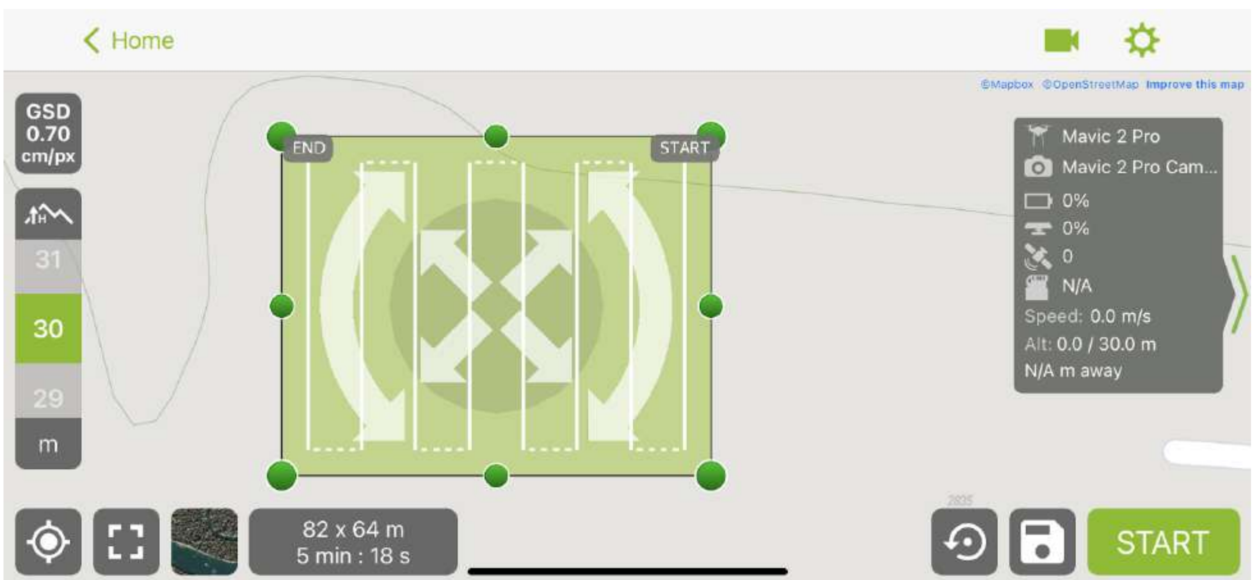


Figure1, Sample of Dashboard on Pix4DCapture. Elevation, grid size, and location can all be specified.

Dropbox was used for the storage of site forms and maps. The platform's requirement to log in provides an additional layer of security for accessing the information of the sites' locations.

GAIA GPS was used for navigation to the sites and provide real time location information which would also be used in conjunction with the Wind Speed app to assess flying conditions.

For weather conditions, in addition to the Wind Speed app, B4UFly, Clime, and Weather apps were also used to plan flights.

Recording

In the recording of each site, there was a standard practice for the safety and flight of each mission. In addition to standard drone safety check, the drone would be flown to the location of the site, and from this an approximate location to assign grid imaging through Pix4DCapture, The approximate altitude of which to image the site, and to be sure that the flight would be within FAA restrictions for line of site observations.

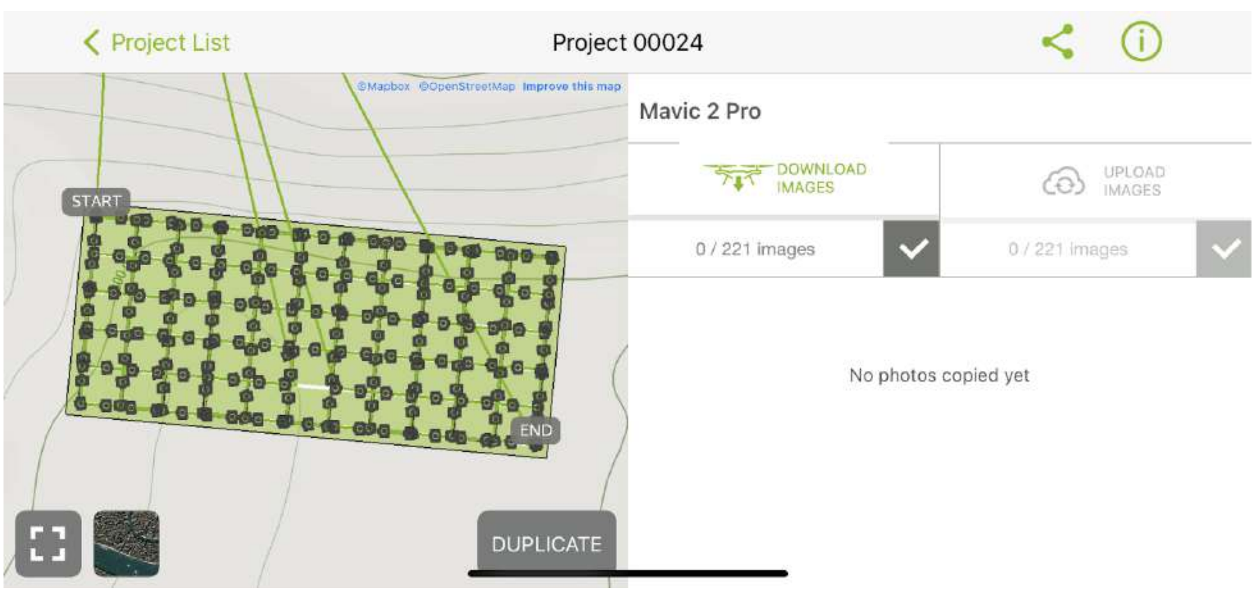


Figure 2, Screenshot of Pix4DCapture record of programmed flight path. 1 battery change in the flight is denoted by the travel lines to home from the middle of the grid. When the battery was changed, the drone could resume flying transects from the last point.

The Drone compass would be calibrated to the site, and at launch would be held at an altitude of 15m to acquire additional satellites before flight. After this, the drone was flown free hand to the location, usually on a cliff side, or at a higher altitude than the launch site, and would be 'measured' for optimal altitude of which to record the site. Factors in this process included; protruding cliff and rock faces; line of sight restrictions; trees; and bird activity.

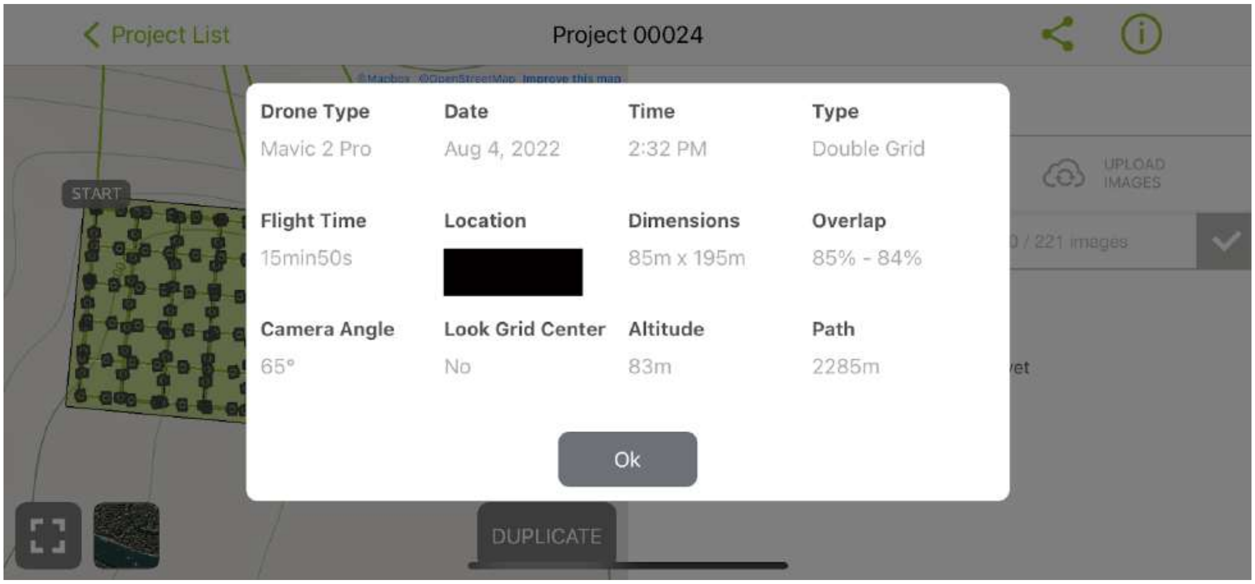


Figure 3, Information of the project is stored for retrieval. Location removed for public viewing.

Analysis

The use of the iphones smaller screen in the field made it easier to carry into areas that required more hiking, and was easier to adjust to eliminate glare. However, the small screen would not show the same detail that the ipad mini could through a larger screen.

While flying, occasional sites were difficult to locate using the existing hand drawn site maps and UTM coordinates that had been changed over time. Being able to fly the site ahead of the transect recording I could compare site forms and discuss with Carl Conner about the location. Using the iPad Mini, site maps, site forms, and large scale location maps could be downloaded for offline use, and use of mapping software allowed for the comparison to real time location.

Future Improvements and Considerations

The constant travel to sites allowed for considerable charging time for drone batteries and mobile devices. Unfortunately, while at the location all three batteries would be flown and in some instances resulted in waiting on the first battery to charge. Because of this, I would get a fourth battery for future projects, since that would provide ~25 minutes of flight time while the first battery finishes charging. This would provide the additional time to bridge the ‘down time’ waiting on other batteries.

Flying within the constraints of the FAA regulations of Line-of-Sight, my assessment of the distance to the site that would be required to safely fly required us to hike much nearer the sites than previously planned. Because of this, the drone would have benefited from a high visibility skin to help it contrast from the background of the areas flown.

A consideration for future flights is the area's local bird activity. Having flown the area in the height of summer, there was eagle activity at two sites and may have benefited from being flown later in the season. Due to time constraints, sites were flown with reduced coverage and with a visible spotter to watch for the bird activity.

Cell signal was only available at some sites, which resulted in the restriction of downloading landscape information to Pix4D. Unless planned and downloaded before departure to the site, using a first responders carrier that I have from my participation with the local Search and Rescue allowed me to have signal in more area than that of those in the field with me. An alternative would be to use a satellite cell provider or starlink for ongoing signal.

3D Modeling

Equipment

To process the nearly 10,000 images taken of the sites, processing power, memory, and the stability of internet speeds all became crucial factors.

As part of my work set-up, I had built a desktop computer in 2020 with the intention of processing large amounts of data. With a selection of components that are intended to streamline the back end of such work, the desktop contains 64GB ram, a 2TB Hybrid Hard Drive, and 500GB Solid State Drive. This provides the memory and speed to process the project on the drive, which reduces any lag from accessing an external or cloud drive. In this research, it was necessary to transfer data between my computer, and the hard drive at the Dominquez Archaeological Research Group, where my data would be stored as part of the greater project of a multiple researcher project. Because of this, I also used a 1TB hard disk as a ‘shuttle’ that I would use for storage and transfer of all relevant data. This includes: All images taken by the drones, separated in folders by site designation and spectrum of photography, Models, Data sets and reports created by WebODM, and Maps created in ArcGIS pro for private use.The space required for this project was 146GB.

Software

The primary software used for the modeling in this project is Web Open Drone Map (WebODM). This web based software compiles multiple images and finds overlapping points to create a point-cloud model. The overlapping points then add a reference for the program to ‘fill’ the space around them with the data from the images. With multiple images, spatial information is deduced by the triangulation of common points. The resulting model can be downloaded for use in geospatial programs, along with a complete report of the results of each processed project. ODM is open source drone image processing software, with WebODM as an internet interfaced application.

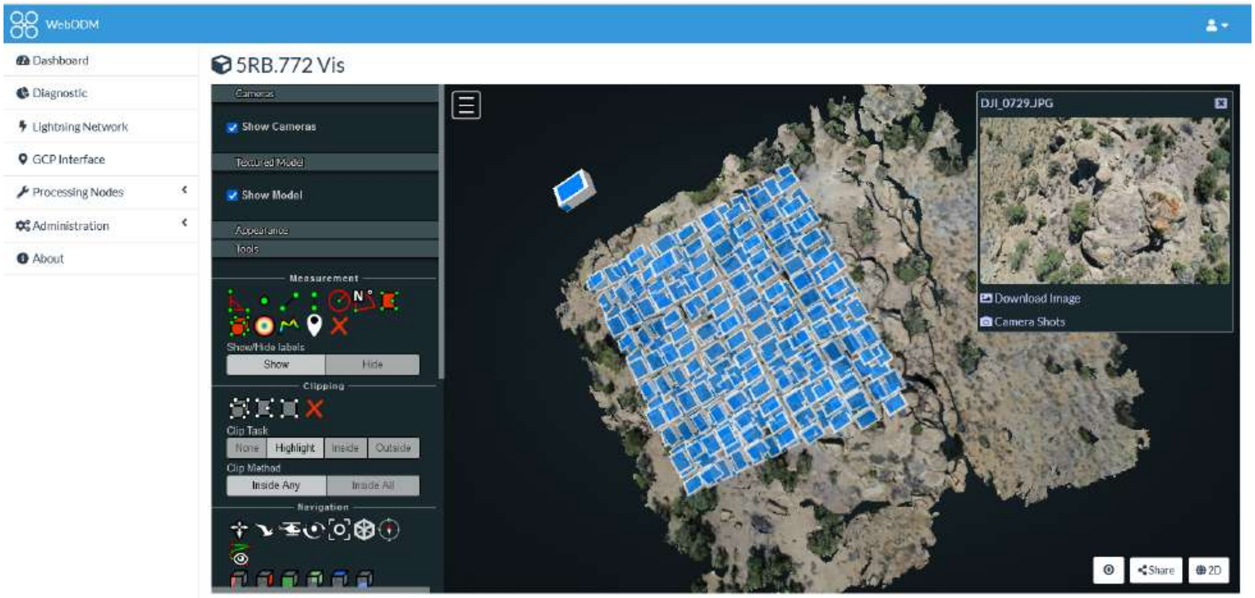


Figure 4, screenshot of WebODM and the ability to differentiate each photo taken by the drone used in the point cloud.

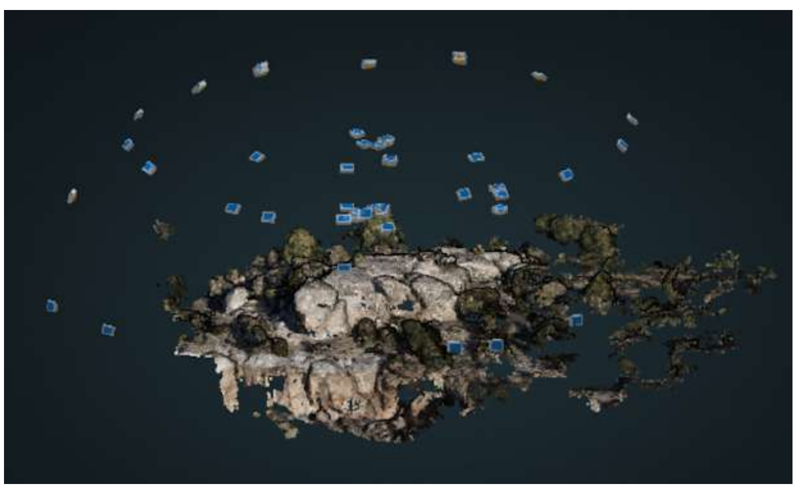


Figure 5, a comparison with an earlier flight of site 5RB.273 where flight was flown free-hand instead of programmed with Pix4DCapture.

In this research, I processed sites with 3 projects; the visible imagery that was taken with the hot mirror filter, the Red Green Neutral, taken with the RGN filter, and Blue Green Neutral, taken with the BGN filter. As stated earlier, there were sites where circumstances hindered the ability to fly with all 3 filters safely, and if able, was only flown with the visible spectrum. Thankfully, WebODM has a function built in for ‘plant health’, which was the main function of the filters for this project. The sites, being mainly rock, produced little to no result with the infrared, though some information came up with the visual spectrum images in DStretch (see Processing). The WebODM interface allows for 3D perspective viewing of the model for ease. For more complex mapping and cartography, additional software was needed.

Figure 6, location of drone for each photograph used in 3D model of site 5RB.772. Note that the top right hand side of the window has options for alternative information to display.

Once the image was processed, the resulting model could be used in most geospatial platforms. For example, the two major platforms tried with this project included QGIS and Esri ArcGIS Pro. Final maps produced were exported in PDF and JPG formats, which can use many standard file readers for viewing.

Processing

The WebODM program makes point cloud compilation easy, as long as the images are pre sorted. Because of this images from each site were sorted on the hard drive by site number, with sub folders with the Visible, RGN and BGN images. Once in WebODM, a new project was created with the site name, and then each sub sub folder is loaded individually, allowing a file package and report to be created for each one individually. For each set of images, WebODM provides the number of images used, (if an image does not have enough points that can be referenced to other images, then it is not used in the model,) the processing time, the status of completion, the date and time it was created, the processing node, options selected, average ground sample distance (GSD), the area in square meters, and the number of overlapping points that were reconstructed.

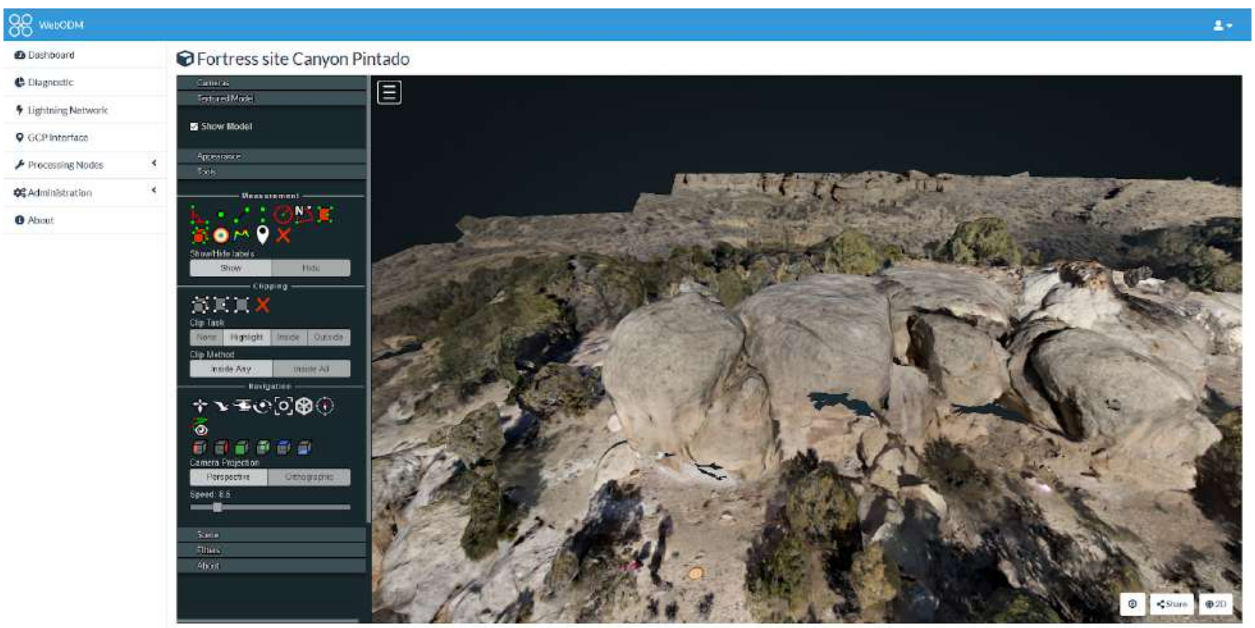


Figure 7, Textured model created from point cloud.

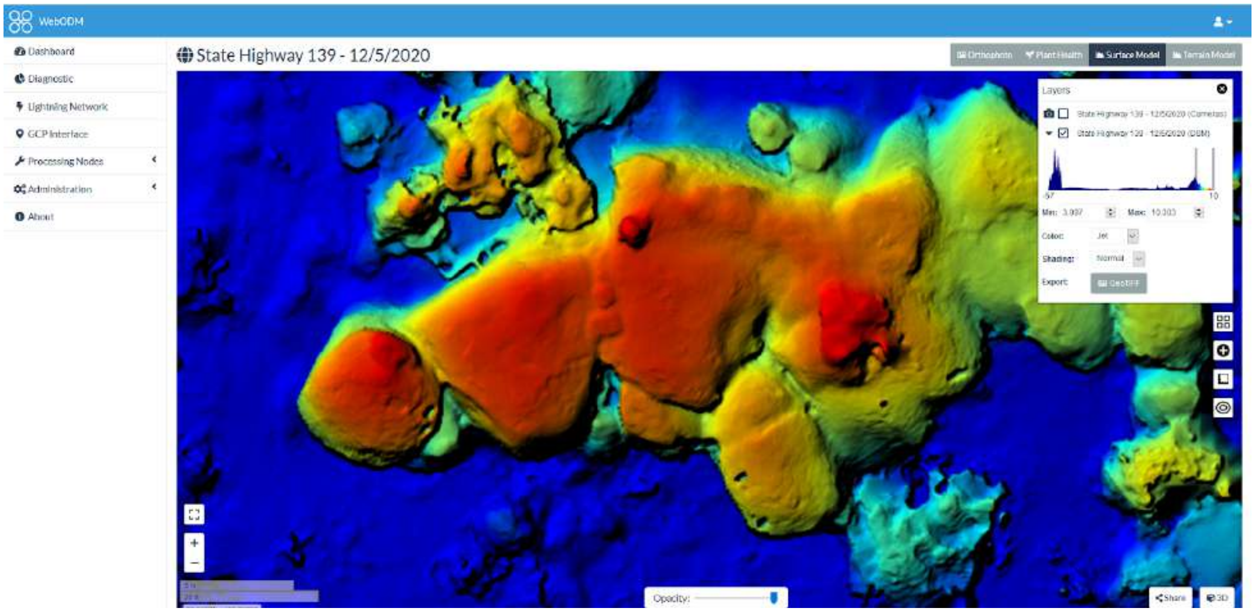
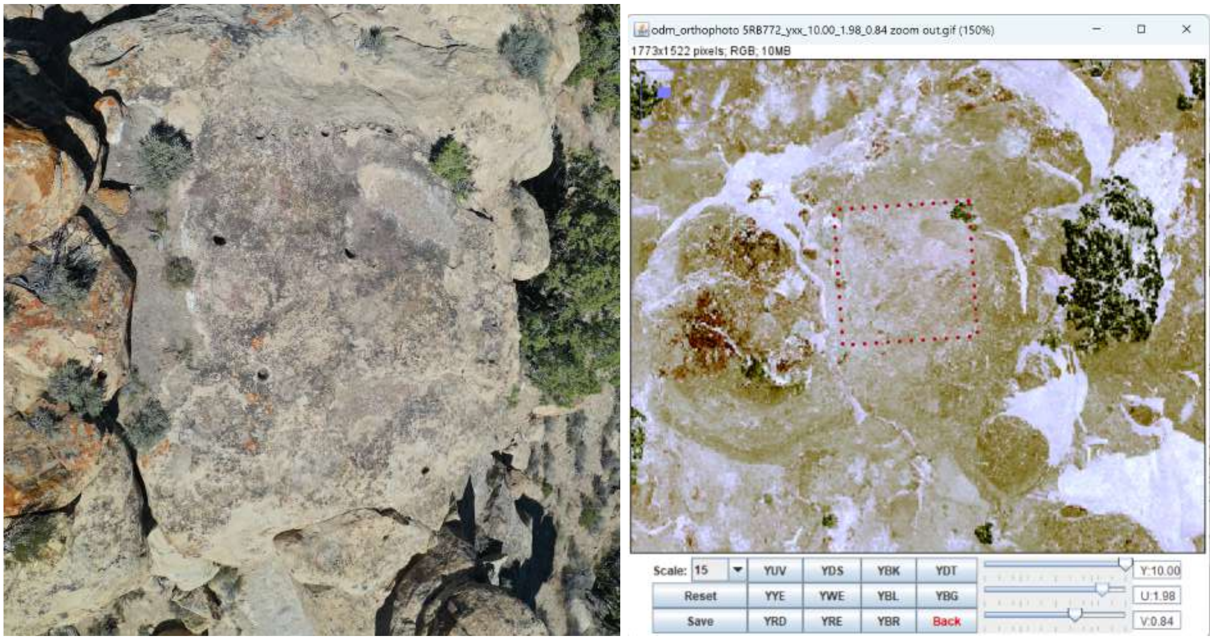


Figure 8, Surface model from DEM showing a gradient elevation of the site.

The resulting data can be downloaded as an Orthophoto, surface model, point cloud, textured model, and the information on the photographs can be downloaded as the camera parameters, or location of camera shots. Information on the quality of the process is outlined in a PDF quality report. All of these are able to be downloaded as a zip folder.

After compiling a random sampling of 6 sites with the infrared imagery, the most common results was that there was little information gathered because of the nature of a site that is primarily culturally modified rock, and little vegetation. However, for this same reason, using DStretch to assess the rock outcrops in a way similar to the process of studying rock art provides a look at the wear that occurred on the rock outcrop. To do this, the orthophoto from WebODM was opened in DStretch on a YUV color correction. The image was set with Y:10.00, U:1.98, and V:0.84 from the fine tuning sliders. This provided a light gradient where there was wear on the rock in the distinctive outline of the post holes, further providing an insight into the habitation of the structure.



Figures 9 a and b, showing the wear on the rock surface of site 5RB.772, and the same site processed in DStretch.

Future Improvements and Considerations

In the process of taking photos in the field, a record of which spectrums were taken was made in the field notes. As long as the same spectrum was not used back to back, it was easily determined which photo group belonged to which site. In the few instances where the site was only flown in visible, and then the preceding site started with a visible spectrum, there was more time and effort needed to differentiate where the images from one site ended and the other began. For this reason, I added a small white board to my field kit with dry erase markers. Before flying a site, I can mark the site identification on the board, and take a single image of the board to signal the beginning of the new site.

The use of infrared in site analysis will be more beneficial in potential future studies of areas surrounding the sites, where vegetation is more abundant and can potentially show routes linked to the site.

Site Maps

Software

To open the 3D model package as a workable 3D model in your preferred GIS program, WebODM creates an Orthophoto, along with Digital Elevation Model, or DEM. This DEM representation can be manipulated in symbology to so its elevation representation as either a gradient, or as contour lines. As seen in Figure 10, the DEM allows for the contextual mapping of the elevation of the site. Additional information later added, like the location information along the sites of the map grid, allowed for a more detailed site map.

Using GIS, the representation as a compiled map allows for a much more detailed and professional product. Both ArcGIS Pro and QGIS allow for the addition of relevant information, as needed for this project. Specifically, as the site forms are being updated with these new maps, the presence of UTM along the grid assists in the location of the site, should future archaeologists require revisiting the sites.

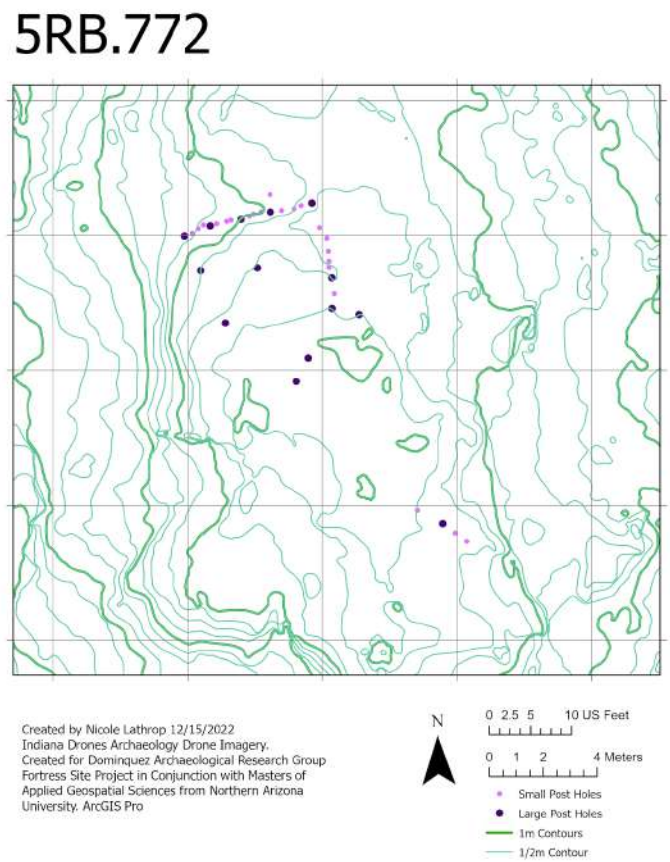


Figure 10, Created in ArcGIS Pro for the Bureau of Land Management, altered to remove location information for public display.

Processing

One of the more helpful features for the cartographic process of these sites is the ability to add contour lines with a few clicks. With the majority of the sites visited being located at the top of a rock outcrop, adding contour lines provides the 2 dimensional representation of a 3 dimensional environment. An area with a low slope, or well placed bridge, may be an indication of the access point into these structures.

When applying this to the study sites, I found that while some sites were large enough that a 1m and 5 m couture line provided ample contextual information, the most precise without getting ‘noisy’ was 1/2m and 1m. This narrower banding allows for better assessment of the slope within the structure.

To mark features, specifically Post Holes, I created a point layer where I Could differentiate between large and small holes. In figure 10 you can see that they are denoted by pink (small) and purple (large). Representing small and large post holes, respectively.

The Data management portion of my project became the most tedious as WebODM exports files categorically. Because of this, each site has its own folder with subfolder organization. To build a cohesive ArcGIS Pro project for the map recreations I needed to create a project with its own folder. I then created site folders in the project folder that would house the Raster data files from WebODM. For the purposes of this project I Copied over the DSM (Digital Surface Model) that functions for the DEM (Digital Elevation Model) layer, and Orthophoto.

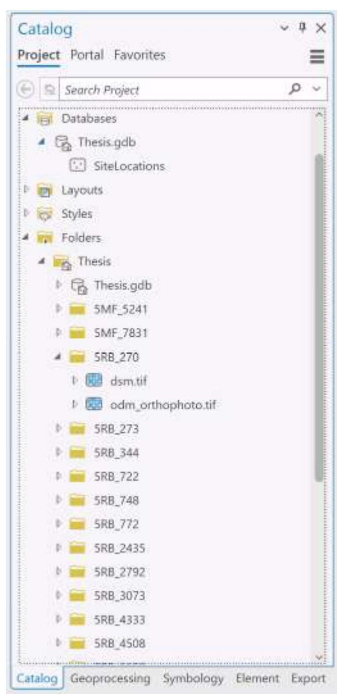


Figure 11, screen shot of the Catalog pane of ArcGIS Pro showing my organization system.

In adding to the map, I did not have ArcGIS Pro Calculate statistics of the rasters because of time constraints. All data was still clear and functional.I grouped the Orthophoto and DSM in the contents pane and labeled the groups by site designation. After double checking that the data was added successfully, I had to re-add data that ArcGIS was not reading correctly on sites 5RB.748, 772, 6868, and 8840. A simple delete and copying them via file manager solved the problem.

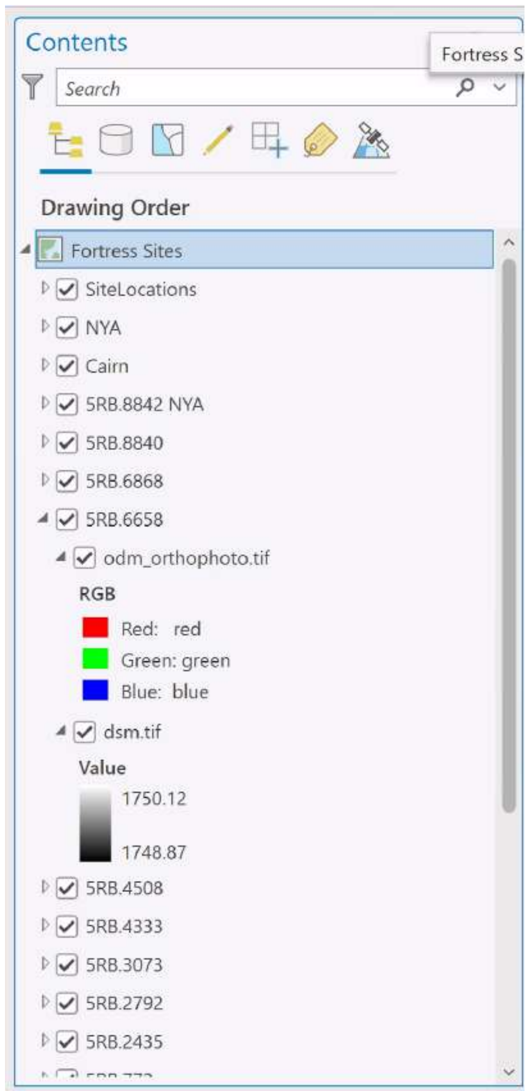


Figure 12, screen shot of the Catalog pane of ArcGIS Pro showing my organization system.

Once all sites were added, I created a point feature layer for the project with the field ‘SiteDesignation’. Using the orthophotos, I was able to zoom to layer on each group of site rasters and mark the center of the site features, adding the respective site designation to the proper field. This provides an overview map of the study area.

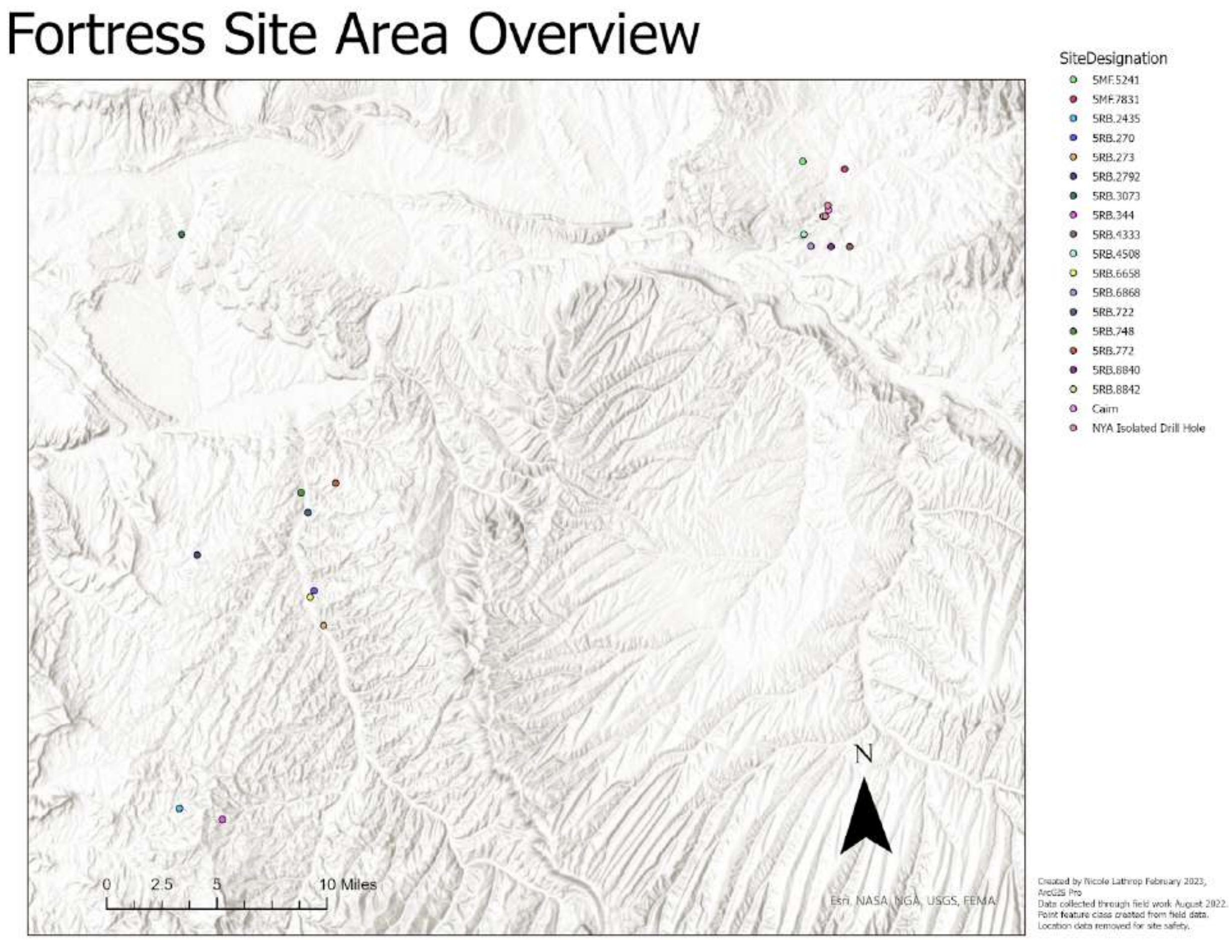


Figure 13, Map created in ArcGIS Pro to show an overview of the study area.

Future Improvements and Considerations

Through personal communication at the Colorado Council of Professional Archaeologists conference (2023), an idea that presented itself would be a repository of digitized site maps that would be accessible to relevant partners (Tribal governments and governmental departments that oversee archaeological sites) so that future researchers have access to the information.

This would be a large project to undertake, with need for buy-in from multiple cultural groups, departments, and agencies.

Using the Overview map, a future analysis could be done for line of sight locations, and test a hypothesis that the solitary post hole drill sites were used as a long distance ‘beacon’ that could be seen from another location.

Results and Discussion

When looking at the variety of these sites, there appeared to be two subcategories of the post hole sites; that where the structure was primarily situated around post holes, and a walled post hole site. For example, 5RB.722, 5RB.2435, and 5RB.3073 are examples of where masonry walls are distinguishable for a structure. The individual rocks can be made out in the drone imagery. The masonry process, and possibly the influence of the terrain it was built on, is shown with more environmental context.

Figures 14, 15, & 16, 5RB.722, 5RB.2435 and 5RB.3073 respectively.

In contrast, 5MF.7831, 5RB.772, and 5RB.6868 are sites where the expanse of rock surface contains little indication of building with masonry, but could indicate a more heavy reliance on the post holes.

Figures 17, 18, & 19, 5MF.7831, 5RB.772, and 5RB.6868 respectively.

Additionally, as opposed to these large sloping, bare rock faces, some of the sites were situated on clifftops, providing an additional feature that these were built for easier defense. These can be seen at 5RB.722, 5RB.3073 and 5RB.2435 (shown above), as well as 5RB.4333, a site that has not yet been assigned a designation, and a Cairn that was visible from 5RB.8840.

Figures 20, 21, & 22, 5RB.4333, Not Yet Assigned (NYA), and Cairns respectively.

Site 5RB.6658 and NYA (above) are incidents of solitary post holes. While it is hard to determine their purpose, it is determined that they were deliberately made and would have been a laborious process to create, leading to further questions of their use.

Figure 23, 5RB.6658, isolated drill site.

When assessing sites over multiple rock formations, such as 5MF.5241, or ‘The Clock Site’, and 5RB.748, there could be less detail in the orthophoto and 3D model because of the natural gaps created by the disrupted line of site around the base of the rocks. A way to correct this in Pix4DCapture is to fly as low as possible with a launch point close to the height of the tallest area of rock, with a maximum (90%) overlap and low camera angle. This allows the drone to capture rock walls of the surrounding outcrops from the sides as it passes.

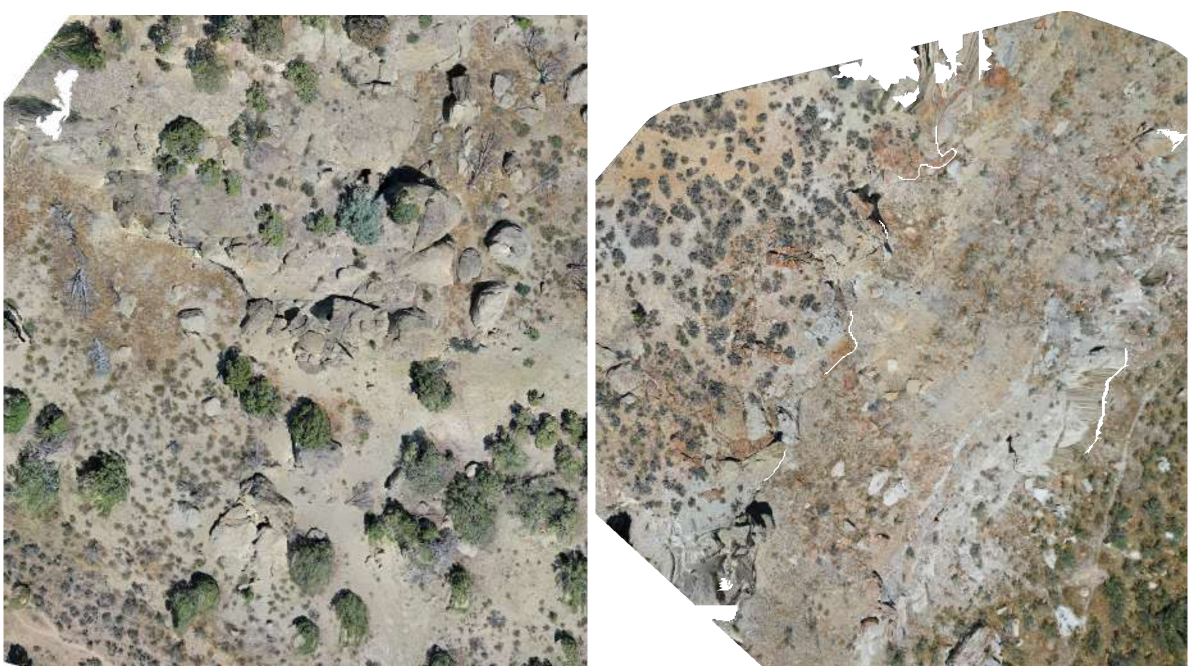
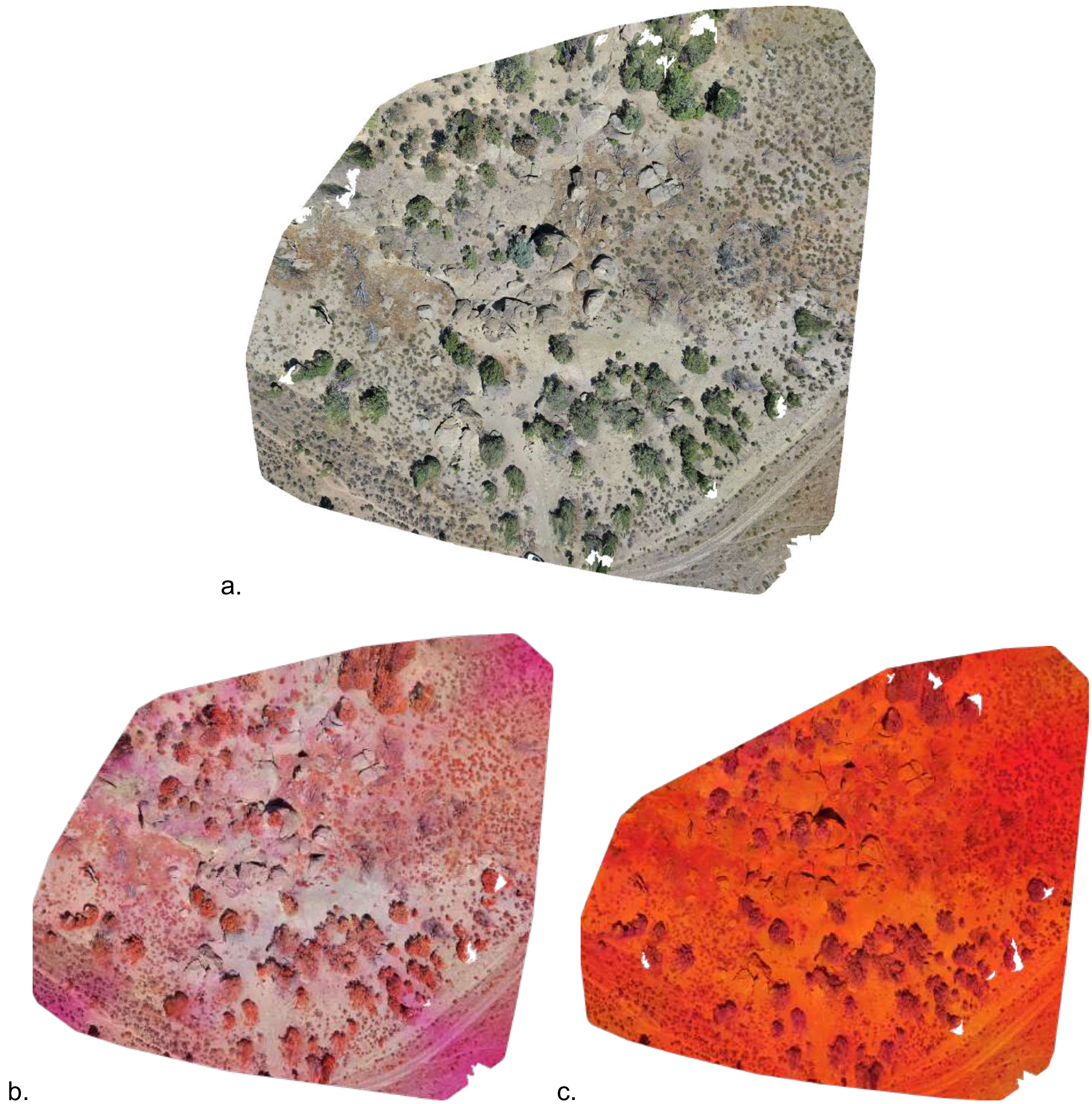


Figure 24 & 25, 5MF.5241, ‘The Clock Site’ and 5RB.748.

We can see from 5RB.6658, 5MF.5241, and 5RB.748 that there is some room for improvement in methodology and technology for images without error. As stated in earlier sections, the use of infrared for the analysis of plant health does not result in much information on a primarily rock site. To demonstrate this, the site 5FM.5241 was flown 3 times, first using Visual, then BGN, then RGN. The results show that the BGN provides the most information on vegetation, though for the sites in such arid areas it doesn't provide enough information for any prevalent research as of yet. In the visible and BGN version, there are game trails that can be made out on the bottom left, as evidence that this technique could be used in future studies pertaining to trails.



Figures 26 a, b & c 5FM.5241 in a)Visual, b)BGN and c)RGN.

Conclusion

This project was aimed for the aerial analysis of sites by drone photography. The accurate mapping by the drone proved that the equipment and method are a highly underrated archaeological tool. While not as costly or as detailed as lidar, the ability for a visual drone to capture the critical information of a site can result in an expansive and accurate dataset for future research.

Recording a site as a 3D model preserves the surface context of the site at that moment in time as a digital representation *in situ*. Every rock, tree, and shifted sand becomes part of the archaeological record. A spatial context that has been preserved so precisely that through digital tools an exact location can be found, with a precise time attached to a visual record.

Archaeologists argue that to best preserve a site, the researchers should refrain from excavation until a more advanced technology can be provided. This is such a technology. Multispectral images, to ground penetrating radar; as drone technology increases in the future, our ability to delve deeper into the past in a non-invasive way becomes a reality. In the areas where we had visited, there was an increase in recreational activity, which puts some sites at risk for vandalism. Using the drone, we were able to record the sites as they sat at this point in time.

By looking at these fortress sites using drone imagery, I am able to create an environment in which the resulting data can be manipulated for a broader picture of the site and its environment. When looking at sites like 5RB.273, we can understand the relationship between the masonry walls, the post holes and the adorning petroglyphs around the base of the rock outcropping. Site 5RB.2435 shows the resourcefulness of the builders to incorporate their surrounding landscape into the designs, with the nearly 100 foot (33 meter) cliff pillar forming the base of the structure, and resulting in a fortress that would have been virtually impenetrable.

Where a Drone offers a birds eye view of an area, photogrammetry provides a way to piece together the different views to solve the ‘puzzle’ in a 3 Dimensional context.

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Appendices

Data Processed

5MF.5241 Visible

Images: 523
Processing time: 01:16:10
Status: Completed
Created on: 8/21/2022, 1:03:29 PM
Processing Node: node-odm-1 (auto)
Options: dsm: true, dtm: true
Average GSD: 4.97 cm
Area: 5,437.17 m²
Reconstructed Points: 25,511,740

5MF.5241 RGN

Images: 312
Processing time: 00:35:14
Status: Completed
Created on: 8/21/2022, 3:03:56 PM
Processing Node: node-odm-1 (auto)
Options: dsm: true, dtm: true
Average GSD: 5.65 cm
Area: 5,088.61 m²
Reconstructed Points: 15,021,276

5MF.5241 BGN

Images: 309
Processing Time: 01:15:02
Status: Completed
Created on: 8/21/2022, 3:05:40 PM
Processing Node: node-odm-1 (auto)
Options: dsm: true, dtm: true
Average GSD: 5.66 cm
Area: 5,093.28 m²
Reconstructed Points: 16,133,734

5MF.7831 Visible

Images: 444
Processing Time: 02:26:44
Status: Completed
Created on: 8/27/2022, 6:57:17 PM
ProcessingNode: node-odm-1 (auto)
Options: dsm: true, dtm: true,
Average GSD: 5.64 cm
Area: 3,665.55 m²
Reconstructed Points: 23,052,942

5MF.7831 BGN

Images: 439
Processing Time: 01:29:52
Status: Completed
Created on: 8/27/2022, 6:59:49 PM
Processing Node: node-odm-1 (auto)
Options: dsm: true, dtm: true
Average GSD: 5.55 cm
Area: 2,305.96 m²
Reconstructed Points: 26,340,268

5MF.7831 RGN

Images: 441
Processing Time: 04:02:58
Status: Completed
Created on: 8/27/2022, 7:03:10 PM
Processing Node: node-odm-1 (auto)
Options: dsm: true, dtm: true
Average GSD: 5.58 cm
Area: 2,309.39 m²
Reconstructed Points: 26,912,780

5RB.270 Visible

Images: 141
Processing Time: 01:29:43
Status: Completed
Created on: 8/27/2022, 10:09:47 PM
Processing Node: node-odm-1 (auto)
Options: dsm: true, dtm: true
Average GSD: 5.11 cm
Area: 1,487,707.81 m²
Reconstructed Points: 6,672,968

5RB.273 Visible

Images: 322
Processing Time: 02:26:13
Status Completed
Created on: 8/27/2022, 10:11:49PM
Processing Node: node-odm-1 (auto)
Options: dsm: true, dtm: true
Average GSD: 5.51 cm
Area: 6,729.91 m²
Reconstructed Points: 10,513,251

5RB.273 BGN

Images:	96
Processing Time:	02:43:12
Status:	Completed
Created on:	8/27/2022, 10:13:00 PM
Processing Node:	node-odm-1 (auto)
Options:	dsm: true, dtm: true
Average GSD:	5.6 cm
Area:	3,988.12 m²
Reconstructed Points:	3,863,505

5RB.273 RGN

Images:	96
Processing Time:	02:56:46
Status:	Completed
Created on:	8/27/2022, 10:14:11 PM
Processing Node:	node-odm-1 (auto)
Options:	dsm: true, dtm: true
Average GSD:	5.53 cm
Area:	3,972.66 m²
Reconstructed Points:	3,599,692

5RB.344 Visible

Images:	191
Processing Time:	00:57:06
Status:	Completed
Created on:	8/27/2022, 10:15:57 PM
Processing Node:	node-odm-1 (auto)
Options:	dsm: true, dtm: true
Average GSD:	2.52 cm
Area:	28,540,788.94 m²
Reconstructed Points:	14,171,876

5RB.344 BGN

Images:	63
Processing Time:	00:56:13
Status:	Completed
Created on:	8/27/2022, 10:21:57 PM
Processing Node:	node-odm-1 (auto)
Options:	dsm: true, dtm: true
Average GSD:	0.37 cm
Area:	772.45 m²
Reconstructed Points:	3,062,807

5RB.344 RGN

Images:	63
Processing Time:	01:09:16
Status:	Completed
Created on:	8/27/2022, 10:22:34 PM
Processing Node:	node-odm-1 (auto)
Options:	dsm: true, dtm: true
Average GSD:	0.29 cm
Area:	772.97 m²
Reconstructed Points:	3,115,740

5RB.722 Visible

Images:	225
Processing Time:	02:51:09
Status:	Completed
Created on:	8/28/2022, 4:47:18 PM
Processing Node:	node-odm-1 (auto)
Options:	dsm: true, dtm: true
Average GSD:	3.12 cm
Area:	1,030.93 m²
Reconstructed Points:	46,991,023

5RB.722 BGN

Images:	154
Processing Time:	03:25:48
Status:	Completed
Created on:	8/28/2022, 4:48:08 PM
Processing Node:	node-odm-1 (auto)
Options:	dsm: true, dtm: true
Average GSD:	2.04 cm
Area:	259.54 m²
Reconstructed Points:	14,441,424

5RB.722 RGN

Images:	155
Processing Time:	04:01:35
Status:	Completed
Created on:	8/28/2022, 4:48:58 PM
Processing Node:	node-odm-1 (auto)
Options:	dsm: true, dtm: true
Average GSD:	2.16 cm
Area:	261.57 m²
Reconstructed Points:	16,044,480

<u>5RB.748 Visible</u>

Images:	102
Processing Time:	04:26:44
Status:	Completed
Created on:	8/28/2022, 4:56:10 PM
Processing Node:	node-odm-1 (auto)
Options:	dsm: true, dtm: true
Average GSD:	2.54 cm
Area:	1,922.87 m²
Reconstructed Points:	12,640,791

<u>5RB.748 BGN</u>

Images:	69
Processing Time:	04:43:18
Status:	Completed
Created on:	8/28/2022, 4:58:47 PM
Processing Node:	node-odm-1 (auto)
Options:	dsm: true, dtm: true
Average GSD:	2.33 cm
Area:	471.64 m²
Reconstructed Points:	7,128,317

<u>5RB.748 RGN</u>

Images:	69
Processing Time:	04:58:13
Status:	Completed
Created on:	8/28/2022, 5:02:30 PM
Processing Node:	node-odm-1 (auto)
Options:	dsm: true, dtm: true
Average GSD:	2.19 cm
Area:	471.71 m²
Reconstructed Points:	6,404,376

<u>5RB.772 Visible</u>

Images:	256
Processing Time:	01:40:28
Status:	Completed
Created on:	8/29/2022, 8:20:03 AM
Processing Node:	node-odm-1 (manual)
Options:	dsm: true, dtm: true
Average GSD:	2.69 cm
Area:	508 m²
Reconstructed Points:	38,662,590

<u>5RB.772 BGN</u>

Images:	253
Processing Time:	01:21:27
Status:	Completed
Created on:	8/29/2022, 8:20:49 AM
Processing Node:	node-odm-1 (manual)
Options:	dsm: true, dtm: true
Average GSD:	2.42 cm
Area:	454.5 m²
Reconstructed Points:	31,020,797

<u>5RB.772 RGN</u>

Images:	251
Processing Time:	01:01:33
Status:	Completed
Created on:	8/29/2022, 8:22:13 AM
Processing Node:	node-odm-1 (manual)
Options:	dsm: true, dtm: true
Average GSD:	2.5 cm
Area:	469.9 m²
Reconstructed Points:	32,049,222

<u>5RB.2435 Visible</u>

Images:	76
Processing Time:	01:47:20
Status:	Completed
Created on:	8/29/2022, 8:23:10 AM
Processing Node:	node-odm-1 (manual)
Options:	dsm: true, dtm: true
Average GSD:	0.75 cm
Area:	1,057.3 m²
Reconstructed Points:	10,269,348

<u>5RB.2435 BGN</u>

Images:	61
Processing Time:	02:26:28
Status:	Completed
Created on:	8/31/2022, 7:22:52 AM
Processing Node:	node-odm-1 (manual)
Options:	dsm: true, dtm: true
Average GSD:	0.35 cm
Area:	1,062.2 m²
Reconstructed Points:	2,296,539

5RB.2435 RGN

Images:	64
Processing Time:	00:19:35
Status:	Completed
Created on:	8/31/2022, 7:23:27 AM
Processing Node:	node-odm-1 (manual)
Options:	dsm: true, dtm: true
Average GSD:	0.64 cm
Area:	1,055.84 m²
Reconstructed Points:	7,503,774

5RB.2792 Visible

Images:	134
Processing Time:	01:21:06
Status:	Completed
Created on:	8/28/2022, 10:20:32 PM
Processing Node:	node-odm-1 (auto)
Options:	dsm: true, dtm: true
Average GSD:	2.56 cm
Area:	537.71 m²
Reconstructed Points:	18,067,438

5RB.2792 BGN

Images:	174
Processing Time:	00:31:00
Status:	Completed
Created on:	8/28/2022, 10:22:35 PM
Processing Node:	Lightning (auto)
Options:	dsm: true, dtm: true
Average GSD:	0.5 cm
Area:	689.82 m²
Reconstructed Points:	17,485,518

5RB.2792 RGN

Images:	174
Processing Time:	00:38:54
Status:	Completed
Created on:	8/28/2022, 10:23:57 PM
Processing Node:	node-odm-1 (auto)
Options:	dsm: true, dtm: true
Average GSD:	2.18 cm
Area:	701.43 m²
Reconstructed Points:	16,792,737

5RB.4333 Visible

Images:	359
Processing Time:	04:16:45
Status:	Completed
Created on:	8/29/2022, 8:30:36 AM
Processing Node:	node-odm-1 (manual)
Options:	dsm: true, dtm: true
Average GSD:	0.78 cm
Area:	25,117.86 m²
Reconstructed Points:	73,885,295

5RB.4333 BGN

Images:	180
Processing Time:	01:16:32
Status:	Completed
Created on:	8/29/2022, 8:31:45 AM
Processing Node:	node-odm-1 (manual)
Options:	dsm: true, dtm: true
Average GSD:	1.82 cm
Area:	4,646.46 m²
Reconstructed Points:	11,721,203

5RB.4333 RGN

Images:	290
Processing Time:	02:44:29
Status:	Completed
Created on:	8/30/2022, 9:15:56 PM
Processing Node:	node-odm-1 (manual)
Options:	dsm: true, dtm: true
Average GSD:	0.8 cm
Area:	12,447.07 m²
Reconstructed Points:	57,885,811

5RB.4508 Visible

Images:	114
Processing Time:	01:06:12
Status:	Completed
Created on:	8/29/2022, 8:36:26 AM
Processing Node:	node-odm-1 (manual)
Options:	dsm: true, dtm: true
Average GSD:	0.94 cm
Area:	12,456.52 m²
Reconstructed Points:	7,697,825

5RB.4508 BGN

Images:	114
Processing Time:	00:41:39
Status:	Completed
Created on:	8/29/2022, 8:42:05 AM
Processing Node:	node-odm-1 (manual)
Options:	dsm: true, dtm: true
Average GSD:	0.98 cm
Area:	12,874.62 m²
Reconstructed Points:	8,267,025

5RB.4508 RGN

Images:	111
Processing Time:	02:13:48
Status:	Completed
Created on:	8/29/2022, 8:43:33 AM
Processing Node:	node-odm-1 (manual)
Options:	dsm: true, dtm: true
Average GSD:	3.34 cm
Area:	12,474.4 m²
Reconstructed Points:	4,822,806

5RB.6658 Visible

Images:	3
Processing Time:	00:02:55
Status:	Completed
Created on:	8/29/2022, 9:01:15 AM
Processing Node:	node-odm-1 (manual)
Options:	dsm: true, dtm: true
Average GSD:	0.33 cm
Area:	9.59 m²
Reconstructed Points:	51,745

5RB.6868 Visible

Images:	408
Processing Time:	01:56:02
Status:	Completed
Created on:	8/29/2022, 8:54:38 AM
Processing Node:	node-odm-1 (manual)
Options:	dsm: true, dtm: true
Average GSD:	0.63 cm
Area:	13,089.05 m²
Reconstructed Points:	47,643,057

5RB.6868 BGN

Images:	392
Processing Time:	04:07:56
Status:	Completed
Created on:	8/29/2022, 8:57:26 AM
Processing Node:	node-odm-1 (manual)
Options:	dsm: true, dtm: true
Average GSD:	0.61 cm
Area:	13,164.03 m²
Reconstructed Points:	44,410,38

5RB.6868 RGN

Images:	402
Processing Time:	02:36:11
Status:	Completed
Created on:	8/29/2022, 8:59:03 AM
Processing Node:	node-odm-1 (manual)
Options:	dsm: true, dtm: true
Average GSD:	0.63 cm
Area:	13,063.96 m²
Reconstructed Points:	47,996,626

5RB.8840 Visible

Images:	131
Processing Time:	00:53:46
Status:	Completed
Created on:	8/29/2022, 9:04:29 AM
Processing Node:	Lightning (manual)
Options:	dsm: true, dtm: true
Average GSD:	0.93 cm
Area:	4,932.44 m²
Reconstructed Points:	13,823,188

5RB.8840 BGN

Images:	138
Processing Time:	00:59:59
Status:	Completed
Created on:	8/29/2022, 9:05:28 AM
Processing Node:	Lightning (manual)
Options:	dsm: true, dtm: true
Average GSD:	1.06 cm
Area:	11,791 m²
Reconstructed Points:	18,290,072

5RB.8840 RGN

Images:	126
Processing Time:	00:48:47
Status:	Completed
Created on:	8/29/2022, 9:06:13 AM
Processing Node:	Lightning (manual)
Options:	dsm: true, dtm: true
Average GSD:	0.95 cm
Area:	4,929.51 m²
Reconstructed Points:	14,360,150

5RB.8842 BGN

Images:	354
Processing Time:	01:16:19
Status:	Completed
Created on:	8/29/2022, 9:10:09 AM
Processing Node:	node-odm-1 (manual)
Options:	dsm: true, dtm: true
Average GSD:	0.65 cm
Area:	18,348.17 m²
Reconstructed Points:	36,531,830

5RB.8842 Visible

Images:	220
Processing Time:	00:42:32
Status:	Completed
Created on:	8/29/2022, 9:17:33 AM
Processing Node:	node-odm-1 (manual)
Options:	dsm: true, dtm: true
Average GSD:	3.89 cm
Area:	18,097.35 m²
Reconstructed Points:	9,268,372

5RB.8842 RGN

Images:	86
Processing Time:	01:10:32
Status:	Completed
Created on:	8/29/2022, 9:20:10 AM
Processing Node:	node-odm-1 (manual)
Options:	dsm: true, dtm: true
Average GSD:	3.6 cm
Area:	13,110.57 m²
Reconstructed Points:	3,146,82

5RB.3073 Visible

Images:	242
Processing Time:	01:51:16
Status:	Completed
Created on:	8/30/2022, 9:13:54 PM
Processing Node:	node-odm-1 (manual)
Options:	dsm: true, dtm: true
Average GSD:	3.6 cm
Area:	8,094.31 m²
Reconstructed Points:	12,461,157

5RB.3073 BGN

Images:	143
Processing Time:	00:55:48
Status:	Completed
Created on:	8/30/2022, 9:17:38 PM
Processing Node:	node-odm-1 (manual)
Options:	dsm: true, dtm: true
Average GSD:	5.11 cm
Area:	6,529.79 m²
Reconstructed Points:	7,103,790

5RB.3073 RGN

Images:	137
Processing Time:	00:28:32
Status:	Completed
Created on:	8/30/2022, 9:19:26 PM
Processing Node:	node-odm-1 (manual)
Options:	dsm: true, dtm: true
Average GSD:	4.91 cm
Area:	6,042.26 m²
Reconstructed Points:	6,267,168

Cairn Visible

Images:	14
Processing Time:	04:21:59
Status:	Completed
Created on:	9/1/2022, 10:04:27 PM
Processing Node:	node-odm-1 (manual)
Options:	auto-boundary: true, dsm: true, dtm: true
Average GSD:	0.3 cm
Area:	610.92 m²

Reconstructed Points:	597,657

NYA Visible

Images:	19
Processing Time:	04:29:50
Status:	Completed
Created on:	9/1/2022, 10:05:19 PM
Processing Node:	node-odm-1 (manual)
Options:	auto-boundary: true, dsm: true, dtm: true
Average GSD:	0.86 cm
Area:	1,259.64 m²
Reconstructed Points:	922,555

NYA BGN

Images:	6
Processing Time:	04:33:22
Status:	Completed
Created on:	9/1/2022, 10:06:35 PM
Processing Node:	node-odm-1 (manual)
Options:	auto-boundary: true, dsm: true, dtm: true
Average GSD:	0.82 cm
Area:	369.36 m²
Reconstructed Points:	653,096

Alternate Data Set

Fortress site Canyon Pintado (5RB.273) Visible

Images:	40
Processing Time:	00:04:56
Status:	Completed
Created on:	5/31/2021, 12:33:34 PM
Processing Node:	node-odm-1 (auto)
Options:	mesh-octree-depth: 12, use-3dmesh: true, pc-quality: high, mesh-size: 300000
Average GSD:	1.94 cm
Area:	4,874.34 m²
Reconstructed Points:	1,130,717

*Programmed Flight Information

Pix4D information key:

Proj:	Project
Date:	M/D format of 2022
Time:	24hr format, MDT
Type:	Double Grid (DG), Single Grid (SG), Circular (C)
FT:	Flight Time
Lat:	Latitude in Degrees and Decimal Minutes (as given by Pix4D)**
Long:	Longitude in Degrees and Decimal Minutes (as given by Pix4D)**
Size(m):	Size of grid flown in meters
%:	Overlap of images percentage
Camθ:	Camera Angle
Alt:	Altitude flown from launch point*
Pic:	Number of pictures taken
Path(m):	flight path distance flown
Site:	Site number
Spec:	Spectrum of images taken. Visible (Vis), Blue-Green-Neutral (BGN), Red-Green-Neutral (RGN)

*Some programmed projects were not flown, resulting in a gap in project number. The reason may have been a duplicated flight path, an error in photography, or as a safety for the benefit of the best imaging possible (especially early in the project where I was still getting used to the system). Other sites were flown several times, as the image overlap may not have been as much due to the altitude of the site above launch point.

** Removed for the safety of the site

Proj	Date	Time	Type	FT	Lat	Long	Size (m)	%	θ	Alt	Pic	Path(m)	Site	Spec
10	8/3	12:18	DG	8min	[redacted]	[redacted]	90x50	80	70	35	169	1011	5RB.4333	Vis
12	8/3	14:06	DG	7m6s	[redacted]	[redacted]	55x112	80	65	50	127	1070	5RB.8840	Vis
13	8/3	14:21	DG	7min	[redacted]	[redacted]	55x112	80	65	50	127	1070	5RB.8840	BGN
14	8/3	14:29	DG	7m4s	[redacted]	[redacted]	55x112	80	65	50	127	1070	5RB.8840	RGN
15	8/4	10:50	DG	21m13s	[redacted]	[redacted]	86x123	80	65	35	395	2403	5RB.6868	Vis
16	8/4	11:12	DG	16m16s	[redacted]	[redacted]	86x123	80	65	35	395	2403	5RB.6868	BGN
17	8/4	11:30	DG	16m40s	[redacted]	[redacted]	86x123	80	65	35	396	2403	5RB.6868	RGN
19	8/4	12:56	DG	7m31s	[redacted]	[redacted]	87x117	80	65	70	115	1372	5RB.4508	Vis
20	8/4	13:12	DG	10m43s	[redacted]	[redacted]	87x117	80	65	70	115	1372	5RB.4508	RGN
21	8/4	13:24	DG	7m37s	[redacted]	[redacted]	87x117	80	65	70	115	1672	5RB.4508	BGN
23	8/4	14:19	DG	11m52s	[redacted]	[redacted]	85x195	85	65	83	221	2285	5RB.8842	Vis
24	8/4	14:32	DG	15m50s	[redacted]	[redacted]	85x195	85	65	83	221	2285	5RB.8842	BGN
25	8/4	14:48	DG	15m22s	[redacted]	[redacted]	85x195	85	65	83	221	2285	5RB.8842	RGN
27	8/7	11:59	DG	9m1s	[redacted]	[redacted]	61x75	80	65	27	206	1265	5RB.5241	Vis
28	8/7	12:10	DG	14m37s	[redacted]	[redacted]	68x76	80	60	27	313	1436	5RB.5241	Vis
29	8/7	12:33	DG	13m6s	[redacted]	[redacted]	68x76	80	60	27	313	1436	5RB.5241	BGN
30	8/7	12:47	DG	28m	[redacted]	[redacted]	68x76	80	60	27	313	1436	5RB.5241	RGN

Proj	Date	Time	Type	FT	Lat	Long	Size (m)	%	θ	Alt	Pic	Path(m)	Site	Spec
32	8/7	14:43	DG	20m13s	[redacted]	[redacted]	50x63	80	60	17	443	1250	5MF.7831	Vis
33	8/7	15:04	DG	17m19s	[redacted]	[redacted]	50x63	80	60	17	443	1250	5MF.7831	BGN
34	8/7	15:23	DG	17m19s	[redacted]	[redacted]	50x63	80	60	17	443	1250	5MF.7831	RGN
37	8/8	11:17	DG	7m48s	[redacted]	[redacted]	64x101	80	60	51	143	1184	5RB.3073	Vis
43	8/8	11:40	C	3m8s	[redacted]	[redacted]	36x37		4	59	90	83	5RB.3073	Vis
45	8/8	11:46	DG	7m44s	[redacted]	[redacted]	64x101	80	60	51	143	1184	5RB.3073	RGN
46	8/8	11:55	DG	7m45s	[redacted]	[redacted]	64x101	80	60	51	143	1184	5RB.3073	BGN
48	8/8	14:26	DG	6m10s	[redacted]	[redacted]	43x54	85	60	42	115	578	5RB.6658	Vis
51	8/8	15:10	DG	7m38s	[redacted]	[redacted]	82x82	85	60	75	125	1156	5RB.270	Vis
52	8/8	15:19	DG	6m16s	[redacted]	[redacted]	72x67	85	60	73	96	839	5RB.270	Vis
53	8/8	15:26	DG	6m50s	[redacted]	[redacted]	84x60	85	60	71	98	851	5RB.273	Vis
54	8/8	15:33	DG	10m4s	[redacted]	[redacted]	84x60	85	60	71	98	851	5RB.273	RGN
55	8/8	15:45	DG	6m31s	[redacted]	[redacted]	84x60	85	60	71	98	851	5RB.273	BGN
57	8/9	11:03	C	2m42s	[redacted]	[redacted]	40x41		4	25	90	95	5RB.722	Vis
58	8/9	11:08	DG	7m59s	[redacted]	[redacted]	25x25	90	70	20	156	261	5RB.722	Vis
59	8/9	11:17	DG	10m18s	[redacted]	[redacted]	25x25	90	70	20	156	261	5RB.722	RGN
60	8/9	11:28	DG	7m34s	[redacted]	[redacted]	25x25	90	70	20	156	261	5RB.722	BGN
61	8/9	12:52	DG	4m4s	[redacted]	[redacted]	30x30	90	70	43	69	245	5RB.748	Vis

Proj	Date	Time	Type	FT	Lat	Long	Size (m)	%	θ	Alt	Pic	Path(m)	Site	Spec
63	8/9	13:02	C	2m19s	[redacted]	[redacted]	44x44		20	50	18	102	5RB.748	Vis
64	8/9	13:05	DG	4m34s	[redacted]	[redacted]	30x30	90	70	43	69	245	5RB.748	RGN
65	8/9	13:11	DG	4m31s	[redacted]	[redacted]	30x30	90	70	43	69	245	5RB.748	BGN
66	8/9	14:02	DG	10m47s	[redacted]	[redacted]	30x30	90	70	20	255	432	5RB.772	Vis
67	8/9	14:14	DG	13m36s	[redacted]	[redacted]	30x30	90	70	20	255	432	5RB.772	RGN
68	8/9	14:28	DG	11m14s	[redacted]	[redacted]	30x30	90	70	20	255	432	5RB.772	BGN
69	8/9	15:27	DG	5m19s	[redacted]	[redacted]	30x30	90	70	30	132	432	5RB.2792	Vis
70	8/9	15:37	DG	7m56s	[redacted]	[redacted]	35x35	90	70	30	175	456	5RB.2792	RGN
71	8/9	15:46	DG	7m53s	[redacted]	[redacted]	35x35	90	70	30	175	456	5RB.2792	BGN
72	8/10	10:27	DG	1m19s	[redacted]	[redacted]	26x27	90	80	75	23	133	5RB.344	Vis
76	8/10	10:33	DG	1m4s	[redacted]	[redacted]	30x30	90	80	63	24	204	5RB.344	Vis
77	8/10	10:34	DG	2m52s	[redacted]	[redacted]	37x35	90	80	63	64	318	5RB.344	Vis
78	8/10	10:40	DG	5m34s	[redacted]	[redacted]	37x35	90	80	63	64	318	5RB.344	BGN
79	8/10	10:48	DG	5m23s	[redacted]	[redacted]	37x35	90	80	63	64	318	5RB.344	RGN
80	8/10	11:48	DG	2m56s	[redacted]	[redacted]	37x45	90	80	70	64	377	5RB.2435	Vis
81	8/10	11:57	DG	5m24s	[redacted]	[redacted]	37x45	90	80	70	64	337	5RB.2435	BGN
82	8/10	12:04	DG	5m29s	[redacted]	[redacted]	37x45	90	80	70	64	377	5RB.2435	RGN

*Updated Site Maps

The accuracy of the 3D models provided an opportunity to create more exact maps than that previously in existence.

Site maps have been created for
5RB.4333
5RB.8840
5RB.6868
5RB.4508
5RB.8842
5RB.5241
5MF.7831
5RB.3073
5RB.6658
5RB.270
5RB.273
5RB.722
5RB.748
5RB.772
5RB.2792
5RB.344
5RB.2435
Unidentified clifftop Cairn

List of Figures and Pictures

ODM Quality Reports

The following pages are the result of the processing through Web Open Drone Map, with downloadable reports. Each report contains:

- Dataset Summary
- Processing Summary
- Previews
  - Orthophoto
  - Digital Surface Model
  - Digital Terrain Model
- Survey Data
- GPS/GCP/3D Errors Details
- Feature Details
- Reconstruction Details
- Tracks Details
- Camera Models Details

ODM Zip Files

From WebODM, downloadable Zip file packages contain:

- Point Cloud file
- ODM_DEM
- ODM_Georeferenceing
- ODM_Orthophoto
- ODM_Report
- ODM_Texturing