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Powerful Pictures: Uncovering Data in Aerial Photogrammetric Imagery

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Abstract

Unmanned aerial systems (UAS) are useful tools for many archaeologist; however, the data within the images captured by these systems is frequently underutilized. This paper discusses the benefits of extracting information embedded in aerial photogrammetric images and using them to improve mapping and documentation of archaeological sites. This paper offers three case studies to provide examples of how aerial photogrammetric imagery can help identify features and patterns not always recognizable from the ground or from standard aerial images.

Keywords: UAS, Photogrammetry, Structure-from-motion, Aerial imagery, Mapping

Introduction

Unmanned Aerial Systems are capable of providing stunning aerial imagery, however these images are often underutilized. In many cases photogrammetric images are used to generate orthomosaics, but often never mature beyond "pretty pictures". Advances in structure from motion (SfM) photogrammetric modeling and geographic information systems offer tools to harvest geospatially relevant and informative data from low altitude aerial imagery. This paper discusses methods and benefits for using aerial photogrammetry to accurately map large-scale sites, identify obscured archaeological features, and measure three-dimensional space. Conclusions are formulated from aerial photogrammetric data captured at three archaeological sites: the Ad Deir plateau in Petra, Jordan; the adobe-walled city of Paquimé in Chihuahua, México; and the Aztatlán site of Santo Domingo located in the coastal plain of Jalisco, México.

This paper specifically discuss ways structure from motion photogrammetric imagery are used to analyze archaeological sites. Examples include digital surface models (DSMs) used for geospatial studies, producing topographic maps with custom contour intervals to update outdated or non-existent maps, creating animations for documentaries and visualization used for public outreach, and generating georectified orthomosaics that integrate with traditional survey data and geospatial databases in basemap formats. Results from the case studies presented in this paper include the production of a topographic map for the Ad Deir plateau, the identification of architectural alignments at the Santo Domingo site, and defining unexcavated regions in Paquimé for future research. This paper concludes that utilizing the data within aerial photogrammetric imagery offers access to a wealth of informative data that can be used to uncover additional and often unseen patterns and information at archaeological sites.

Definitions

Photogrammetry

The concepts and practice of photogrammetry can be traced back several centuries to early studies in perspective, projection, and the development of photography (CPT 2008:1). There are many individuals who have contributed to the modern practice of photogrammetry, but these achievements rest on the shoulders of scientists and artists alike. Names such as Di Vinci, Lambert, and Dürer are on a long list that built the foundation for photogrammetric imagery. Anton Schenk (2005:3) suggests that there is "no universally accepted definition of photogrammetry." He does, however, offer his own definition of photogrammetry as "the science of obtaining reliable information about the properties of surfaces and objects without physical contact with the objects, and of measuring and interpreting this information" (Schenk 2005:3). CAST (2018) defines digital photogrammetry as "a well-established technique for acquiring dense 3D geometric information for real-world objects from stereoscopic image overlap and has been shown to have extensive applications in a variety of fields."

Photogrammetry targets can include anything from planets, mountain ranges, and buildings to the human body, industrial parts, and even small items such as coins, ceramic sherds, and any number of things whose shape can be recorded via a sensor, but typically with a camera (Schenk 2005:4). There are essentially two types of digital photogrammetry today: aerial and terrestrial or close-range. Aerial photogrammetry involves capturing imagery from an aerial platform or vehicle, but typically from an airplane or UAV. Close-range photogrammetry is usually performed at ground level and at a small scale using a variety of cameras, It is most successful using higher resolution, full-frame cameras with a fixed focal length lens. Advances in camera quality and software applications used to process the images are making close-range photogrammetry very popular. The same is true with aerial photogrammetry as UAVs are growing in capability and usability. In many instances, the terms photogrammetry and structure-from-motion are used interchangeably today, but there are some technical differences as noted below.

Structure-from-Motion (SfM)

Matthew Westoby et al. (2012:301) state that structure-from-motion has it origins in the computer vision community of the early 1990s and is based off algorithms developed in the 1980s. Structure-from-Motion (SfM) "operates under the same basic tenets as stereoscopic photogrammetry, namely that 3-D structure can be resolved from a series of overlapping, offset images" (Westoby et al. 2012:301). Structure-from-motion differs from traditional photogrammetry, however, in that it does not require previously established camera positions and orientation, nor does it necessarily need known control points. It can calculate three dimensional structure based on a set of highly overlapped and offset images (Westoby 2012:301). Westoby et al. (2012:301) explain that structure-from-motion creates the camera positions and scene geometry simultaneously through the "automatic identification of matching features in multiple images." Although structure-from-motion is capable of constructing structure without reference points, results are often improved by placing physical targets, such as high-contrast ground control points, before photographs are captured (Westoby et al. 2012:301).

In practice, the object in question must be photographed from multiple angles with a high degree of overlap, thus structure is created from the movement of the sensor or camera around the target. Natan Micheletti, Jim Chandler and Stuart Lane (2015:2) explain that the "scale invariant feature transform" algorithm is used to identify "common feature points across the image set, sufficient to establish the spatial relationships between the original image locations in an arbitrary 3-D coordinate system." The data is then processed through a "sparse bundle adjustment" which transforms the measured coordinates into a sparse 3-D point cloud (Micheletti, Chandler & Lane 2015:2). The sparse point cloud is then used to create a dense point cloud using "multi-view stereo techniques" (Micheletti, Chandler & Lane 2015:2).

Generating the dense point cloud requires distinct variation in texture and can be sensitive to lighting conditions. Two different SfM applications were used in the case studies for this paper: Pix4D's Pix4Dmapper and Agisoft Photoscan Pro. Both have similar capabilities which were used to generate a variety of datasets in all three case studies. The following sections discuss the power of SfM photogrammetry to extract informative and actionable information beyond a static aerial image.

Figure 1. Map showing the location of Petra in southwest Jordan.

Case Studies

Ad Deir Plateau, Petra, Jordan

In early 2013, faculty, staff, and students from Brigham Young University (BYU) planned a pedestrian archaeological survey of a very remote portion of the UNESCO World Heritage site of Petra, Jordan known as the Ad Deir Plateau (Figure 1). The plateau is located 1.5 kilometers northwest of the ancient Nabatean city center of Petra in the rugged desert mountains. The archaeological features at Ad Deir generally date to the first century A.D. The Ad Deir Plateau is accessed using a trail that starts in the Petra city center and winds through slots canyons before reaching the top of the plateau. Little is understood about why and how the Nabateans used this mountain top to build some of the larger structures in Petra. Archaeological features found on top of the Ad Deir plateau include massive barrel-vault covered cisterns, rock cut tombs, pools, and complex water channels. The "Monastery," a large monumental structure and centerpiece for the entire area, stands about 45 meters above ground and measures approximately 50 meters in width (Figure 2).

Accurate topographic maps for the Ad Deir plateau are rare at best. Generating an accurate topographic map of the region was a critical first step for a successful archaeological pedestrian survey and documentation of the plateau. Creating this map presented a daunting task due to the geographic size and extremely rugged terrain. Traditional terrestrial topographic surveying methods were not possible with the time and resources available, and the extreme terrain would have placed the surveying crew in exposed locations. Hiring a pilot with the necessary plane, aerial camera, and capability to process the images was also well outside the project budget.

In order to document the plateau and all the associated archaeological features BYU archaeologists used a fixed-wing UAS made by Gatewing and Trim-

Figure 2. Photo of the Ad Deir Monument located on the Ad Deir Plateau in Petra, Jordan. Photo courtesy of Joseph Bryce.

ble. This survey grade UAS, called the X100, was used to collect aerial imagery that was later used to generate georeferenced imagery that provided the foundation for various analyses and structure from motion (SfM) modeling. The X100 is fully autonomous, although users do have the ability to take control of the aircraft in emergency situations. The unmanned aerial vehicle (UAV) portion of the system is launched via a catapult which propels the aircraft into the air at a high rate of speed (Figure 3). The X100 lands on underside of the fuselage causing the folding propellers to fold backward to avoid damage. The X100 is made of expanded polypropylene (EPP) foam which is reinforced by a carbon fiber structure. It uses one lithium polymer battery that can power the entire aircraft and its associated systems for 45 minutes. The X100 has a 1 meter wingspan and can fly up to 80 kilometers per hour with an 2500 meter maximum ceiling and a 53 kilometer range. The camera is mounted inside the flight frame underneath the X100 and produces 10 mega pixel images which can provide a ground sampling distance (GSD) range from 3.3 to 25 cm.

A series of six ground control points (GCPs) were placed across the plateau prior to flight, and their positions were recorded using a Trimble GeoXH GPS with a tornado antenna. The GCPs were used to refine georeferencing during post processing. The flight over Ad Deir took approximately 30 minutes and covered a square kilometer. The X100 was launched and landed approximately 2.5 kilometers northeast of the plateau in one of the only open, flat fields in the area. The UAV flew at nearly 300 meters in altitude and captured 285 3648 x 2736 pixel photographs during 16 north-south transects. The resulting GSD was 11 cm per pixel which provided good resolution for identifying large architectural features. Smaller archaeological features were not as easily recognized. The images collected by the X100 were processed using Pix4Dmapper made by the Swiss company Pix4D.

An orthomosaic, survey grid, DSM, and contour

Figure 3. PPhoto of the Gatewing X100 fixed-wing UAS and catapult prior to take-off. The launch area was located approximately 2.5 kilometers northeast of the Ad Deir Plateau in the Al Beidha region. Photo courtesy of Bruce Allardice.

lines (5 meter interval) were generated from the captured images using Pix4Dmapper (Figure 4). These datasets were extremely valuable for planning the pedestrian survey across the plateau. The orthomosaic was imported into Avenza's MAPublisher which was used to create a virtual survey grid across the site. Each grid represents a 50 by 50 meter survey area on the ground. This grid was uploaded to a GPS and used by surveyors to identify their locations within a given survey block. The pedestrian survey covered 40 acres (16 hectares) and documented 533 separate archaeological features.

The Ad-Deir survey would not have been nearly as successful without the aid of the X100 UAS. The aerial orthomosaic allowed the survey team to more accurately assess the terrain and establish a plan to efficiently survey a very rugged location containing numerous archaeological features. In addition, the X100 was able to photograph, in high resolution, nearly a square kilometer of terrain which would have been too costly, both in time and accuracy, to document with a total station, GPS, or traditional aircraft. The data produced from the images acquired from the flight allowed for the generation of a very accurate topographic map, orthomosaic, DSM, and animations used in a documentary. These datasets were combined with linear, point, and polygonal GPS data collected during the pedestrian survey which resulted in a map showing the position and relationship between the numerous archaeological features, as well as their placement on the landscape. Several previously unmapped architectural features located on top of the steep, high cliffs northwest of the Monastery were also observed during image analysis.

Paquimé, Chihuahua, México

The UNESCO World Heritage site of Paquimé is located in the Chihuahuan desert of northern México (Figure 5). Charles Di Peso (1974:370) noted that Paquimé reached its zenith around

A.D. 1300 and measures approximately 88 acres or 36 hectares in size. Paquimé was built around a central polity with ceremonial mounds, multi-level structures, and Mesoamerican- style ball courts. The city was built of massive adobe walls and stone masonry and represents a collaborative organization

Figure 4. Orthomosaic generated by Pix4Dmapper from the images captured during the X100 flight. Contour lines were produced from a digital elevation model also created from the orthomosaic. The contour lines are shown superimposed over the orthomosaic.

Figure 5. Map showing the location of Paquimé in northern México.

of labor. Di Peso (1974:370) elaborates that Paquimé was built by a "massive labor force, which, operating under the strict control of a few individuals, produced a telltale pattern of wall abutments, underground plaza drain systems, formalized plazas, public entries, subterranean ceremonial structures, and staggered outer wall designs." Paquimé was among the largest, socially complex ancient communities in Northern México and the American Southwest. It was an impressive center of commerce, religion, and political power. Mike Whalen and Paul Minnis (2003:315) consider Paquimé to be one of the largest, and most complex, ancient communities north of Mesoamerica. Paquimé was a powerful trade center locally, but was also connected to a wider trade network. Paquimé traders likely interacted with Aztatlán cities along the Pacific coast, communities in the jungles of the Yucatán, and desert villages in the American Southwest. Items from these trade partners include millions of marine shell pieces from the western coast, copper items from the mountains along the western coast, and pottery from sites in the American Southwest. Evidence of parrots likely imported from the Yucatán were discovered in the form of breeding pens and hundreds of sacrificial macaw and turkey burials located throughout the city. Sometime around the beginning of the fifteenth century (c.a. 1450 A.D.), however, Paquimé began to unravel, and the site was eventually abandoned.

Di Peso excavated a large portion of Paquimé during the late 1950s and early 1960s. During his time at Paquimé Di Peso acquired aerial imagery of the entire site from multiple angles and altitudes. The aerial images he captured are extremely useful for viewing the city layout and its relationship to the surrounding terrain, water sources, and other natural resources. Di Peso's images provide a valuable historic view of Paquimé during Di Peso's excavations.

Following Di Peso's tradition of recognizing the value of aerial imagery to better visualize the enormity of Paquimé, archaeologists from BYU conducted aerial reconnaissance of Paquimé in the summer of 2015 using the fixed wing X100 UAS. Similar to the Ad Deir flight, eight GCPs were placed across the landscape and recorded using a Trimble GeoXH GPS. Positions for each GCP were processed using Trimble's Pathfinder Office with the majority of the GCPs recorded at between 30–50 cm in accuracy.

The take-off and landing locations were about 700 meters northwest of the center of Paquimé. Flight planning was performed using Gatewing's Quickfield software, and in-flight monitoring was maintained using Micropilot's Horizon 3.4, which runs on a Trimble Tablet PC. The X100 flight over Paquimé covered 0.54 km2 (133 acres or 53 hectares) in about 32 minutes, and flew 150 meters above the ground. The flight plan had a forward and sideways overlap of 80 percent. Weather conditions, as well as wind speed and direction were monitored using a Kestrel 4500 weather meter. During the flight the camera captured 422 3648 x 2736 pixel photographs. Each photo was taken with a 6.0 mm focal length, 1/250 shutter speed, f/4.0, and an ISO of 100. These photographs provided the raw data needed to produce a series of new maps, models, and visualizations using Pix4D's Pix4Dmapper software. This data was later post-processed using Agisoft Photoscan.

Pix4Dmapper used to calculate a 5.67 average ground sampling distance (GSD) based on the 150 meter flight altitude and camera settings. The quality check after initial processing returned a median of 24,761 key points per image, with all images enabled. The relative difference between initial camera parameters and optimized parameters was 0.07% which is well under the recommended 5% variation. Pix4Dmapper calculated 14,608.6 matches per calibrated image and determined a mean RMS error of 0.094 m for the eight ground control points. In addition, 2D links between matching images were strong over the majority of the target area. Based on the high accuracy and overlap, Pix4Dmapper was able to successfully compute corrected camera positions and generate automatic tie points between the photographs. This produced accurate, georeferenced maps and models in a variety of formats. Results include a georectified orthomosaic of the entire city of Paquimé, a DSM used for slope surface analysis, and a georeferenced plan map of Paquimé with a 50 cm contour interval. In addition, Pix4Dmapper was used to create 3D visualization animations from numerous angles and vantage points.

Documenting Paquimé using a small UAV to collect aerial images, combined with the numerous tools provided by Pix4Dmapper, offered the ability to efficiently and accurately map this ancient city at a high level of detail. Analysis of these aerial images provides new insights that traditional methods might not achieve without an exorbitant amount of

Figure 6. One of the 422 aerial photographs captured by the X100 to create an orthomosaic of Paquimé.

time and funding. In addition, total station or GPS mapping methods would be problematic at Paquimé, because portions of the city cannot be accessed due to their fragility.

Based on the point cloud generated using Pix4Dmapper, an orthomosaic was compiled from all 422 separate photographs (Figure 6). The point cloud also provided the ability to calculate and measure noted features in three dimensions. For example, measurements of various buildings and architecture were possible using the polyline, surface, and volume tools in Pix4Dmapper. For example, based on measurements from the Pix4Dmapper volume tool, "Reservoir 2" could hold approximately 828 m3 (828,000 liters/218,734 gallons) of water when completely full (Figure 7). In this case, these tools are helping evaluate the number of people that may have lived in Paquimé based on what is understood about human water consumption in hot and arid environments, compared to the capacity of Paquimé's reservoirs.

From the same point cloud 50 cm contour lines in shapefile format were generated to provide elevation data for a topographic map drafted from the orthomosaic. A DSM was also exported to ESRI's ArcMap for slope analysis and hillshade modeling. In addition, a polygonal mesh was constructed from the point cloud for creating 3D models and animations. A topographic map was drafted in Adobe Illustrator using Avenza's MAPublisher plugin.

The orthomosaic and the DSM slope model provided the background to digitize all of the archaeological features mapped by Di Peso. The 50 cm contour shapefile was imported into the Adobe Illustrator map using the same Avenza plugin, thus maintaining georeferencing for all digitized elements. This is likely the first comprehensive topographic map of Paquimé that includes all of the architectural

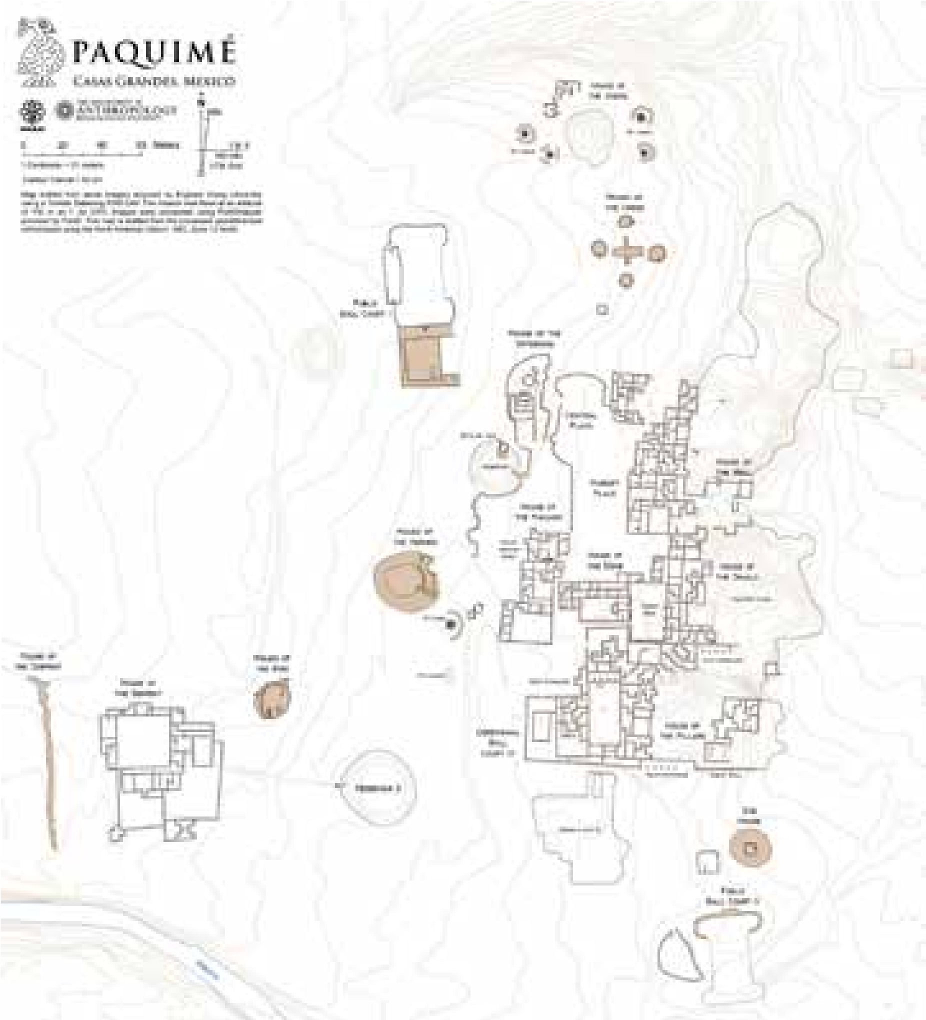

Figure 7. Map drafted in Adobe Illustrator using the Avenza MAPublisher plug-in. Contours were generated from a digital elevation model produced from the orthomosaic created in Pix4Dmapper. Architectural features were drawn directly from the orthomosaic.

features noted by Di Peso in a georeferenced format. This is an important resource that provides precise spatial information for future conservation and exploration efforts.

The DSM generated in Pix4Dmapper was also imported into ESRI's ArcMap for slope analysis and hillshade models to visualize the variation in terrain and architecture across Paquimé (Figure 8). The slope analysis results show steeper angles with warmer colors and flat surfaces in cool colors. The large pit ovens located near the "House of Ovens", on the north end of Paquimé, are especially visible due to their steep sides which display as red rings.

Interestingly, two round circles visible in the orthomosaic, located between the "Mound of the Heroes" and "Reservoir 2", were thought to be additional pit ovens; however, they barely appear in the slope analysis with only a 2.8–7.70 slope.

The results from the slope analysis also helped identify several areas that are likely unexcavated portions of Paquimé. Mounds to the east of the "House of the Skulls" and northeast of the "House of the Well" are quite visible in the slope analysis results and in the hillshade model. In addition, further east are two areas that look like they may be structural, based on their shape, size, and proximity to Paquimé proper. Moving south, to just below the "Ceremonial Ball Court II", Di Peso's "Unit 15" is very visible in the slope analysis model, and is another probable unexcavated area of Paquimé. Linear features, including aqueducts, and possible terrain alterations can be seen as well. It is unclear whether some of the linear elements are modern or ancient, but this data will help find these features during additional field work.

A hillshade model which uses a gray-tone shaded relief to enhance variation in surface terrain was also helpful for visualizing the site. This is similar to the color gradient used in the slope analysis, but it represents a smoother surface. Similar to the slope analysis image, the same unexcavated areas, structures,

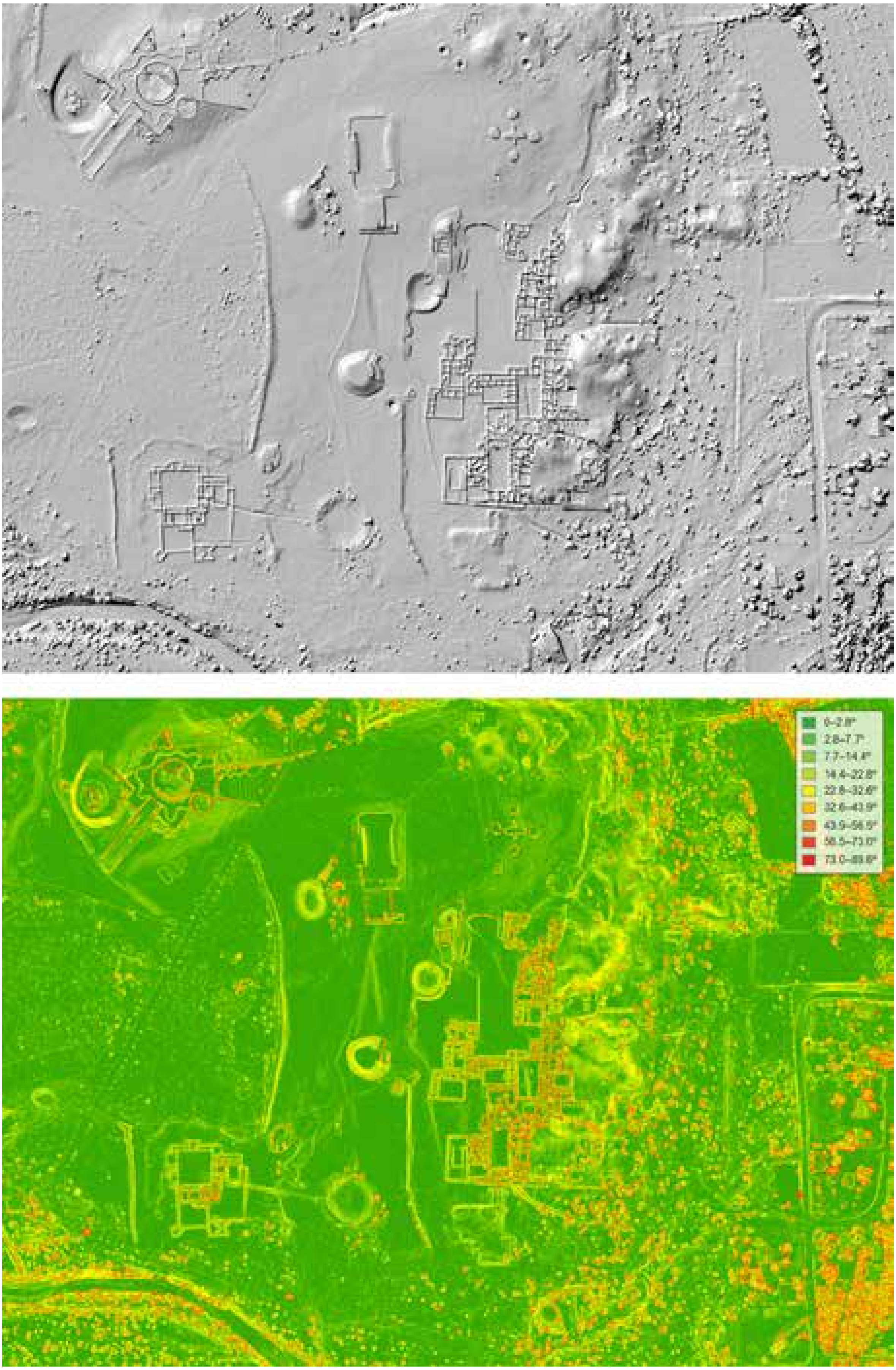

Figure 8. Images of the digital surface model (above) and the slope analysis results (below).

Figure 9. Map of west México showing the location of the Santo Domingo site near the modern city of Puerto Vallarta, Jalisco.

and linear features are quite visible. Both hillshade and slope analysis models have proven useful for identifying these subtle changes in the terrain that are not evident in the orthomosaic alone. This short exercise shows the importance of using multiple methods to examine aerial images of archaeological sites. The ability to import the DSM into ESRI's ArcMap helped identify important architectural features at Paquimé that may not have been visible otherwise. Consequently, this new information will help with future exploration or protection of the remaining uncovered portions of the city.

Santo Domingo Site, Jalisco, México

The Santo Domingo site is an unexcavated Aztatlán site located on the Pacific coastal plain of West México (Figure 9). It is located in the hills above the modern town of Ixtapa and roughly 8 kilometers northeast of Puerto Vallarta. Susan Evans and David Webster (2001:58) explain that West Mexican Aztatán sites date from A.D. 900 to A.D. 1450 and spread from along the Pacific coast from "central Jalisco up to the Sinaloa/Sonora border, and extended up into the western fringe of the Mexican plateau from the Jalisco/Michoacan border area in the south to central Durango in the north." Michael Mathiowetz (2017:1), Daniel Pierce (2017:218), and Charles Kelley (2000) note that trade was an integral part of Aztatán culture in West México, and there is good evidence they were trading cacao, finished copper ornaments, marine shell, pottery, cloth, and obsidian to areas far outside their homeland.

In the Spring of 2017 a team of BYU archaeologists joined Dr. Michael Mathiowetz from Riverside City College and INAH archaeologist Mauricio Garduno Ambriz as part of an initial effort to document several important Aztatlán sites located in the coastal heartland in Nayarit and Jalisco, México. A total of five sites were flown using a DJI Phantom 4 Pro UAS. The goal was to collect photogrammetric imagery of each site to produce georeferenced orthomosaics, topographic maps, and digital elevations models. Three of these sites (Las Animas, San Juan de Abajo, and Ixtlán Del Rio) are considered Aztatlán political centers (Mathiowetz 2017:2).

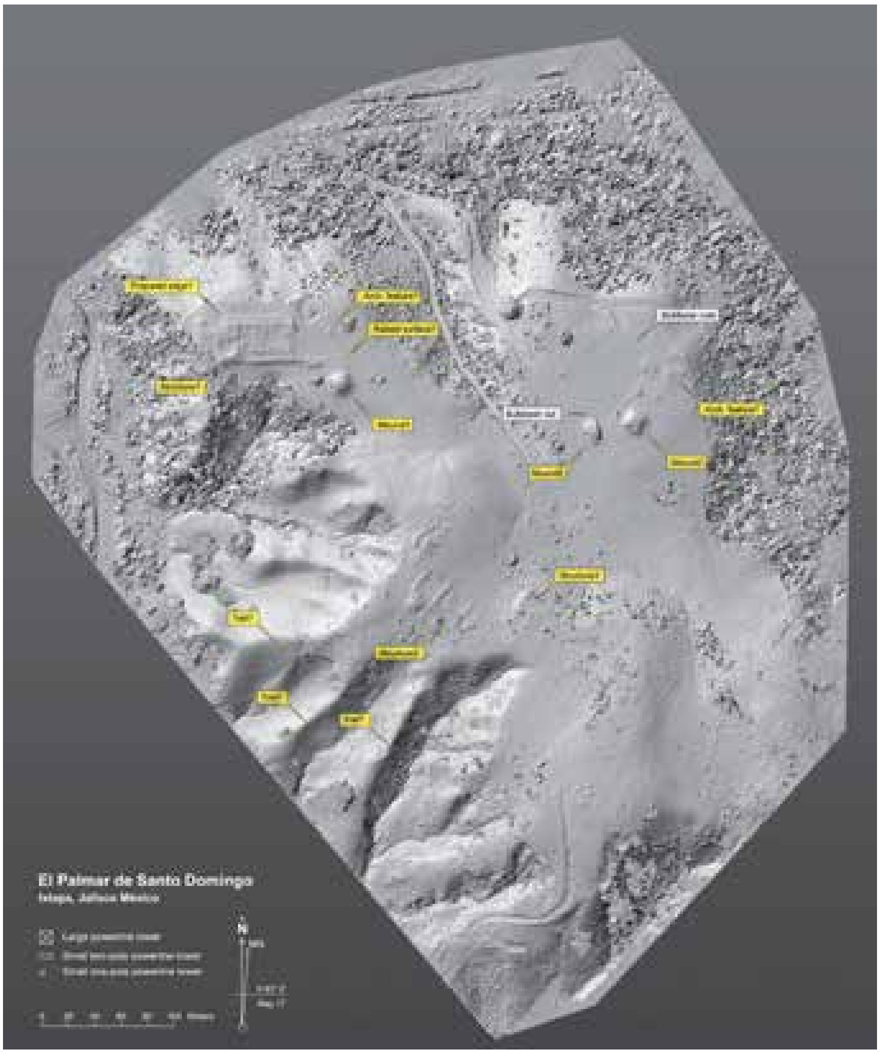

Figure 10. Annotated map of the Santo Domingo site with a DSM generated from Agisoft Photoscan as the base layer. Note the visible bulldozer tracks and damaged mound in the northeast portion of the site which were not visible in the orthomosaic.

These flights started the "first long-term, extensive regional survey and excavation program in the Aztatlán coastal heartland" (Mathiowetz 2017:2). The goal for incorporating UAVs in this project was to provide detailed maps as part of the larger documentation effort needed to conserve and excavate these critical, but generally understudied Aztatlán sites. The flights at the Las Animas, San Juan de Abajo, and Ixtlan Del Rio sites were all successful in achieving our goals; however, we were asked to fly and additional site named Santo Domingo that is currently under immediate threat from residential development.

The site was flown using a DJI Phantom 4 Pro (P4P). This UAV is a small, multi-rotor UAV is capable of flying for about 30 minutes at varying altitudes and a range of 3 to 7 kilometers. Flying at these distances is not recommended, however, as many regulations require continual line-of-sight with any UAV. The P4P has various "smart" capabilities including obstacle avoidance using infrared sensors and vision systems. The onboard camera is mounted to a gimbal and has a 1 inch CMOS sensor capable of 20 megapixels. The P4P was flown at the sites in México using DJI's Ground Station Pro app. This app allows users to easily define a flight plan, overlap percentage, flight time, camera settings, and others useful settings. Once calculated, the flight plan is uploaded to the UAV and then automatically flown with minimal user intervention unless required. Take-offs and landings are typically automatic, and can be performed in small areas, unlike fixed-wing UAVs which require larger clearings. For the Santo Domingo flight, the P4P flew at an altitude of 100 meters to clear large power lines and towers cutting through the site. The UAV covered an area of about 0.25 km2 (67 acres or 27 hectares) in approximately 15 minutes. During the flight, the onboard, gimbal-mounted camera recorded 156 5472 x 3078 pixel georeferenced images. These images were captured using the DJI FC6310 camera with a 9 mm lens. The camera was set to f/6.3 with a shutter speed of 1/640 and ISO 100. Each photo was automatically geotagged for georeferencing purposes.

Images captured from the Santo Domingo site were processed using Agisoft's Photoscan Pro in order to produce a variety of outputs using SfM processing. All 156 photos were accurately calibrated and aligned resulting in 138,352 unique tie points between the images and a ground sampling distance of 3.39 cm/pixel. A dense point cloud consisting of 22,575,078 points was generated from the camera alignments. A polygonal mesh consisting of 1,505,003 total triangular faces and 756,518 vertices was then generated from the dense point cloud. Based on the dense point cloud, an orthomosaic and DSM were created to examine the site for the location and association of architectural features not easily visible on the ground. In addition, a tiled texture model was produced to examine the model texture in high resolution. This is one of Photoscan Pro's more powerful tools, because "it allows for responsive visualisation of large area 3D models in high resolution" (Agisoft Photoscan 2018:19).

Previous pedestrian surveys and maps by Joseph Mountjoy (2003) documented several mounds and possible wall alignments at the site. Recently, local archaeologist noted where construction work was underway to develop the area for housing. In one area a large mound had been cut through with heavy equipment. Initial examinations of the orthomosaic did not reveal any identifiable traces of architectural elements or alignments, but the DSM offered a much more useful view. The DSM was imported into ESRI's ArcMap which was used to generate a hillshade that revealed several well defined architectural features (Figure 10). These features include three multi-room, walled structures, three mounds, two unidentified architectural features, and two prepared platform areas. Recent bulldozer cuts are visible throughout the eastern part of the site, along with where Mound 2 was cut through. In addition, several ridge lines appear to be flattened and may be prehistoric trails used to access the Santo Domingo site. Further examination is required to test this hypothesis. Based on these results, a hillshade created from a DSM, which was based on a dense, high resolution point cloud created using SfM, proved extremely valuable for identifying these features.

These datasets were used to map these Aztatlán architectural features quickly and accurately, as well as note the presence of modern bulldozer activity damaging features at the Santo Domingo site.

Conclusions

This paper described a few examples of how aerial photogrammetry and structure-from- motion modeling can be used to accurately map large-scale sites, identify obscured archaeological features, and measure three-dimensional space. Harnessing the data within these images offers the potential to uncover additional, and often unseen patterns and information about the archaeological sites we study. This was true for all three case studies. Results from the Ad Deir flight provided extremely useful information to plan and execute a controlled and organized survey of a particularly rugged and complex area. In addition, the SfM data were integral in creating a high-resolution topographic map of the Ad Deir plateau. Models generated from the SfM also provided useful animations of this dynamic terrain to help viewers visualize the archaeological complexity of the plateau, as well as see the interconnected nature of the site itself. At Paquimé, data generated from aerial imagery captured via a UAV also provided the framework for a topographic map of the site, as well as a host of other valuable analysis to identify unexcavated portions of the city. The integration of geospatial analysis with SfM models also proved to be a powerful combination of tools to analyze reservoir capacities at Paquimé. This information could lead to additional studies about the available water resources and the population size these reservoirs could have sustained. Finally, the flight over the Aztatlán site of Santo Domingo in West México resulted in an SfM model also analyzed with geospatial tools to identify architectural features not easily visible on the ground or in aerial imagery. In addition, the SfM model was able to show bulldozer activity and damage to the site surface and at least one prehistoric mound.

Unmanned Aerial Systems are capable of providing stunning aerial imagery, and with advances in SfM and geospatial analysis, we have access to tools that can vastly improve our remote sensing capabilities. The cost and time to learn how to use these instruments and software is less expensive and quicker than ever before. Additional advancements and the miniaturization of various radar, LiDAR, and multispectral sensors will offer future tools to document, analyze, and discover archaeological sites at high levels of detail. The future of UAS use in archaeological research will only continue to grow as he related technologies continue to develop.

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