Assessing Terrestrial Laser Scanning in Complex Environments

An Approach from the Ancient Maya Site of Pacbitun, Belize

Jennifer Weber and Terry G. Powis

ABSTRACT

The majority of terrestrial scanning projects in archaeology have focused on heritage documentation, preservation, and the three-dimensional (3D) reconstruction of prominent sites and objects. While these are very important archaeological foci, not many have used terrestrial scanning methods for prospection and feature analysis, similar to the way many have employed airborne LiDAR. While airborne LiDAR scanning is able to situate and analyze archaeological sites on an expansive scale, the ground-based method also captures and defines any landscape anomalies or depressions from cultural features that have remained invisible to the naked eye due to environmental restrictions. In an attempt to test this recording method, we set out to paint a non-invasive, 3D digitized picture of the ancient Maya site of Pacbitun, Belize, using terrestrial scanning to distinctly detail Pacbitun's structures, plazas, causeways, and karst features. This paper details the process through which 3D terrestrial scanning was executed at Pacbitun and three associated peripheral caves during the 2012 and 2013 field seasons. We discuss the potential laser scanning has for visual analysis in archaeology and evaluate application difficulties encountered in the field, as well as current data interpretation issues.

This paper presents the results of a terrestrial laser scanning (TLS) survey at the ancient Maya site of Pacbitun in Belize. Given their potential to acquire large and precise three-dimensional (3D) data sets in short amount of time, terrestrial laser scanners are increasingly utilized in archaeological investigations. While terrestrial scanning continues to be applied mainly for the close range documentation of structures and objects, we set out to assess whether or not the method can serve as a cost-effective alternative to airborne laser scanning (ALS) in complex environments. In addition, we wanted to assess its potential advantages in terms of time and accuracy over traditional recording practices. Therefore, we conducted a TLS survey during the 2012 and 2013
summer field seasons, detailing the site's structures, plazas, and causeways. Specifically, our goals were to test (a) the practicality of implementing TLS in a tropical environment and rugged terrain; (b) if and to what extent a TLS survey might be advantageous over traditional survey methods in such complex environments; and (c) whether or not the results of the TLS survey can compete with ALS data for prospection purposes.

**BACKGROUND**

**Laser Scanning Technologies**

At the most basic level, laser scanning accurately and repeatedly measures distance based on time, creating coordinates (Opitz 2013). Operating machines come as either aerial systems with airborne laser sensors (ALS) or as terrestrial systems with terrestri-al laser sensors (TLS) (Pirotti et al. 2013; White 2013). Airborne laser systems are mounted on an airplane or helicopter and are generally referred to as LiDAR, while a TLS system is comprised of a 3D scanner mounted on a tripod (Masini et al. 2011; Remondino 2011). In an ALS survey, a laser scanner sends out a pulse that can be reflected back to the moving sensor from multiple encountered targets. The sensor's integrated global positioning system (GPS) records and calculates the altitude and position of each reflection. With the help of geographic information systems (GIS) or computer-aided design (CAD), a digital elevation model (DEM) can then be constructed from the collected point cloud data (Devereux et al. 2008; Gallay et al. 2013; Masini et al. 2011; Sittler et al. 2007; White 2013). Thus, ALS (LiDAR) can be seen as beneficial for georeferenced mapping and prospection, as well as for regional landscape studies that are focused upon the detection of archaeological remains under a canopy of vegetation (Challis et al. 2011; Chase et al. 2012; Giardino 2011).

As mentioned, TLS systems are operated from fixed positions from where they record all that is in their field of view, producing large point clouds of x, y, z data. Here, the recorded coordinates are also stored as point clouds, which can then be used to create high spatial resolution digital terrain models or DTMs. Most such scanners also have in-built digital cameras allowing them to capture color data while scanning (Armesto-González et al. 2010; Chase et al. 2012; Clawges et al. 2007; McCoy and Lade-foged 2009; Pirotti et al. 2013; White 2013). Generally, terrestrial laser scanning is preferred for precision surveys, documentation, and the creation of 3D models of archaeological objects and features in confined, small areas (Gallay et al. 2013; Haddad 2011; White 2013). The capacity and speed of TLS are especially beneficial for projects concerning preservation of heritage and archaeological sites; as they are increasingly endangered by natural and man-made threats (Armesto-González et al. 2010; Núñez et al. 2013; Remondino 2011). For example, studies have shown that ancient desert palaces located next to an international highway connecting Jordan to Saudi Arabia and Iraq are affected by several environmental conditions, the worst of these being vibrations that are caused by heavy trucks, creating cracks in the walls of the palaces (Al-kheder et al. 2009). To assess damage and conservation needs, two of these affected desert palaces, Amra and Kharanah, located east of Amman, Jordan, were documented using 3D laser scanning in combination with digital photogrammetry and GIS technology (Al-kheder et al. 2009).

While other methods of acquiring 3D data, like photogrammetry, can be more economically feasible, terrestrial scanners usually not only work faster in comparison but also provide better texture documentation (Grussenmeyer et al. 2008; Lerma et al. 2010). Hinzen and colleagues (2012) used a terrestrial scanner at a Roman theater site in Pinara, Turkey, to investigate recorded inclinations of stone rows from the auditorium, interpreted to have been caused by seismic tectonic movements. The inclination had been previously recorded by ALS; however, a subsequent TLS survey was conducted to create a higher resolution 3D model of the site. From it, inclination values of individual seat rows were measured and compared to those recorded from the ALS survey data. The smaller and consistently increasing inclination numbers derived from the more precise TLS data yielded the hypothesis that measurement errors during the ancient construction times could be the cause, or an additional cause, for the displaced stones (Hinzen et al. 2012).

**Study Site**

Since the early 1980s, a number of archaeological investigations have contributed to the knowledge of Pacbitun's history with regard to site habitation, settlement distribution, and population size (Healy et al. 2007). From the late 1980s to the early 1990s, archaeologists from Trent University, Canada, focused much of their attention on settlements within 1 km of the Pacbitun site core. Since then, one of the goals of the Pacbitun Regional Archaeological Project (PRAP) has been to conduct a complementary survey to further identify and describe structures in the site core and along the periphery that may yield evidence of ritual landscape use, ancient settlement, social stratification, and environmental modification.

The ancient Maya site of Pacbitun is located approximately 10 km south of the Belize River near San Antonio, Cayo District, Belize (Figure 1). First inhabited during the Middle Preclassic period (ca. 800 B.C.), Pacbitun reached its peak of cultural development during the Late Classic period (ca. A.D. 600–900), at which time the inhabitants of the site likely controlled an area of 9 km². Monumental architecture constructed at the site dates to ca. 300 B.C., suggestive of a move from an egalitarian village to a settlement with an emerging elite class and increasing social stratification (Healy 1992). Recent ceramic analyses indicate that the site was possibly abandoned by the beginning of the tenth century (Healy et al. 2007). The .5 km² core zone of the site consists of five primary plazas (A–E) that are surrounded by a variety of masonry structures (Figure 2). There are also three causeways present at Pacbitun: Mai Causeway, Tzul Causeway, and Tzib Causeway. Mai Causeway begins adjacent to Structure 11 in the site core and runs east for approximately 273 m, before terminating in front of Structure 10. The Tzul Causeway also starts at Structure 11 but runs south-west into the periphery where, after about 900 m, it intersects with another ancient Maya road, which was named Tzib Causeway. Below this confluence, Tzul Causeway continues into the foothills for about 1.2 km and terminates in front of Tzul’s Cave. Tzib Causeway measures
FIGURE 1. Location of Pabitun, Cayo District, Belize.

FIGURE 2. Pacbitun Site Core (after Healy 1990:Figure 3, with modifications by Jennifer Weber).
about 600 m in length and connects a plazuela group to a minor center (Weber 2011).

While the initial settlers of the valley focused primarily upon productive river bottom lands, Maya colonists may have later started to expand to nearby, adjacent lands (Powis 2009). Pacbitun is situated at the juncture of two ecozones: the lowland tropical rainforest and the Mountain Pine Ridge (Healy 1990; Healy et al. 2004). These contrasting micro-environments and variable local resources likely played a role in site selection. Limestone lowlands are located to the north in a broadleaf rainforest, providing access to farmable land (Healy 1990; Powis 2009), and the Pine Ridge to the south provides access to pine, granite, and slate. Settlement studies at Pacbitun have indicated a population rise from the Preclassic through Classic periods, and population estimates indicate that ca. 5000–6000 people occupied the site at its zenith (Healy et al. 2007). This complements an apparent increase in maize production during the Late Classic Period, evidenced by the construction of numerous agricultural terraces in the hilly zones surrounding the site. The increase in construction suggests that land was already in use at the time, forcing people to spread out into less desirable terrain for farmland (Healy et al. 2004; Weber 2011). As Healy and colleagues (2004) note, the residents of Pacbitun used animals—collected from undisturbed and cut forests—for both subsistence and ceremonial purposes. Although Pacbitun is located farther from a riverine ecozone than other sites of similar size, river turtles and freshwater gastropods have been recovered, which is suggestive of frequent trips to nearby creeks (Healy et al. 2004).

The Caves

Many of the caves around Pacbitun had been previously looted and are now under threat due to increased tourism in the area (Spenard 2012). Under consideration of time, we selected three caves (Actun Lak, Tzul’s Cave, and Crystal Palace Cave) to create some level of preservation through 3D scanning.

Actun Lak or “Pottery Cave” was initially documented in the mid-1990s and is situated to the south of Pacbitun, at an elevation of approximately 269 m. The cave consists of three chambers, five ledges, and an entrance area (Spenard 2011, 2012). Lak was named for the great abundance of ceramic sherds that blanket the interior surface of the cave floor. Chamber 1 is the largest chamber in the cave, measuring 23 m in length, 14 m in width, and 10 m in height (Spenard 2012). The chamber ends at a natural doorway atop an elevated ridge, beyond which lies Chamber 2, where a speleothem altar and sloth bones were recovered. Chamber 2 measures 11 m by 13 m in width and 2 m in height. Chamber 3 measures only a few meters across and largely consists of a sloping, muddy passageway that ends abruptly after a 180-degree turn (Spenard 2012).

Tzul’s Cave lies at the end of Tzul Causeway and is a long, narrow cave situated at the peak of a steep hill at an elevation of 259 m. The cave measures approximately 35 m in length and is roughly V-shaped, with six rooms (Rooms A–F) (Powis 2010). While Room A is the longest and narrowest, no artifacts were recovered from it. It is connected to the smallest room, Room B, which contained some sizable Late Classic (ca. A.D. 600–900) rim sherds. Room C contains various sizable niches with placed rim sherds and was sealed at the west end by a circular piece of slate, ca. 50 cm in diameter, which was placed to block entry to Room D. The actual diameter of the opening from Room C to Room D was much larger than the slate slab. Consequently, a small wall, 1 m in height, was built beneath the orifice in Room D, which narrowed the opening between the two rooms, allowing the slate slab to be mortared in place. Room D contains a few complete serving dishes and broken olla sherds. Another slate slab was also used to block entry from Room D into Room F. Room E lies to the north of Room D and contains a cache of 13 complete pottery vessels that date to the Late Classic period (Powis 2010).

Crystal Palace Cave is also located south of Pacbitun, to the east of Tzul’s Cave. Outside of the cave is a single house mound located 15 m northwest of its entrance. Surface collections from the top of the mound yielded predominantly Late Classic pottery sherds. The cave is U-shaped and measures approximately 55 m in length, with a height of about 4.5 m and a width of 17 m. The entrance itself is relatively large, measuring about 4 m by 2 m (Weber 2011; Weber and Powis 2011). After a 2-m descent, there is a large and open main chamber. The entrance gradually slopes downward, allowing access to more than one person at a time. Inside, two sets of manmade stairs were located, as well as numerous caches of vessels (broken plates, bowls, and ollas), and broken stalactites and stalagmites, suggesting a possible relation to ritual usage, as well as water collection and/or food offerings to Maya deities (Healy et al. 1996). Two of the ceramic vessel caches were placed beneath roof collapse in two separate locations within the cave (Weber 2011; Weber and Powis 2011).

METHODS

Equipment and Technology Used

The terrestrial scanner used at Pacbitun was the Leica C10 scan station, a time-of-flight 3D long-range scanner that allows for a 360° rotation and has a range of up to 300 m. Time-of-flight (TOF) or pulse-based scanners measure the time that it takes for the light of an emitted single pulse to hit an object and for the reflected echo to travel back to the instrument (Table 1) (Doneus et al. 2009; Opitz 2013; Remondino 2011; White 2013). The resolution produced by the Leica C10 measures up to 6 mm at a 4-mm distance (Table 2). Like most terrestrial scanners, the Leica C10 instrument is restricted by line-of-sight limitations, and resolution quality is affected by distance. Because of this, most scanning projects will need to be set up at multiple locations to capture the entire desired area or feature and to avoid shadows caused by line-of-sight restrictions. In order to connect these multiple location scans, the scanner is provided reference points (targets), which can be used to stitch the individual scans together. While two targets can be used at a minimum, three to five targets are preferable.

At Pacbitun, up to eight reference points, four 15-cm (6-inch) round targets and four 7.5-cm (3-inch) rectangle targets, were employed during scans. These were situated on tripods and had to be leveled before scanning, as did the scanner itself. Each target was given an identification number and sighted at each station. For backup purposes, a flag was placed in each target location with the identified station and target number used in each data file. The number of scans collected on any given day...
was weather-dependent, as rain showers interrupted the scanning process for a variable amount of time almost daily. Given the tropical environment of the dense jungle, the site core had to be cleared to maximize ground and structure visibility and to reduce post-processing time. Software used for post-processing was Cyclone 7.3 in 2012 and Cyclone 8 in 2013. After transferring the data into the program and filtering out erroneous points, the acquired point clouds from each scan were merged to obtain a complete model of the scanned target. This process uses the reference points, which—assuming that no error occurred during the scanning process—are automatically recognized (Romanescu et al. 2012).

### Scanning Process:
### Site Core and Cave Sites
In 2012, scanning was focused upon archaeological prospection and conservation purposes with the intent of scanning the entirety of the site core. This consisted of Plazas A, B, C, D, and E, the Eastern Court, the Waterhole, the Mai Causeway leading to Structure 10, and the site core portion of Tzul Causeway. In 2013, we returned to Plaza A to document excavations and discovered features. Scanning began in Plaza A to assess visibility, scan position coverage, and estimate how many scan stations would be necessary to capture the plazas and causeways. After the initial test scans in Plaza A, scanning started at Structure 11 and progressed east on Mai Causeway toward Structure 10. Once the length of the causeway (about 273 m) was determined and data from Structures 10 and 11 were collected, we moved the scanning operation to Pacbitun’s modern entrance road just southwest of Plaza A. From here, we continued to travel southwest on Tzul Causeway, which is approximately 525 m in length (within the site core). Once we passed Structure 30, the last structure in the site core before heading into the periphery, scanning continued until the causeway was no longer visible due to a modern road leading to the village of San Antonio. After completing both site core causeways, we moved through Plaza B and then Plaza A, while waiting for the remaining plazas to be cleared of brush. We then continued to Plaza C, moved through Plazas D and E, the Waterhole, and, finally, the Eastern Court. One excavation unit, Unit 1 in Plaza D, was scanned to test whether a stratigraphic profile could be sufficiently recorded.

Given the significant amount of cultural material found in caves within the Pacbitun periphery and the ideological significance the caves may have had to the ancient people inhabiting the area (Powis 2010; Spenard 2011, 2012; Weber 2011), incorporating a sample of them into the scanning project at Pacbitun was a logical expansion of our research. However, the scanning of the caves should be viewed as an experimental project, designed to test the scanning method in karst environments. In 2012, scanning was carried out at Actun Lak Cave, one of over 30 caves associated with Pacbitun that is located in its southern periphery (Powis 2010, Spenard 2011, 2012; Weber et al. 2012). Two additional caves were scanned in 2013, Tzul’s Cave and Crystal Palace Cave.

---

### TABLE 1. Specifications of Scanning Systems.

<table>
<thead>
<tr>
<th>Scanning Technology</th>
<th>Collection Mode</th>
<th>Processing Sensor Systems</th>
<th>General Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time-of-flight or “pulse-based”</td>
<td>Linear</td>
<td>Discrete Return or “Echo” Sensors (records a limited number of laser pulses, based on a threshold)</td>
<td>ALS and TLS Mid- to long-range</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Multiple Pulse Sensors (like discrete return but can produce multiple laser points at one time)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Full waveform</td>
<td>Full Waveform Sensors (continuous laser beam; entire returned waveform is recorded)</td>
<td>ALS and TLS Mid-range</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bathymetric Sensors (records water depth; uses two laser points at once that measure different wavelengths)</td>
<td>ALS off- or near-shore</td>
</tr>
<tr>
<td>Phase-based</td>
<td></td>
<td>Transforms the transmitted laser pulses into multiple phases, measuring the phase shifts of the reflected signals</td>
<td>TLS Mid-range</td>
</tr>
<tr>
<td>Other</td>
<td>Geiger</td>
<td>Photodiode technology; sensors are more sensitive, thus requiring more post-processing time</td>
<td>ALS Long-range</td>
</tr>
</tbody>
</table>

### TABLE 2. Technical Specifications of the Leica C10 Scanner.

<table>
<thead>
<tr>
<th>Instruments</th>
<th>Leica ScanStation C10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application</td>
<td>Terrestrial</td>
</tr>
<tr>
<td>Measurement Range/Rate</td>
<td>60 μrad / 60 μrad (12° / 12°)</td>
</tr>
<tr>
<td>Accuracy</td>
<td>6mm (position) / 4mm (depth)</td>
</tr>
<tr>
<td>Field of View</td>
<td>360° x 270°</td>
</tr>
</tbody>
</table>
Actun Lak. Toward the end of the 2012 field season, we decided to move out of the site core and scan Actun Lak. Out of the abundant peripheral caves at Pacbitun, Actun Lak presented itself as a good candidate for 3D scanning, not only because of the large quantity of artifacts and features, but also because the cave is currently endangered by tourist development and looting threats (Powis 2010; Spenard 2012). Four scanning stations were set up inside the cave and two scans were conducted outside: one near the entrance and one down the slope leading to the cave.

Tzul’s Cave. Tzul’s Cave is significant not only because of its abundance of ancient pottery deposits but also because Tzul Causeway—running from the Pacbitun site core into the periphery—terminates in eyesight of it, suggesting a ritual and practical connection between the two features (Powis 2010; Weber 2011). The entrance to the cave abruptly descends vertically into a small terrace, and all chambers are connected through very narrow niches, making it a challenging cave for 3D laser scanning (Figure 3). However, given the cultural significance of this cave to the Pacbitun site, it was selected after we explored whether the scanning equipment could physically fit through the chamber connections. In total, 13 scans were conducted in and round Tzul’s Cave.

Crystal Palace Cave. Crystal Palace cave had not been mapped prior to the 2013 scanning project and was the second cave location selected in 2013. This cave is covered with an abundance of stalactites and stalagmite formations and has sherd deposits in various different locations, including niches that are difficult to access (Powis 2010, Weber 2011). Fourteen scans were carried out to capture Crystal Palace Cave.

RESULTS

Sixty-five site core scans were carried out in 2012 and nine scans were carried out in 2013, for a total of 74 scans from the site core. In total, 33 scans were conducted during the cave surveys in 2012 and 2013. Overall, the C10 Leica scan station proved to be very robust and easy to operate even on hilly terrain and in the humid, tropical environment. The main operating obstacles during the scanning process were the lack of visibility due to vegetation coverage and the structure height, which affected optimal target placement in the plazas. This resulted in varying target positions and distances from the station and prolonged scanning times. The problem would be minimized when the areas could be cleared through chopping and/or burning prior to scanning. Once chopped or cleared, the scanning operations moved swiftly through the site. For example, Mai Causeway is surrounded by modern agricultural fields, and the brush around it could be mostly cleared, which allowed us to collect and post-process scan data fairly quickly. Thus, Structure 10 was recorded within a few hours and, once processed, the data revealed the
well-defined base of the structure with the attached Mai Causeway. Even though Structure 10 had been recorded through traditional survey methods, its structural base is not clearly visible to the naked eye, and it has never been as observable as through the results of the laser scanning process (Figure 4).

Another example of the advantageous speed and level of accuracy of TLS scanning was the recording of archaeological units. During the 2012 scan of Unit 1 in Plaza D, we noted that the different stratigraphic layers are very well defined when scanned, and images here can further serve the analysis process (Figure 5). In comparison with traditional profiling, 3D scanning can save a significant amount of time. In our case, the scan of Unit 1 took about 20 minutes. As Doneus and Neubauer (2005) note, 3D documentation of stratification through the use of terrestrial scanners provides high topographic detail and texture, helping to make the excavation process more efficient. They add that the 3D laser scanner can indeed be seen “as a future standard tool for the high resolution 3D recording of single surfaces on a stratigraphic excavation” (Doneus and Neubauer 2005:231).

We also decided to scan a stepped platform discovered in 2013 in Plaza A in the site core. In the fall of 2012, a geophysical survey was conducted across Plaza A at the site (Skaggs et al. 2014). One circular anomaly was detected in front of Structure 3. To identify the anomaly, a small trench (measuring 4 m by 1 m) was positioned on the north side of Plaza A. Trench 1 contained four smaller subunits, designated as Units A–D. Upon encountering the anomaly, the trench was expanded by placing another larger trench (Trench 2) adjacent to Trench 1. Trench 2 measured 12.5 m by 3 m. Both trenches were placed atop the circular anomaly that measured 3 m in diameter. Trench 1 was positioned so that it would bisect the anomaly east-west. Initially, we encountered five plastered plaza floors, then a platform ~1 m in depth. Located below the plaza floors but above the platform was a retaining wall. This wall was likely part of a much larger stone-lined crib, used to hold soil and rocks, for the building of Plaza A. It was this excavation that prompted the large-scale investigation of the earlier platform. The platform was not circular in form (as previously thought).

Likewise, the platform originally located in Trench 1 was later expanded (Trench 2) due to its size. Given that this is an ongoing excavation, our current information may change during future investigations. Currently, we know that the platform is buried (<1 m) beneath the present-day ground surface and appears intact but heavily burned. It seems that the Maya abandoned the platform subsequent to burning it and covered it before building successive plaza floors above it. Based on ceramic analysis, the feature tentatively dates to the late Middle Preclassic period, ca. 600–300 B.C. The platform measures 16.5 m east-west by 3 m north-south by 1.5 m high. It has five steps that face eastward, and, if symmetry is to be expected, then it would measure approximately 25 m long by 10–12 m wide. The summit has not been exposed, so there is no information available at present that would allow us to identify whether it supported a perishable superstructure. And, given the early date of the stepped platform, it may actually be a radial building with four
staircases placed equidistant to one another. Scanning revealed detailed structural features and traces of burning on the original surface (Figure 6). The platform was scanned in about two hours, providing detailed information for profiling, measurements, and analysis.

The TLS scans of Actun Lak, Tzul’s Cave, and Crystal Palace did provide a level of detail and visible access that would have been hard to accomplish with traditional survey methods (Buchroithner and Gaisecker 2009). In cases of endangered sites, like Actun Lak, TLS scanning can also provide a certain level of preservation (Figure 7). The scans of Actun Lak’s Chamber 3 (Figures 8 and 9) offer an example of how the use of a 3D scanner can compensate for restrictions in complex karst environments with hard-to-reach cavities and niches. As previously mentioned, Chamber 3 is not easily accessible and only a few meters in size (Spenard 2012). Whereas physical access may not always be an option and/or may endanger the natural and cultural integrity of a chamber, the scanned images can be used to further contribute to its analysis.

DISCUSSION

The Practicality of Terrestrial Laser Scanners in Complex Environments

The terrestrial scanning project conducted at Pacbitun was the first of its kind in the Belize Valley; therefore, there are no direct comparisons with previous results from other projects in the area. While the in-depth analysis of the scanning data is an ongoing project, a few comments can be made regarding the collection process. Using a TLS scanner at Pacbitun in two different kinds of complex environments, in a tropical jungle and inside karst features like caves, created some incredibly detailed imagery in a relatively short amount of time, as described in the examples in the previous section. However, achieving this came with a set of difficulties.

One of the main issues was heavy vegetation. In some areas, clearing was simply not possible. For example, the remnants of Tzul Causeway border the jungle to the south, and the vegetation proved too dense for removal and also unsuitable for controlled burning. Therefore, this area was very constricting, which made optimal target placement difficult, requiring prolonged scanning. In addition, scanning heavy vegetation increased post-processing times significantly, given that a large amount of data had to be eliminated and structures had to be carefully distinguished from the surrounding environment. This required good knowledge of the site, as well as patience. Programs that can aid in eliminating large numbers of points at once, like Cyclone II TOPO, were of only limited help because they require height input for elimination, and many of the site’s structures are as tall as the tallest trees surrounding them.

Although we did not encounter the same vegetation issues in the caves as we did within the site core, the natural environment here remained challenging. At Actun Lak, it took a significant amount of time to get the scanner and other
Assessing Terrestrial Laser Scanning in Complex Environments (cont.)

equipment safely up a hill, then down the steep pathway to the cave location and into the cave chambers. Delays during the scanning process were primarily based on lighting issues and humidity. Aside from the scan just inside the entrance of the cave, the others were all affected by the lack of light. To compensate for this, flash lights were arranged to highlight the scanning targets, so that the scanner could capture the imagery. The logistics of getting the scanner to, into, and back from the caves in 2013 remained challenging, given that the scanner and equipment also had to be carried up and down the hillside and into and through the caves. In the furthest chambers of both caves, line of sight to previous targets was not achievable, and the slippery and rugged terrain inside the chambers made it impossible to level the station. In these cases, we conducted scans without targets or proper station leveling, with the intention to merge these data sets during post-processing. To save time, we abandoned the image capturing feature, eliminating the lighting issues that we encountered during the scan of Actun Lak at the cost of decreased color quality of the texture images during post-processing.

Undoubtedly, scanning techniques can be better suited than their 2D alternative for the representation of irregular structures, as well as for cultural and natural deposits at closed sites, because they are a better fit for recording more accurate locations and more precise textures and colors of objects (Gonzalez-Aguilera et al. 2011; Núñez et al. 2013). However, as Ruether et al. (2009) note, due to the complex environment and difficulty of finding suitable vantage points, it is almost impossible to obtain perfect scans in cave sites. Consequently, many of the caves that have been laser scanned are easily accessible and open, without too many logistical obstacles. One of the few projects we have encountered that was conducted under similarly difficult circumstances as the Pacbitun cave survey is Buchroithner and Gaisecker's (2009) 3D survey in the complexly shaped Dachstein South Face Cave in Styria, Austria. Here, researchers faced similar logistical challenges, including difficult cave access, the need to maneuver equipment through very tight niches and to rappel people through various locations inside the cave, extreme temperatures, humidity, dirt, and dripping water (Buchroithner and Gaisecker 2009). While the Dachstein South Face Cave in the Alps is certainly larger and even more rugged, its 3D survey also included the aid of several professional climbers, while the cave surveys at Pacbitun relied on a small team. Certainly, we have captured areas of the caves that would not have been reachable through traditional survey methods; however, the different data sets from these scans are not easily combined and require much post-processing time and effort.

FIGURE 6. Plan view of excavated Units A-O/Trenches 1 and 2 in Plaza A (left) (courtesy of Terry G. Powis), and images of the scanned platform (right).
FIGURE 7. Plan view of Actun Lak with marked scan positions (left) and images of the scanned cave (right).

FIGURE 8. Raw data image of Chamber 3 in Actun Lak.
TLS vs. Traditional Survey Methods and ALS

A prominent and pioneering example of the advantages of scanning surveys over traditional ones can be seen in the data from the ancient Maya site of Caracol in Belize. While traditional mapping techniques had been in use for over 60 years (Chase et al. 2011), only 23 km$^2$ of settlement and 3.5 km$^2$ of terracing had been archaeologically recorded (Chase et al. 2011; Healy et al. 1983). Chase and colleagues (2011) state that the ability to map an ancient settlement within a dense jungle continues to be hindered not only by the covering foliage but also by the amount of funding and time required to undertake the effort. Thus, even the best surveyed sites in the Maya region are represented by only a limited portion of the landscape, meaning that broader interpretations are often derived from incomplete samples (Chase et al. 2011, 2012). However, the recently conducted ALS survey revealed an array of previously mapped and undiscov- ered structural groups, agricultural fields, and causeways, making it possible to identify features throughout the entire 200-km$^2$ area (Chase et al. 2011). Similar to the Caracol survey, an ALS survey at the site of Izapa in Chiapas, Mexico, redefined the site’s estimated size and exposed new mounds and features that were not detected using traditional terrestrial surveys (Rosenwig et al. 2013).

The TLS surveys at Pacbitun set out to test whether or not a terrestrial scanner can compete with similar, although smaller-scaled, prospective findings. For example, in an attempt to test whether or not we could observe causeway remnants of the Tzul Causeway in front of Tzul’s Cave, we scanned the spatial area in front of the cave’s entrance. The causeway itself is visually observable to about 10 m from the cave entrance. To investigate why the causeway appeared to stop in this particular location, we set out to test whether or not a section of it may have eroded away. We wanted to determine whether the scanner could pick up this termination point and to learn about the relationship between this causeway and the cave. However, after the area was scanned, no visible trace of the causeway could be detected. Does this mean that it did not exist, or that the scanner could not pick it up? Or were the images simply not interpreted correctly?

A similar analysis attempt was made at the Tzul Causeway, which had been documented to run from the vicinity of Structure 25 into the periphery. During a 2010 survey, remnants of the causeway between Structures 25 and 11 had been located, but due to this area being overgrown and the surrounding area of Structure 11 being disturbed by various modern road constructions, no clear visible remnants of the causeway were recorded. A preliminary analysis of the scanned data from this location revealed what may be features of Tzul Causeway running from Structure 11 toward Structure 30, as well as another feature that is subject to further investigation. While structural elements will likely be subtle due to the disturbed nature of the area, the newly found linkage between Mai and Tzul Causeway in the site core raises several new research questions concerning the Pacbitun causeway system itself (e.g., are we dealing with two separate roads or a single lengthy one?) and the function of structures associated with the connection area. These questions can be answered only by conducting additional test excavations. Should these be negative for any causeway remnants as well, we must still look at the topography, as well as at other interpretations methods (e.g., ritual usage in front ancient Maya caves). It is only through holistic analysis that we can conduct archaeological interpretive mapping with laser methods.
TLS generally proved to be more efficient than traditional recording methods when scanning cleared structures or units, and less efficient in heavy vegetation compared with ALS, but it also comes with its own set of issues. While scanning the castle of Haut-Andlau in Alsace, France, the surrounding relief and ditches in combination with the limited field of view of the scanner prevented the capturing of a reliable point cloud of the upper parts of the towers (Grussenmeyer et al. 2008). At Pacbitun, we experienced similar difficulties during the scanning of the buried Middle Preclassic (ca. 600–300 B.C.) stepped pyramid in Plaza A. Even though six stations were placed around the unit—as close to the edges as possible, and one station placed in it—the vertical angles of the steps could not be captured within the confinement of the unit (Figure 10). Other sources of errors can be caused by sensor calibration, scanner positioning, and object surfaces (Opitz 2013). At Pacbitun, scan misalignments caused by location or surface errors became most apparent while surveying the caves, which naturally present various surveying obstacles. Certainly, combinations of different techniques, such as terrestrial scanning combined with photogrammetry or airborne LiDAR, can help cover many of these scanning limitations and enhance data quality, cost permitting (Pirotti et al. 2013).

Non-Expert Usage and Data Interpretation
Aside from dead angles, confined and irregularly shaped cave environments, and obstruction caused by vegetation, most errors in the data sets acquired in the open areas at the Pacbitun site core were the result of handling errors and are, in theory, avoidable, depending on the surveyor’s experience. The potential for error caused by non-experts handling scanner equipment and obtaining 3D imagery is a serious consideration and should not be ignored when planning a scanning project, particularly since many archaeological projects will not have the financial means to engage professional survey assistance on top of the already high costs for hardware and software (Gonzalez-Aguilera et al. 2011).

The 3D surveys at Pacbitun were no exception and, at times, were conducted as a “learning-by-doing” approach. While some might argue, correctly, that data quality suffers under such circumstances, it is common in archaeology for amateurs to use new data collection sources. It is because of this that many argue for open and interdisciplinary data exchange, as well as for reproducible data models. As Beck (2013:254) states, “Over time, a deeper understanding of the underlying data quality will occur on a data set by data set basis...Where appropriate, incorrect data can be corrected at source, resulting in a more accurate knowledge-base.” As with GIS, data derived from spatial technologies will continue to undergo a qualitative evolution, but in order for this to occur, the technologies and methods must first be used. Therefore, we agree that technological boundaries in archaeology should continue to be pushed, as long as any corrective measures, as well as data acquisition techniques and methods, are properly disclosed and discussed.

An issue related to user errors is noted by Doneus and Kuehtreiber (2013), who argue that interpretation of the data derived from these technologies is context-based and, thus,
provisional and dependent upon our understanding of the individual historical, topographical, and environmental research context. Therefore, the interpretation of laser data is never really complete, nor should it be held as true or false (Doneus and Kuehtreiber 2013; Risbøl 2013), especially while there are no standardized protocols for data interpretation (Seidel 2011). Thus, Doneus and Kuehtreiber (2013) call for integrated, multi-scale interpretations that include different prospection methods, excavation, and environmental studies.

CONCLUSION

While there are limitations to terrestrial laser scanning (e.g., economic aspects, environmental restrictions, the difficulty of handling the equipment in spatially confined areas, and the possibility of scanning errors), it can offer the fast acquisition of large and precise 3D data sets, which can then be used to create incredibly detailed images. The fact that a project is located in a tropical setting doesn’t necessarily mean that the considerably more expensive ALS is the only option. In areas where the vegetation could be easily controlled (e.g., through prior burning), as was the case at Structure 10 in the Pacbitun site core, the scanned data provided 3D images that can almost compete with ALS. If absolutely no clearing or burning is possible, then one might be better served by a traditional or ALS survey, since the post-processing times for intact, heavily vegetated scan areas can prove to be very tedious and time consuming. The same goes for applying TLS methods in karst environments. While scanning a cave is a fast way to create detailed 3D imagery, if the cave is too rugged and wet, a combination with other methods like photogrammetry might be a more suitable option.

The scanning surveys conducted at the site of Pacbitun during the summers of 2012 and 2013 have helped to reveal previously undiscovered features and provide detailed 3D documentation. While the analysis of these data is ongoing, the interpretation of the scanned data from Pacbitun has, and continues to be, predominantly informed by previous research and historical accounts, and it is conducted with the intent of ground-truthing our findings. These results will aid in the further analysis of the site’s development and increase our understanding of the ancient Maya people who once lived in and around Pacbitun and its hinterlands.

Acknowledgements

We would like to extend our appreciation to Drs. Jaime Awe and John Morris of the Belize Institute of Archaeology for their continued support of our research program at Pacbitun. We would also like to thank the Department of Geography and Anthropology at Kennesaw State University for their academic support of our laser scanning project. We thank Jon Spenard for his contributing research in Actun Lak and our fellow PRAP staff members who helped hauling the large amounts of heavy equipment that had to be secured safely every morning and every evening. Of course, we could not have completed any of the scanning without the intensive site clearing and support in navigating equipment through caves and jungle by our local field assistants from San Antonio, Cayo District, Belize. Terry Nutt and Matthew Mizell of Leica Geosystems Solutions in Duluth, Georgia are thanked for their technical support and training with the C10 scanner. Paul F. Healy and Norbert Stanchly are thanked for reading early drafts of this paper. Paola Garcia is thanked for translating our abstract into Spanish. Finally, we are indebted to the Alphahood Foundation for their continued financial support that made this project happen.

Data Availability Statement

The data sets supporting the results of this article are available in the tDAR repository, ID-No. 392772 / https://core.tdar.org/project/392772.

REFERENCES CITED


Giardino, Marco J.

Gonzalez-Aguirre, Diego, Pablo Rodriguez-Gonzalez, Juan Mancera-Taboada, Angel Muñoz-Nieto, Jesus Herrera-Pascual, Javier Gomez-Lahoz, and Inmaculada Picon-Cabrera

Grussenmeyer, P., T. Landes, T. Vogehtle, and K. Ringle

Haddad, Naif Adel

Healy, Paul F.


Healy, Paul F., C.G.B. Helmelke, J.J. Ave, and K.S. Sunahara

Healy, Paul F. Bobbi Hohmann, and Terry Powis

Healy, Paul F., John D. H. Lambert, J. T. Amason, and Richard J. Hebda

Healy Paul F., Rhan-Ju Song, and James M. Conlon

Hinzen, Klaus G., Stephan Schreiber, and Sebastian Rosellen

Lerma, José Luis, Santiago Navarro, Miriam Cabrelles, and Valentín Villaverde

McCoy, F.D., and T.N. Ladefoged

Masini, Nicola, Rosa Coluzzi, and Rosa Lasaponara

Núñez, Amparo, Felipe Bull, and Manel Edo

Opitz, Rachel S.

Piratti, Francesco, Alberto Guarnieri, and Antonio Vettore

Powis, Terry G.


Remondino, Fabio

Risbel, Ole

Romanescu, Gheorge, Vasile Cotiugă, and Andris An ndulesi

Rosenswig, Robert M., Ricardo López-Torrijas, Caroline E. Antonelli, and Rebecca R. Mendelsohn

Ruether, Heinz, Michael Chazan, Ralph Schroeder, Rudy Neeser, Christoph Held, Steven James Walker, Ari Matmon, and Lisa Kolska Horwitz

Seidel, D.

Sittel, B., H., Weinacker, M. Gueltunger, and L. Koupaliants

Skgags, Sheldon, Terry Powis, and Jennifer Weber
2014 Searching for Patterns: Applying Spatial Technologies at Pacbitun, Belize. Manuscript on file, Department of Chemistry and Chemical Technology, Bronx Community College, Bronx, New York.

Spennard, Jon

Weber, Jennifer
2011 Investigating the Ancient Maya Landscape: A Settlement Survey in the Periphery of Pacbitun, Belize. Unpublished M.A. thesis, Department of Anthropology, Georgia State University, Atlanta, Georgia.

Weber, Jennifer, and Terry G. Powis
2011 The Role of Caves at Pacbitun: Peripheral to the Site Center or Central to the Periphery? In Research Reports in Belizean Archaeology 8:199–207. Belmopan, Belize.

Weber, Jennifer, Jon Spenard, and Terry Powis

White, Devin Alan

Authors

Jennifer U. Weber ■ Rheinische Friedrich-Wilhelms-Universitaet Bonn, Department of Anthropology of the Americas, Oxfordstr. 15, 53111 Bonn, Germany (s5jewebe@uni-bonn.de)

Terry G. Powis ■ Kennesaw State University, Department of Geography and Anthropology, 1000 Chastain Rd., MD 2203, SO Bldg. 22, Rm. 4048 , Kennesaw, GA 30144-5591 USA (tpowis@kennesaw.edu)