Defining Best 3D Practices in Archaeology

Comparing Laser Scanning and Dense Stereo Matching Techniques for 3D Intrasite Data Recording

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Over the past 10 years, the use of new technologies for the three-dimensional (3D) documentation and reconstruction of cultural heritage sites has changed how we approach archaeological research. Becoming even more "digital," archaeology is officially part of the *digital village* described by Zubrow (2006:12). The use of 3D laser scanners and photogrammetric methods is now well established in the field. One of the main reasons behind this diffusion is the potential these techniques offer to preserve information digitally through time.

ABSTRACT

This research aims to investigate the potential use of three-dimensional (3D) technologies for the analysis and interpretation of heritage sites. This article uses different 3D survey technologies to find the most appropriate methods to document archaeological stratigraphy, based on diverse environmental conditions, light exposures, and varied surfaces. The use of 3D laser scanners and dense stereo matching (DSM) techniques is now well established in archaeology. However, no convincing comparisons between those techniques have been presented. This research fills this gap to provide an accurate data assessment for the Las Cuevas site (Belize) and represents a starting point for the definition of a sharable methodology. Tests in Las Cuevas were conducted to compare both accuracy and density reliability in cave environments using two different techniques: triangulation light laser scanner and DSM. This study finds that DSM is the most economical, portable, and flexible approach for the 3D documentation of archaeological sites today. In fact, DSM allows the 3D documentation process to be done more efficiently, reducing both data acquisition and processing time. Nonetheless, the quantitative comparison presented in this paper underscores the need to integrate this technique with other technologies when the data acquisition of micro-stratigraphy is required.

Este ensayo analiza la potencialidad de las tecnologías 3D para el análisis e interpretación del patrimonio histórico y cultural. Este trabajo usa diferentes técnicas 3D con el fin de encontrar los métodos más apropiados para documentar la estratigrafía arqueológica, basados en diversas condiciones ambientales, exposición a la luz y variedad de superficies. A pesar de que actualmente se ha establecido el uso de las técnicas de laser escáner 3D y de la técnica fotogramétrica (DSM) "dense stereo matching" en el campo arqueológico, considero no convincentes las comparaciones que se han hecho hasta el presente entre estas dos técnicas. Esta investigación colma este vacío proveyendo una detallada evaluación de los datos de los asentamientos arqueológicos de Las Cuevas (Belize) y representa un punto de partida concreto hacia la definición de una metodología compartible. Utilizando dos técnicas diferentes, la triangulación de la luz del escáner láser y DSM, se hicieron análisis en Las Cuevas para comparar la precisión y la fiabilidad de densidad en entornos rupestres. Este estudio encontró que el DSM es más económico, portátil, y flexible para la documentación 3D de sitios arqueológicos en la actualidad. De hecho, el DSM permite el proceso de documentación 3D reduciendo tanto la adquisición de datos como el tiempo del proceso. No obstante la comparación cuantitativa presentada en este ensayo, cabe subrayar la necesidad de integrar dicha técnica con otras tecnologías, cuando la adquisición de datos requiere una micro estratigrafía.

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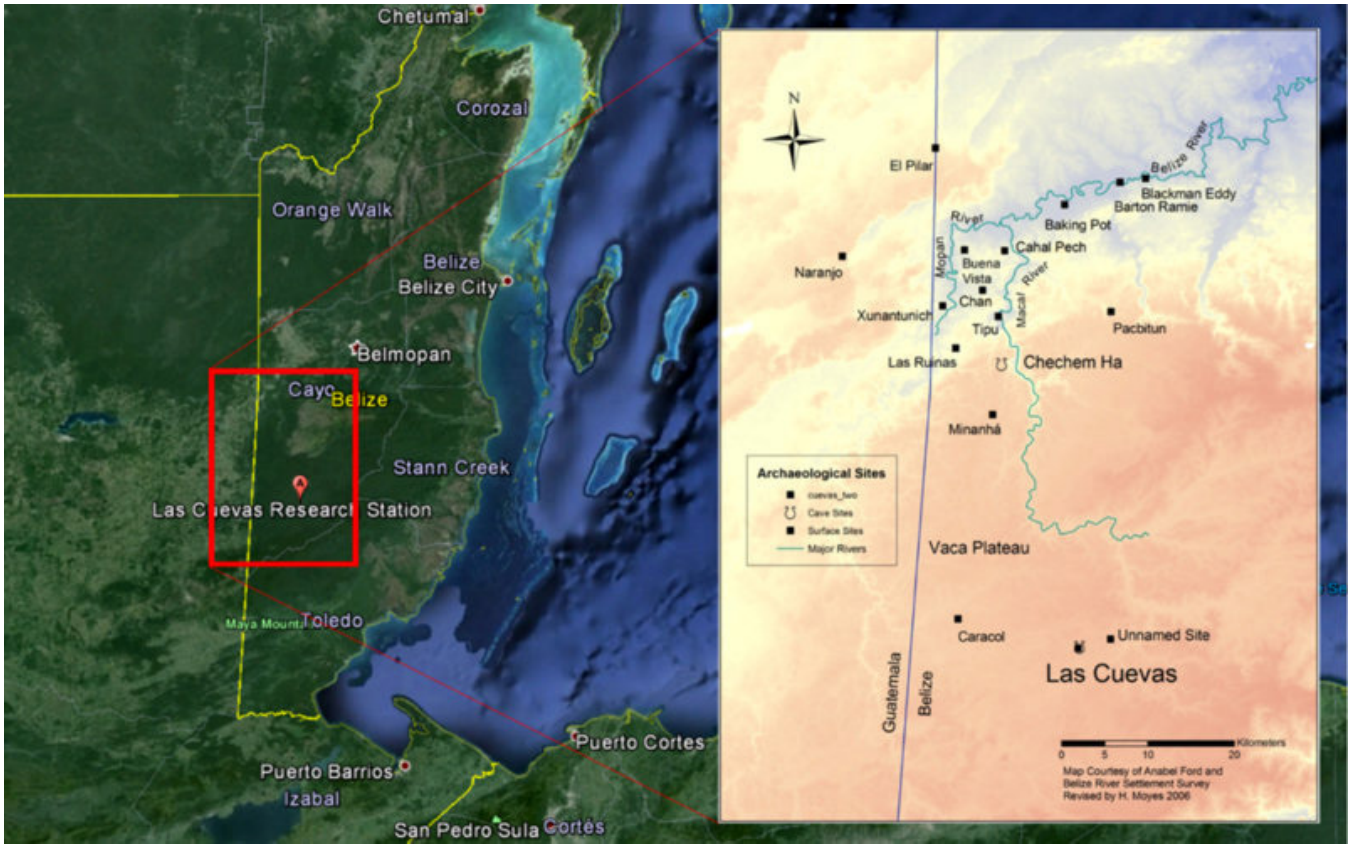


FIGURE 1. Digital Elevation Model of Belize showing location of Las Cuevas (courtesy of the Las Cuevas Archaeological Reconnaissance).

Recently, time of flight (ToF) and triangulation laser scanner (TLS) technologies have become more common in archaeology and have proven to be powerful tools for the 3D documentation of archaeological sites (Addison 2008; Dell'Unto et al. 2008; Fröhlich and Mettenleiter 2004; Galeazzi et al. 2007; Koch and Kaehler 2009; Lerma et al. 2010; Neubauer et al. 2005; Zubrow 2006). But the cost of scanners (US$40,000 to US$100,000) and their usability still present serious obstacles for more widespread use. ToF scanners are excellent for the recording of large structures or objects and are capable of imaging such features at great distances. But their accuracy is poor, especially at close ranges. Archaeologists have thus turned to TLS technologies to image smaller areas and finer details of archaeological contexts, given their proven ability to record details of sites with high accuracy and precision. However, these scanners are often large and bulky and are therefore difficult to use in remote or challenging field contexts. As a result, researchers have turned their attention to more usable and cost effective techniques, such as Dense Stereo Matching (DSM), in contexts where precision, accuracy, and ease of use are required. To date, however, there have been few studies that compare the relative advantages of TLS and DSM technologies.

In this article, we compare DSM and TSL techniques at the Las Cuevas site, located at the Las Cuevas Research Station in the Chiquibul Forest Reserve in western Belize (Figure 1). This site is a Maya center located approximately 14 km east of the mammoth polity of Caracol (Chase et al. 2011; Moyes et al. 2011). Las Cuevas is of particular interest because of a large cave with an extensive dark zone tunnel system traveling directly beneath the architectural complex of the site core. This site is a perfect case to test different 3D documentation techniques and to integrate them into a precise working plan. The most interesting aspect of this site for 3D documentation is its variety of architectural and environmental contexts, difficulty of access, and challenging light conditions. There are a number of buildings, including temples, range structures, and a ball court. This complexity offers a wide range of environmental conditions—dark recesses of caves, areas in shaded sunlight under the jungle canopy, and areas of more direct sunlight in locations that have been cleared of brush or exposed by tree fall. Thus structures, variability in lighting, and other kinds of features occur in close proximity for documentation. These characteristics not only represent a perfect test to distinguish which 3D survey technology is most appropriate for each structure category, but also present a good opportunity to examine the integration of techniques and the results of their application.

Although 3D technologies were employed in most of these contexts, the research presented in this paper is focused on developing a coherent methodology for the use and integration of TLS and DSM 3D documentation technologies in cave environments and to explore the potential of DSM for the acquisition of archaeological stratigraphy. This was possible thanks to a precise data assessment based on a qualitative comparison of the 3D surfaces acquired using DSM and laser

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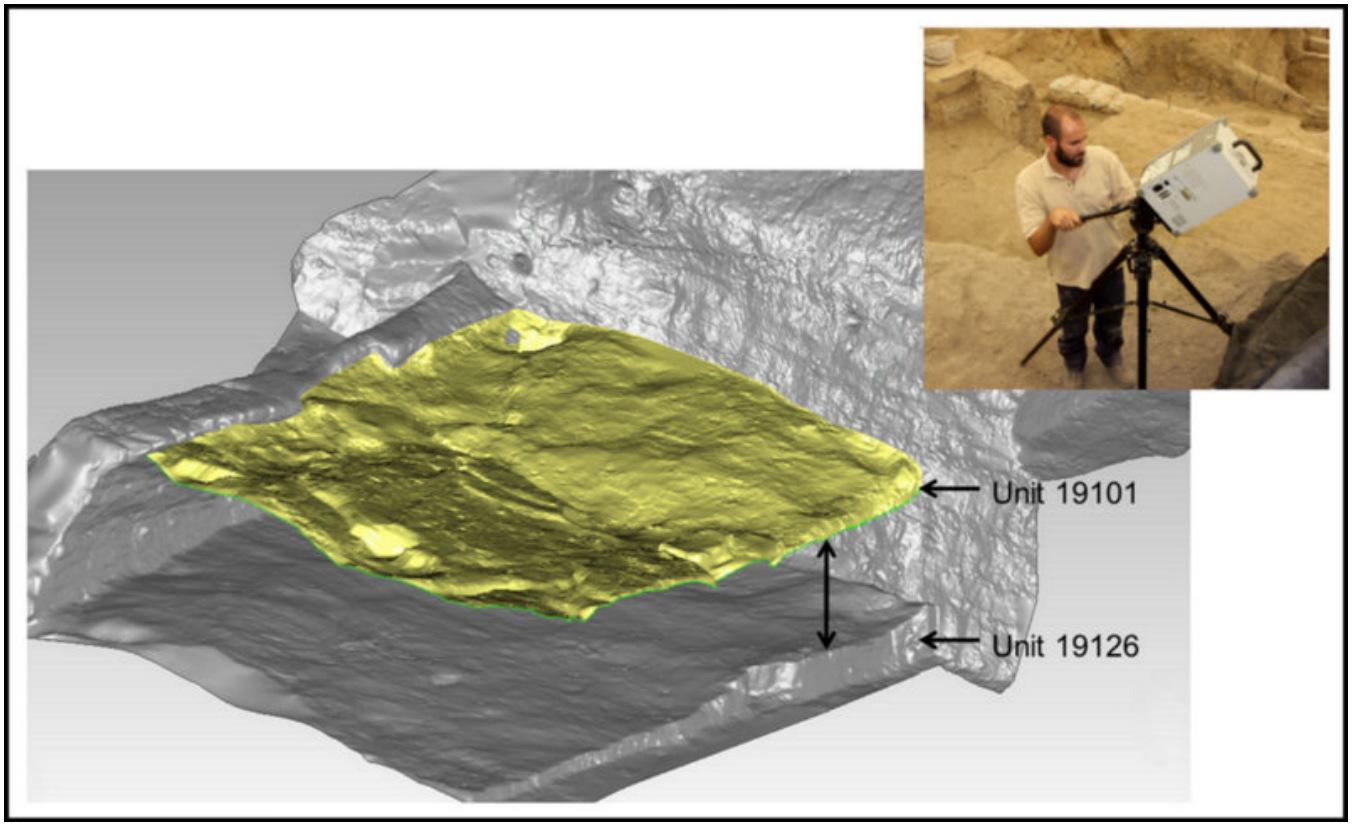


FIGURE 2. The 3D stratigraphic units of the settlement's houses, B. 86, Çatalhöyük, Turkey (Konica Minolta Vivid 910 Laser Scanner).

scanning techniques at Las Cuevas. This study aims to contribute to the definition of an overall methodology that is still missing in archaeological research, as noted recently by Dellepiane and colleagues (2012:203): "although some claim that dense stereo reconstruction is a mature alternative to 3D scanning, no convincing comparison has been presented until now. Recently, some initial effort has been made in this direction, but an overall methodological definition and accurate data assessment are still missing."

Whether the cheaper and more portable DSM technique gives results similar to the more expensive laser scanner technologies in terms of level of detail is one of the most debated questions in digital archaeology today (Callieri et al. 2011; Dellepiane et al. 2012; Doneus et al. 2011; Fratus de Balestrini and Guerra 2011). The potential to record the site in 3D just by taking pictures represents a revolutionary change in archaeological practice, favoring the unprecedented dissemination of 3D representations in archaeological documentation.

Two areas of the cave—one in the Entrance Chamber and another further into the cave (Chamber 1)—were excavated and surveyed using a TLS device (Minolta Vivid 910) and DSM (mid-range/prosumer Nikon D90 DSLR camera and lenses). The entire excavation process was digitally acquired, including nine strata in the Entrance Chamber and eight strata in Chamber 1.

MATERIALS AND METHODS

Review of Technology

In the past 10 years, ToF laser scanner technology has proven to be very powerful in the 3D documentation of general archaeological contexts. Unfortunately, this method cannot produce millimetric and sub-millimetric precision, which is often required for the 3D reproduction of micro-stratigraphy and very fine, detailed features (Galeazzi et al. 2010:102; Koch and Kaehler 2009:1). For this reason, the use of optical measurements systems (e.g., the TLS devices, such as the Konica Minolta VIVID 910) is well established today, demonstrating one of the best solutions for the acquisition of millimetric and sub-millimetric archaeological features and data (Güth 2012; McPherron et al. 2009).

An earlier study conducted in the summer of 2010 on the stratigraphic units of Building 86, a mud-brick house, in Çatalhöyük, Turkey, helped us to clarify the advantages and disadvantages in the use of two laser scanner technologies onsite: a TLS Konica Minolta Vivid 910 and a ToF Trimble CX. A total of 27 stratigraphic layers were scanned by each device (Figure 2).

The Konica Minolta Vivid 910 is able to reach a level of detail within a millimeter (TELE X: ± .22 mm, Y: ± .16 mm, Z: ± .10 mm), with a scan range of .6 to 2.5 m, while the Trimble CX can reach a detail between 8 mm and 1 cm (considering the post-processing phase), with a scan range of .5–350 m.

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The Minolta's data recording time is slower than that of the Trimble, which can acquire large areas in a few minutes of work. However, the data post-processing is faster; in fact, the Minolta is able to acquire textures (under good light conditions) and surfaces, while the Trimble does not have this capability. The Trimble, in fact, can acquire only point clouds that have to be triangulated and texturized in the post-processing phase. Unfortunately, the Konica Minolta Vivid 910 cannot work in a direct light condition. For this reason, we were forced to cover the excavation area prior to scanning the layers. Since the team was not prepared for this kind of situation, it was not possible to have a perfect light distribution with the cover. So the textures acquired by the scanner were not homogeneous enough to be used in the 3D models of the layers. The textures of the layers were acquired through a high-resolution digital camera in an attempt to georeference them to the 3D surfaces of the layers during post-processing. There are two negative aspects associated with this kind of texturing procedure: (1) the alignment of the map to the 3D model is made manually through control points, and the accuracy of their matching is not always guaranteed; and (2) manual matching is extremely time-consuming.

The fieldwork proved that, when using the Minolta, it is possible to obtain very detailed 3D meshes in the acquisition of stratigraphic layers and confirmed that the ToF scanner cannot produce sub-centimeter precision, which is often required for high quality site documentation (Koch and Kaehler 2009:1).

The use of photogrammetric techniques for the 3D documentation of archaeological sites has been tested in different digital archaeology projects (Galeazzi et al. 2007; Pierrot-Deseilligny et al. 2011; Remondino and El-Hakim 2006; Sanz et al. 2010). These techniques, used to create simplified 3D metric models with a photorealistic aspect, provide for image-based modeling. With these techniques, it is possible to calculate measurements, build 3D models through digital pictures, and create 3D metric models with a photorealistic aspect. Advances in photogrammetric technologies during the past decade have led to the development of several new tools that allow one to obtain three-dimensional information from unorganized image sets. The use of sophisticated DSM software, both commercial and open source, is currently well established in archaeology and largely used for the 3D documentation of archaeological stratigraphy (Dellepiane et al. 2012; Doneus et al. 2011; Fratus de Balestrini and Guerra 2011). DSM approaches create 3D data starting from a series of uncalibrated images. The different steps of the 3D reconstruction process are image matching, camera parameter estimation, and density matching. The results of this computation may be similar to a series of range maps associated to each input image. The processing of image sets usually takes a few hours. This technique is cheaper than laser scanner technologies, and the acquisition is possible using a medium quality camera and post-processing software. Moreover, the DSM technique is more usable; the training required to acquire the basic knowledge for the use of this technique is considerably less compared to the training necessary for data acquisition and post-processing using a laser scanner. The main problems in the use of this technique are the lack of scale information and the absence of a convincing comparison between this documentation method and 3D laser scanning. Although some attempts have been made in this direction (Doneus et al. 2011; Fratus de Balestrini and Guerra 2011), the definition of a coherent methodology has yet to be achieved. According to Doneus et al. (2011:87), in fact, "investigations under different controlled conditions are necessary to assess the image-based modeling more thoroughly and quantify whether and under which conditions SfM (Structure from Motion) approaches are a reliable documentation technique for archaeological excavations."

Site Description

Directed by Holley Moyes (Moyes et al. 2012), the Las Cuevas Archaeological Reconnaissance (LCAR) began investigating Las Cuevas (Figure 1) in 2011. Until recently, the site received little investigation with the exception of one notable project. In 1957, working for the British Museum, Adrian Digby (1958) and the Commissioner of the Belize Department of Archaeology, A. H. Anderson, conducted excavations at the site and produced a sketch map. Digby wrote a brief article for the *London News* describing the site and reporting his excavations. Anderson (1962) mentioned a 1938 visit to Las Cuevas in his paper for the Americanists' Congress, but there are no other reports.

The current investigations by the LCAR address cultural dynamics during the Late to Terminal Classic periods (ca. A.D. 700–900), a time of severe stress in the ancient Maya world, by examining the ritual life of a Maya community on the eve of collapse. Recent studies (Aimers 2007; Demarest et al. 2004:546) question the use of terms such as "collapse" or "fall" because they are colorful but misleading. However, Demarest and his colleagues suggest that the events of the late ninth century do represent changing political systems and ideologies. In other words, instead of representing the total failure of an entire civilization, the "collapse" has been redefined as the decline of the elite class and the abandonment of the institution of kingship in the Maya Lowlands. Most Mayanists agree that there was, in fact, a major change in both population and social organization, and it is clear that many sites were abandoned during the mid to late ninth century.

Las Cuevas offers an excellent venue for exploring this issue. On the surface, Cuevas seems to be typical of many Late Classic sites found in Belize, such as Baking Pot, Floral Park, Blackman Eddy, or Minanha (Iannone 2004). However, this site has something that these other sites do not—a large cave system that runs directly beneath the main plaza. The cave entrance is situated below the eastern pyramid. While it is not unusual for Maya sites to be associated with caves, we rarely see such a direct connection or such an extensive tunnel system beneath a site core (Moyes and Brady 2012). The cave entrance itself is massive, cathedral-like, and architecturally modified, suggesting that it was used for large public events. One of the goals of the LCAR is to articulate constructions in the cave with those of the surface site to produce a picture of the ritual life of the community and contextualize ritual practice within the sociopolitical, as well as the natural, environment.

The Las Cuevas surface site consists of 24 structures, including a ball court, surrounding two plazas and a U-shaped *plazuela* group. The structures are positioned around a dry cenote (sinkhole) whose southern edge is ringed by long, low platforms. The opening of the cave system is located at the base of the cenote. Terraces and stairs descend from the southeastern side of the cenote, behind structures 11 and 12, to the cave entrance

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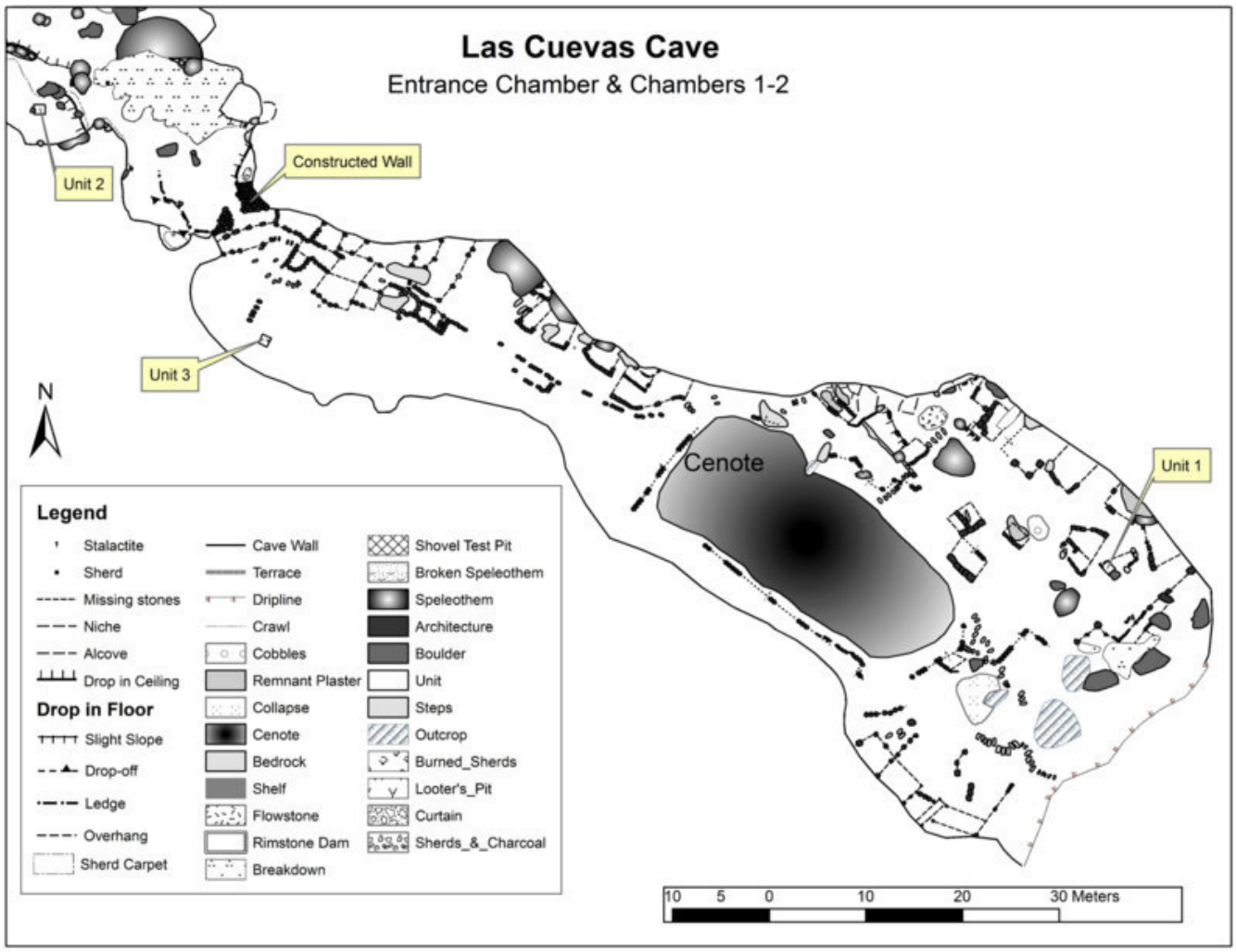


FIGURE 3. Map of Las Cuevas illustrating placement of Units 1, 2, and 3 in the cave (courtesy of the Las Cuevas Archaeological Reconnaissance).

(Moyes et al. 2012). Located directly inside the cave's cathedral-like Entrance Chamber is an additional cenote with a natural spring at its base (Figure 3). Test excavations, both in entrance contexts and deeper within the cave, were conducted to establish the site's chronology.

Methodology

Two test units were placed in the cave. Barbara Voorhies supervised cave investigations. Laura Kosakowsky analyzed the ceramics for chronology using type-variety designations established for Lowland Maya sites (Gifford 1976). The site was surveyed using a Sokkia 650X 6" reflectorless total station and a Topcon 3" total station. Data were displayed and organized using a Geographic Information System (ArcGIS 10.2). A digital elevation model (DEM) of the site, a plan view map of the constructions in the site core and plazuela group (Figure 4), and a map of the cave were created (Figure 3; Moyes et al. 2011).

Unit 1 (Cave Entrance Chamber) was of particular interest. This unit located in the twilight area near the cave entrance. It measured 1.2 m on the N-S axis and 1 m on the E-W axis as was excavated in 9 levels to bedrock. The unit cut into a partially eroded platform with a plaster floor. A second floor was encountered below, suggesting that there was more than one phase of construction within the cave. Initially it was thought that this earlier construction may have been quite old, but ceramic analysis clearly demonstrated that this was not the case and that the cave was modified on more than one occasion in the late part of Late Classic period. A total of 316 sherds were excavated within the unit, of which 62 were identifiable to type. Although there were redeposited sherds from the Late Preclassic Sierra Red Group (300 B.C.–A.D. 250) and Early Classic period (A.D. 250–550) Petén Glosswares, both constructions primarily contained sherds dating to the Spanish Lookout/Tepeu II complex, which dates between A.D. 700–900. Additional artifacts encountered included chert flakes, a chert biface, and animal bone, suggesting that, rather than representing a unique cave assemblage, the artifacts recovered from the soils of the platform are typical of mixed fills removed from contexts elsewhere at the site (Moyes et al. 2011:17–19).

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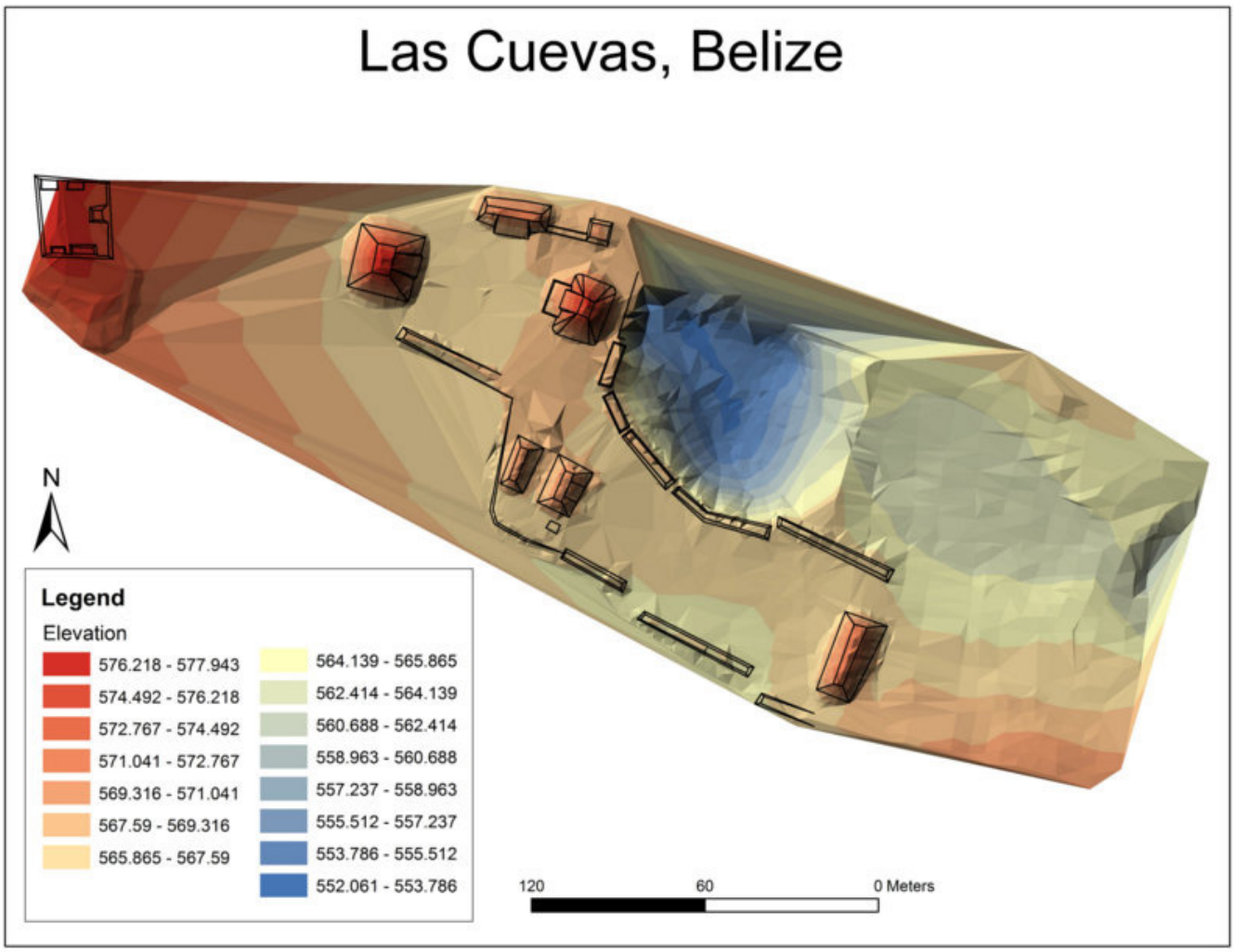


FIGURE 4. Digital Elevation Model of Las Cuevas site core and plazuela group (courtesy of the Las Cuevas Archaeological Reconnaissance).

Unit 2 (Cave Chamber 2) was located in the dark zone of the cave on the east side of a protruding rock that was surrounded by abundant flat-lying sherds. It was a 1-x-1-m test unit excavated in six levels and was terminated when sterile clay was encountered at 60 cm below the surface. The diagnostic ceramics belonged solely to the Spanish Lookout Ceramic Complex pertaining to the late part of the Late Classic Period (Moyes et al. 2011:19–21).

The excavation process of Units 1 and 2 was completely recorded in 3D using the TLS, Minolta Vivid 910 (Figure 5), and DSM. All the units' levels were scaled to real measures and aligned using the measurements made with the total station. Four targets located at the four corners of the excavation area were taken as reference points to align the total station data survey and the 3D models. In this way, the models can be easily brought into the same reference frame used for the survey of the site and georeferenced.

The characteristics of the cave environment (medium-to-no natural light conditions) allowed a better control on the lighting of the excavation area. Eight artificial lights were used to give a more homogenous distribution of the light on the area to be scanned. A regular lighting distribution was obtained by positioning the lights around the excavation area on tripods (two meters above the ground surface). The first positive aspect in the use of the TLS technique is the extreme detail of the meshes acquired (Figure 6). The second benefit consists of the possibility of acquiring meshes and not point clouds. This made it possible during the post-processing phase to avoid point cloud filtering, alignment, and triangulation, saving almost half of the total post-processing work time. One of the negative aspects of this technique is the low resolution of the textures. The camera integrated in the scanner, in fact, is a low-resolution camera (number of output pixels: 307,000/FINE mode; 76,800/FAST mode). Moreover, this technique is not recommended for scanning large areas for two main reasons. First, the post-processing and alignment of the different meshes obtained from the scans will be extremely time-consuming. The Minolta, in fact, allows acquiring just a small area at a time. The optimal distance (.6–1.2 m) of the device for 3D measurement to the target area to be scanned results in a surface of about 80x80 cm. Secondly, the

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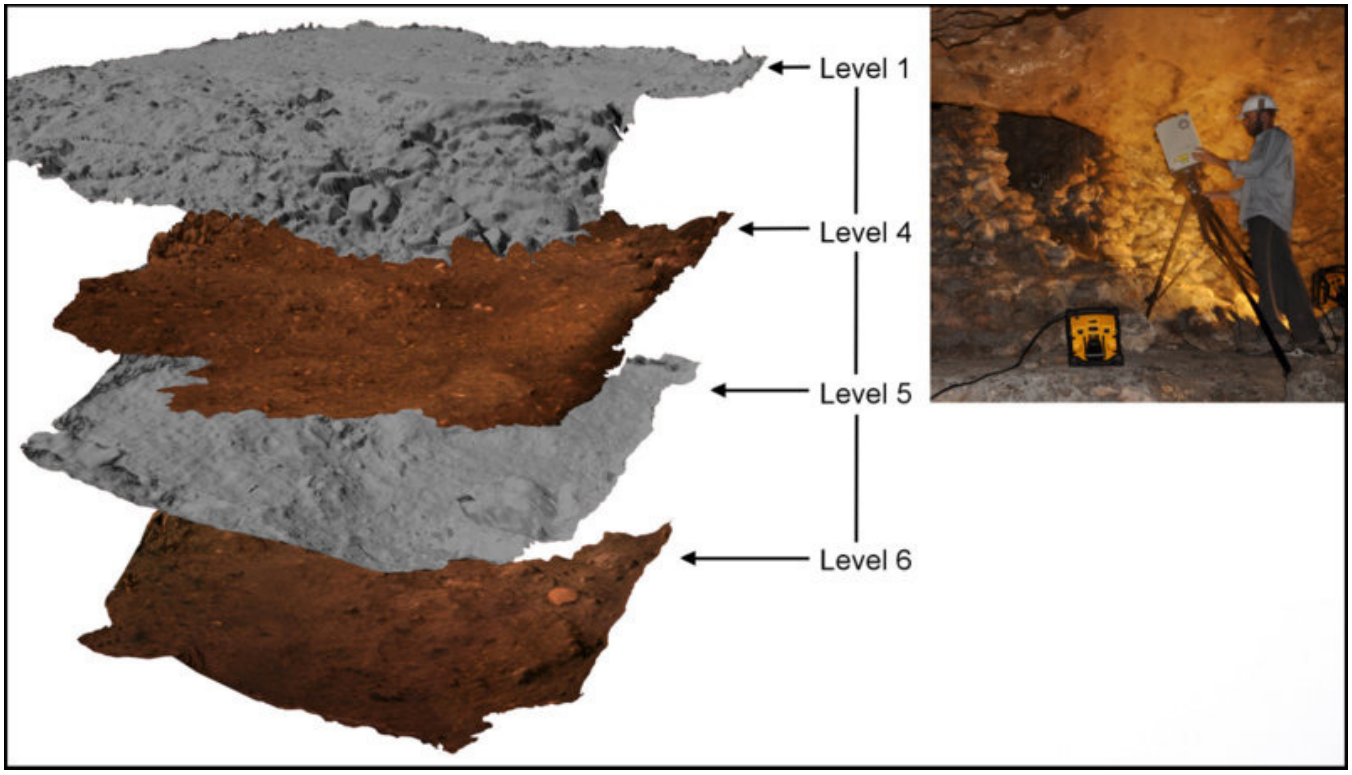


FIGURE 5. 3D stratigraphic sequence of Unit 1 (Cave Entrance Chamber).

high level of humidity in the cave environment has a negative effect on laser scanner performance. After about an hour and an half, the hardware stopped working properly. Despite this, the time was sufficient to acquire measurements of a 6-m^2 surface; the acquisition of a larger area would drastically slow down the excavation process.

The same unit's measurements were acquired using DSM. The purpose of this paper is not to give an overview and comparison of the different DSM software. Some evaluations have already been done between different DSM software, showing that it is possible to obtain similar numerical results from the different systems (see Callieri et al. 2011 and Dellepiane et al. 2012 for a thorough discussion). The differences between them are in terms of data density, resilience to non-optimal photo dataset, visual quality of data, and tools flexibility (Callieri et al. 2011). Given the remote context of Las Cuevas, PhotoScan (Agisoft LLC 2011) seemed to be the best choice between the different tools available, as it can be executed on a local, non-Internet connected machine. The lack of Web connectivity and access to cloud-based services is typical of many archaeological projects in remote areas. Thus, the potential to perform tests directly in the field is the best approach to developing a strong processing pipeline. Moreover, it gives us the opportunity to refine, in real time, the acquisition process during excavation.

Another advantage in the use of PhotoScan is that it is the only DSM software that allows complete 3D model restitution (alignment, creation of the geometry and texture). In addition, thanks to the graphic interface, it is possible to manage the geometry and texture creation separately from the alignment.

All the images used for the data acquisition were acquired using a Nikon D90 with 60 mm Nikkor lens, with a resolution of 12 MPixel. Each acquired level was generated with a number of images varying from 26 to 35. Dellepiane et al. (2012) demonstrated the repeatability and effectiveness of dense stereo reconstruction tools. The measurement of the geometrical deviation between two 3D models of the same excavation area, acquired in different moments during the fieldwork campaign, was less than 1 cm for 90 percent and less than .5 cm for 50 percent of the mesh (Dellepiane et al. 2012:6).

Another positive aspect of the DSM approach is the possibility of consistently reducing both acquisition and post-processing time. The acquisition time for a 2-x-2-m surface with the Minolta laser scanner was about 20 minutes, while the image capture for the DSM process took around five minutes. The post-processing of the same surface with the Minolta took about one hour of work (mesh optimization and alignment). With PhotoScan, data processing took about four hours; however, the real work time (the data loading) only took about 15 minutes, and the rest was machine processing.

RESULTS AND DISCUSSION

This study shows metrical comparison of the 3D models of one of Las Cuevas's levels (Level 6, Unit 1), collected during the 2011 fieldwork campaign using TLS and DSM. The comparison of the co-registered surfaces was performed in commercial (CS; Rapidform, now known as 3D Systems Geomagic; Rapidform 2014) and open source (OS; MeshLab; Meshlab 2014) point cloud and

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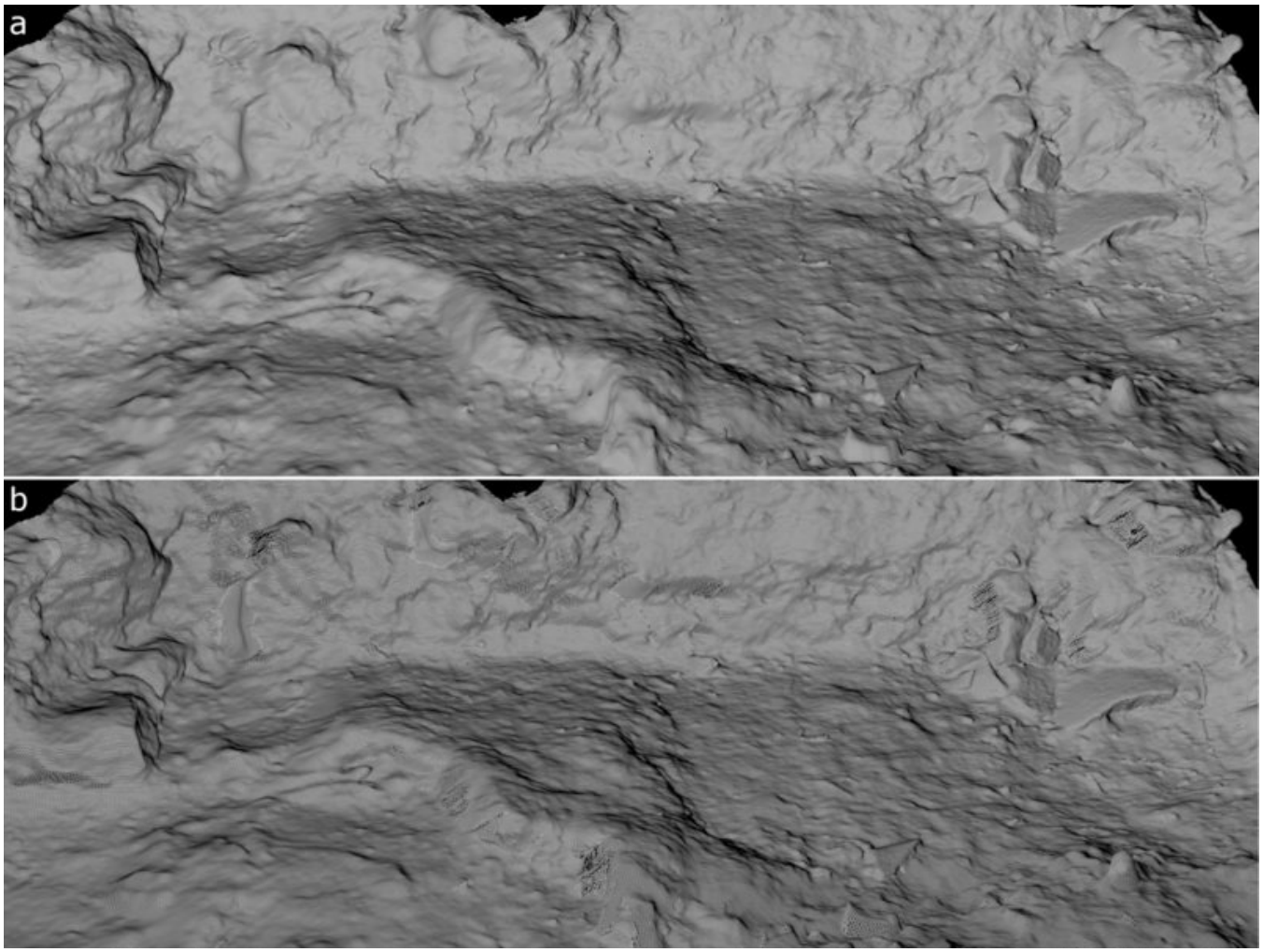


FIGURE 6. 3D model of Unit 1, Level 6 (Cave Entrance Chamber), acquired through the triangulation laser scanner, Minolta Vivid 910: (a) mesh; (b) wireframe.

mesh processing software and was based on the shortest point-to-mesh distance considering the normal to the mesh faces. The estimated distances between surfaces allows for the calculation of a wide range of quality metrics of the 3D models. Using different software for the comparison on the same 3D models increased the reliability and relevance of the test.

The CS allows for the calculation of the root mean square (RMS), which describes the average absolute accuracy between surfaces, and the standard deviation (SD), which is an index of the surface's noise (the measure of the variation in the measures). The OS calculates the mean deviation between surfaces (the average of the sum of the squares of the deviations) and the RMS. The number of produced points for Unit 1, Level 6, was 670,278 for TLS and 90,971 for DSM. The difference in term of density between the TLS and the DSM is evident (Figure 7). In this paper. we investigate whether the different densities of the models correspond to higher or lower accuracy. To do so, quality metrics from the 3D comparison were computed and are presented in Table 1.

The comparison run with CS and OS software between TLS and DSM models shows very close values for the RMS (1.706–1.910 mm; Figure 8). The comparison showed that 65.18 percent of the model point comparisons, obtained through the DSM technique, fell within ± 1.5825 mm from the average (.6369 mm). More interestingly 96.36 percent of the point comparisons in this model fell within ± 3.165 mm from the average.

The color-coded image shows that the vertical section of the unit's level was less accurate than the horizontal-central part of the layer (orange-red from ± 2 mm to ± 7 mm; yellow ± 2 mm; Figure 8). For this reason, we decided to run a second metrical comparison considering just this part of the 3D models (Table 2).

For this part of the models, the number of produced points was 392,694 for the TLS and 42,117 for the DSM. The comparison run with CS and OS software on the horizontal-central part of the models shows very close values for the RMS (1.171–1.258 mm; Figure 9). The 68.94 percent of the point comparisons in the model fell within ± 1.1513 mm of the average, and 95.6 percent of the point comparisons fell within ± 2.3026 mm of the average.

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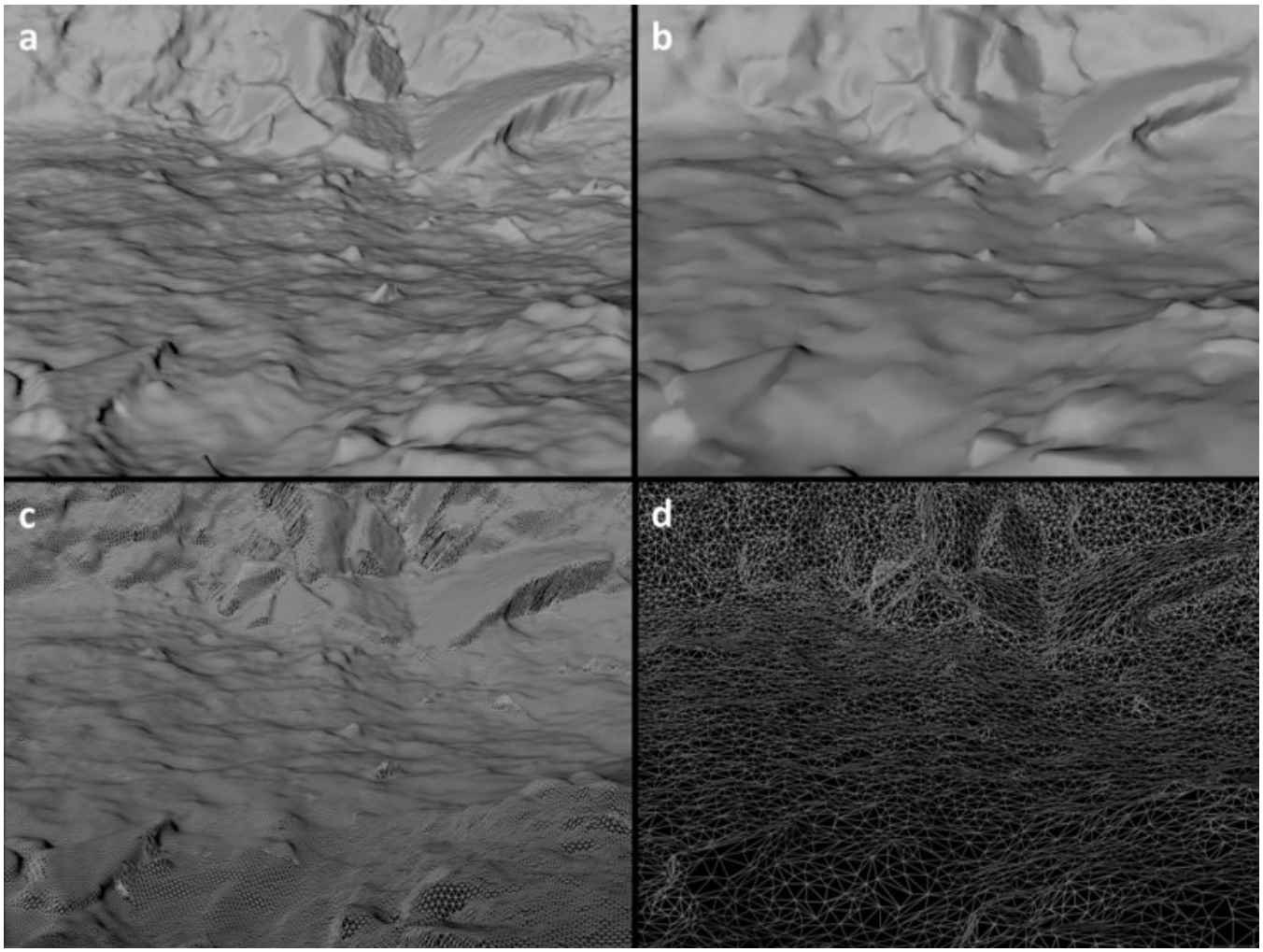


FIGURE 7. Three dimensional models of Unit 1, Level 6 (Cave Entrance Chamber), acquired using two different techniques (TLS and DSM): (a) TLS mesh; (b) DSM mesh; (c) TLS wireframe; (d) DSM wireframe.

These results confirm that the horizontal-central part of the acquired unit's level presents a lower geometrical deviation compared to the entire 3D model (including the vertical sections). These data show that 95.6 percent of the point comparison deviations are between – 2.3026 and +2.3026 mm, and 68.94 percent of the deviations are between – 1.1513 and +1.1513 mm. When considering also the vertical section of the level, 96.36 percent of the point comparisons deviated between – 3.165 and +3.165 mm, and 65.18 percent deviated between – 1.5825 and +1.5825 mm. This demonstrates that geometrical deviation between the 3D models acquired using the two techniques increases in the marginal area of the surface; this could be related to the camera focusing during the capture of the images. The central part of the picture is usually the area that is most in focus during the capture. The focusing quality frequently degrades as the absolute distance from the focal point increases. For this reason, the margins (the most distant areas from the focal point) are more blurred. The test conducted by Koch and Kaelher (2009:6) on the relief of the Apadana Palace in Persepolis, Iran, indicated a similar result, showing that the center of an image reached a higher accuracy (± 1 mm) than the margins (± 3 mm).

The DSM technique gave good results in term of mesh accuracy (SD between – 3.165 and +3.165 mm), even though the difference between this technique and the triangulation laser scanner technology was still relevant. The comparison of the 3D models obtained from the two techniques, in fact, showed that only the TLS technology allowed for the preservation of all figure details and features contained in the strata (Figure 7). For this reason,

TABLE 1. Descriptive Statistics for TLS and DSM Deviation Measurements Considering the Entire Mesh.

TLS-DSM	STD (mm)	Mean distance (mm)	RMS (mm)
CS (Rapidform)	± 1.582	-	1.706
OS (Meshlab)	-	1.520	1.910

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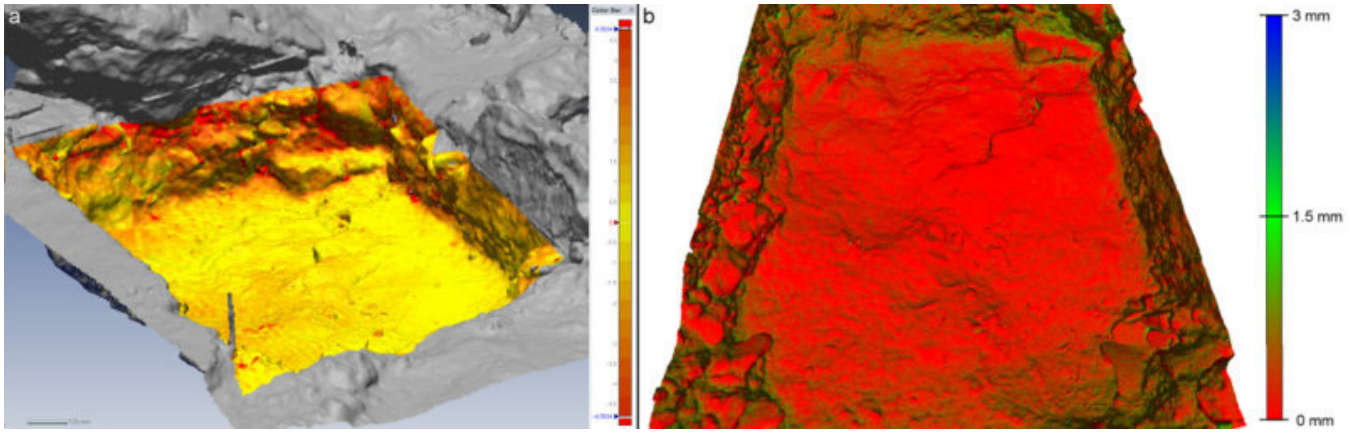


FIGURE 8. Geometrical deviation of the aligned 3D models (TLS and DSM): (a) commercial software (Rapidform); (b) open source software (Meshlab).

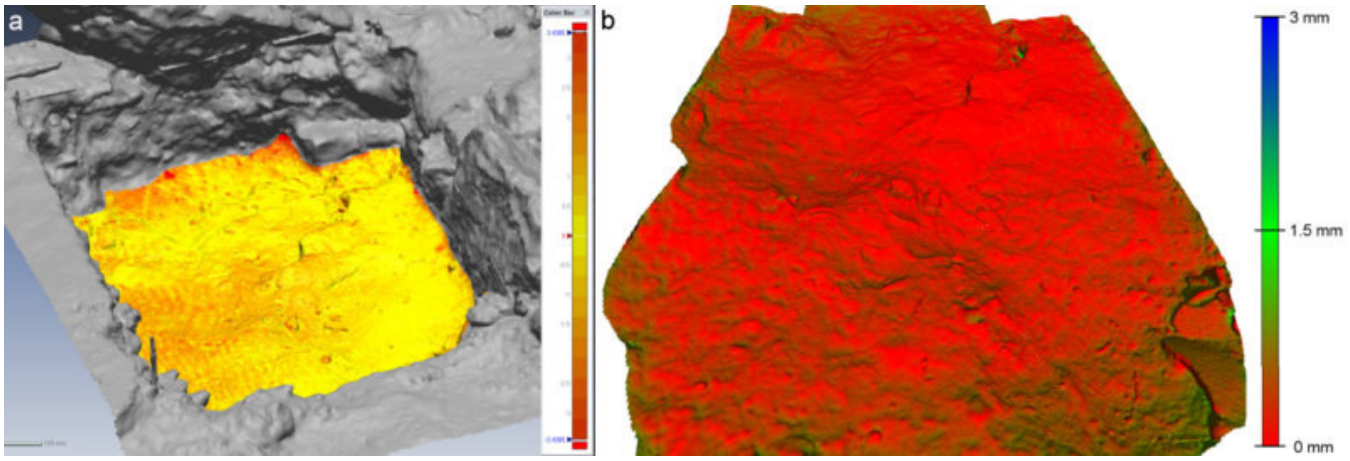


FIGURE 9. Geometrical deviation of the horizontal-central part of the aligned 3D models (TLS and DSM): (a) commercial software (Rapidform); (b) open source software (Meshlab).

we believe that the DSM technique should be integrated with other techniques when the goal of the acquisition process is data collection of micro-stratigraphy or artifacts of less than 3 mm in maximum dimension (Güth 2012; McPherron et al. 2009). Nonetheless, the mesh comparisons reported here demonstrate that the improvement in DSM technique in the last few years renders it one of the most powerful and suitable technologies for 3D data acquisition of archaeological contexts. The DSM technique is powerful for two main reasons: first, a micro-stratigraphic acquisition is not always necessary; and, second, there is a considerable difference in terms of costs, usability, data processing, and post-processing between this technique and laser scanner technologies.

The preservation of the unit texture quality was problematic for both of the 3D recording methods. The use of external lights negatively affected the texture color in the Minolta data acquisition. Lighting problems, which are very common in cave environments, were also evident in the integrated camera of the laser scanner (Figure 10a). The camera flash was used instead of external lights for the DSM data acquisition in an attempt to avoid these effects on the texture color, but the result was exactly the same: the texture color of the unit was altered (Figure 10b).

CONCLUSIONS AND FUTURE IMPROVEMENTS

The interest in archaeological 3D documentation has greatly accelerated over the past decade. Today 3D technologies are being used more commonly in archaeology, and the use of technologies is well established for the documentation of archaeological sites (e.g., Craig et al. 2006; Dellepiane et al. 2012; Dell'Unto et al. 2008; Doneus et al. 2011; Galeazzi et al. 2007; Neubauer et al. 2005). However, there are only a handful of scholars who have made quantitative comparisons between different techniques onsite (Dell'Unto et al. 2006; Koch and Kaehler 2009). The research presented here compared two techniques: triangulation light laser scanner and dense stereo matching. This onsite, comparative analysis is fundamental to achieving a complete and comprehensive understanding of the technical functions, research-related potential, and practical applications of these technologies and how to integrate them effectively into the 3D documentation process.

The results obtained in the first Las Cuevas 3D documentation campaign showed the considerable flexibility of DSM for logis-

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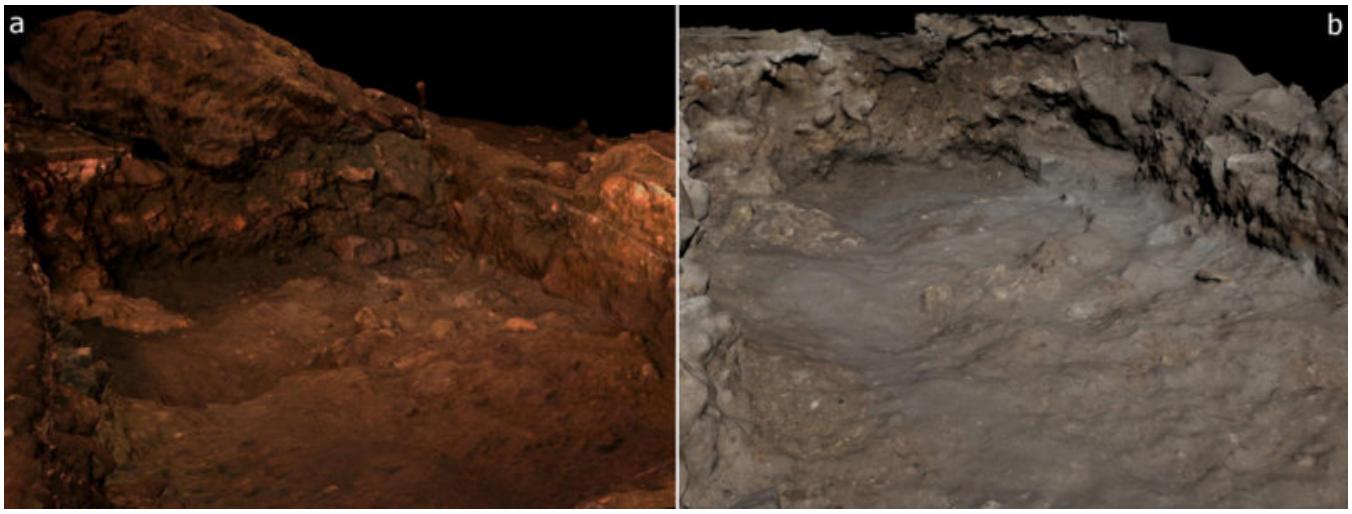


FIGURE 10. 3D texturized models of Unit 1, Level 6 (Cave Entrance Chamber), acquired using two different techniques (TLS and DSM): (a) TLS; (b) DSM.

tics, data acquisition, and post-processing time. This technique saved 15 minutes for the data acquisition (5 minutes vs. 20 minutes) and 45 minutes for the data processing (15 minutes vs. 60 minutes), without considering the machine processing in this estimation (about 3.5 hours), when compared to the TLS method. With these results, we can conclude that, in this particular environment, acquisition through TLS technology slows down the excavation process more than DMS data recording, especially for an area larger than 6 m^2.

The results of this study demonstrate the potential of DSM for 3D documentation of archaeological sites, confirming recent improvements in this technique's ability to capture the level of detail needed for research purposes. This technique has good reliability in the metric representation of the unit information, and more importantly, it is the most economical, portable, and flexible approach for the 3D documentation of archaeological sites. However, when preservation of *all* feature details is paramount, optical laser scanner techniques seem more suitable for the 3D reproduction of a unit's micro-stratigraphy in cave environments. For now, the integration of optical laser scanner with DSM seems like the optimal solution for the acquisition of archaeological features that require less than 3 mm of accuracy (Güth 2012; McPherron et al. 2009).

This study suggests that future improvements to this research are necessary and that they should take several forms. First, additional tests will be conducted at Las Cuevas in dark areas to understand how camera flash light used during the DSM acquisition affects detail and quality of the DSM 3D model's meshes. Different light sources will be tested to find a reliable and optimal lighting method for DSM acquisition in cave environments. Also, since the TLS showed some limitations in 3D documentation of archaeological stratigraphy (i.e., extreme difficulty working in direct light conditions; limited optical 3D measurement range), the DSM technique will be compared with a phase shift variation laser scanner to understand whether this technology could better serve these research aims. Finally, since the texture quality was a common issue for the different techniques, the improvement of color detail using the input images to re-project the color information (Callieri et al. 2008) could be a possible extension of this research.

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TABLE 2. Descriptive Statistics for TLS and DSM Deviation Measurements Considering Just the Horizontal-Central Part of the Mesh.

TLS-DSM	STD (mm)	Mean distance (mm)	RMS (mm)
CS (Rapidform)	± 1.1513	-	1.171
OS (Meshlab)	-	.912	1.258

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Data Availability Statement

All the data collected at Las Cuevas will be archived in the California Digital Library's Merritt repository (http://merritt.cdlib.org/) and will be available by request to the University of California Curation Center (http://www.cdlib.org/services/uc3/contact.html).

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