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From stucco to digital: Topometric documentation of Classic Maya facades at Holmul

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ABSTRACT

This article addresses the use of a structured light 3d scanner to document ancient Maya architecture. A rationale for the project is outlined along with some practicalities of operating the equipment in remote locations and archaeological tunnels. The two case studies describe the documentation of painted stucco friezes at the archaeological site of Holmul, Guatemala, by the Corpus of Maya Hieroglyphic Inscriptions of the Peabody Museum of Archaeology and Ethnology, Harvard University. Holmul buildings boast some of the most elaborate and well-preserved stucco sculptures in the Maya world. The paper concludes with highlighting the current challenges in creating and using high-resolution 3d replicas for research and conservation purposes.

1. Introduction: saving ancient Maya heritage

Archaeologists working in the Maya area face formidable conservation challenges. The humid and hot tropical climate with its rapid wet-dry cycles, aggressive biota (microbial biofilms, fungi, and algae), and the relative fragility of the ancient Maya construction materials (limestone and stucco) combine into a perfect storm of threats to anything that may not be transferred to a protected environment immediately upon its excavation (Ginell and Kumar, 2004; Straulino et al., 2013). The situation is further compounded by the lack of resources and the remote location of many archaeological sites, which may be completely inaccessible during most of the rainy season. Then there is always the possibility of looting and vandalism. Researchers often face a choice between a faster, potentially more damaging, and less substantive inquiry, versus exposing the site to some of the risks outlined above while a more comprehensive and efficient research and conservation strategy is developed.

The Ancient Maya practice of carefully burying the foundations or even superstructures underneath later buildings leads to complex construction sequences, which often contain well-preserved facades. The latter provide the archaeologists with a unique window into the indigenous history and worldview (Fash, 1998; Fash and Fash, 1996). The common study approach is combining surface excavations with tunneling to minimize damage to later buildings. This approach is best illustrated by several projects at the site of Copan in Honduras (Fash et al., 1993, 1992; Sharer et al., 2005; Williamson, 1993). In the case of Copan, a cut to the site core created by the Copan River facilitated tunnel excavations (Sharer et al., 1992), whereas the Late Classic 'mosaic' construction technique enabled partial removal, reconstruction, and conservation of entire buildings (Fash, 1992; Fash et al., 1993). The tunnel excavations at Copan produced some of the most spectacular examples of Early Classic Maya painted stucco architecture (Fash, 2011).

Copan projects also illustrate challenges in assuring the long-term conservation of the excavated buildings. Studies at Copan and elsewhere indicate that protective roofing alone does not guarantee the preservation of the structures (Espinosa-Morales et al., 2014; Fash et al., 1993; GCI and IHAH, 2006; Ortega-Morales et al., 2013). The main problem is that the roof by itself does not prevent extreme variation in humidity and temperature and does not necessarily inhibit the colonization of the limestone or stucco surface by fungi and bacteria. A more comprehensive cover solution may be prohibitively expensive and unwelcomed by local communities and national authorities, who rely on tourism. The tunnels seem to be a safer option. In fact, some current Copan tunnels were created after open-air excavations to preserve access to certain sections of the excavated buildings. However, the environment inside the tunnels, while substantially more stable than the temperature and humidity on the surface, still differs from the pre-excavation conditions. Colonization of the surface by bacteria and fungi still happens. The tunnels may effectively unseal previously impenetrable elements of the construction sequences. Tunnels also change the way the weight is distributed in what used to be a near-monolithic fill. The exposed façade walls end up under additional stress, which may cause deformation and damage, particularly to the stucco surface,

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which may begin to break and detach from the wall masonry. Larger sections of buildings may start to gradually re-settle causing additional damage. For example, the so-called Xukpi stone at Copan is slowly torn apart by the movement of the floor and the walls around it. The process is recent, so it is likely to have been caused by the extensive tunneling around the monument.

One possible solution is to re-bury the excavated buildings entirely and even cover the originals with replicas (Hansen and Castellanos, 2004; Kovác et al., 2015). However, it does not necessarily resolve the issue of the long-term change caused by the initial excavation. Moreover, archaeologists often follow in the footsteps of looters and devise research and conservation strategies in the context of the extensive damage already done by the illegal excavations. For example, some 270 looters' trenches and tunnels were registered in the core area of a major archaeological site of Naranjo in the department of Petén, Guatemala, during the initial stage of the project (Fialko, 2009). Many more illegal trenches and tunnels have since been detected as the survey expanded to incorporate the periphery of the ancient city. The damage to the compromised structures may be on-going, and even the best conservation effort cannot stop it.

2. Documenting Maya buildings: methods and techniques

The implication of the conservation challenges outlined above is that timely and accurate documentation of the exposed architecture is an essential component of archaeological projects in the Maya area. Drawings and photographs remain the dominant documentation methods. However, both suffer from apparent limitations in representing three-dimensional objects. Technical drawings are a key analytical tool and conduit of information in the academic community, but it is hard to use the reduced information in a drawing for a purpose other than the one intended by its maker (Daston and Gallison, 2010[2007] Fash, 2012). Photographic documentation also depends on specific goals and choices of a photographer, and it may be hampered by field conditions, especially the constrained environment of tunnel excavations (Garrison et al., 2016).

Fortunately, several new documentations techniques are now available to the archaeologists working in the Maya area. Photogrammetry is, perhaps, the most accessible and versatile option. Recent efforts to create digital replicas of the stucco facades at Uaxactun (Kovác et al., 2015), Chilonché and La Blanca (Castillo and Domíngue, 2014), and El Zotz (Fisher et al., 2012; Taube and Houston, 2015) illustrate the advantages of the technique that enables rapid large-scale 3d documentation of entire buildings at a fraction of the cost of other methods. However, photogrammetry has its drawbacks. The results are not apparent until data-processing, which may not happen in the field. So, for example, if the building is back-filled, there would be no second chance to record it. Although there is no theoretical limit to the resolution of the images, the practical challenges of creating and processing very large data sets (manually shooting hundreds of overlapping close-range, same-focal-length photographs of a massive stucco frieze in a narrow tunnel is not as easy as flying a drone over a landscape) mean that the actual resolution is not in the sub-millimeter range, and the overall accuracy of 3d models of buildings is relatively low.

Lidar laser scanners offer a more efficient, albeit costlier, alternative to photogrammetry. The process requires fewer captures, the point cloud may be previewed during the documentation process, and the overall accuracy is greater. Recent comparison of lidar and photogrammetry results at El Zotz (Garrison et al., 2016) and Chilonche (Cosme et al., 2014; Lorenzo and Cosme, 2014) exemplify these benefits of the technology. Laser scanners work equally well in all lighting conditions including bright sunlight. Lidar data may also be combined with photogrammetry (Remondino et al., 2009). However, the top resolution of the lidar-based 3d models does not exceed 2–3 mm. While it may be adequate for most documentation and visualization purposes, such resolution carries the risk of omitting or under-documenting small carved/molded features. If the goal of the documentation is monitoring the conservation of a building or an artifact, significant changes may happen in the sub-millimeter measurement range (Hess et al., 2015). Finally, a 2–3 mm resolution may be too low for a faithful and realistic full-scale replication of the building façade with a 3d additive printer or a milling machine.

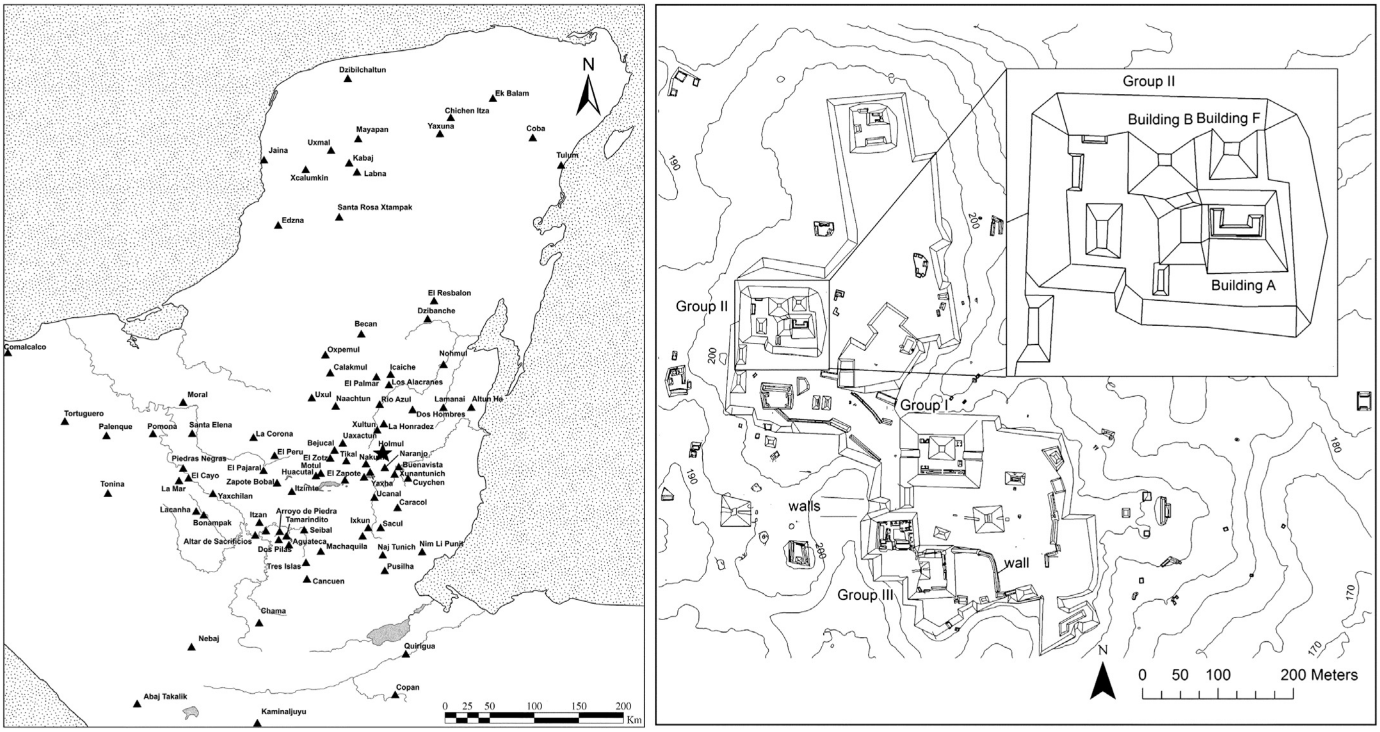
Structured-light scanners have superior resolution/precision and modular architecture (with an option of opting for more detail at a cost of scanning speed), but using them involves additional logistical and operational challenges such as constant external power supply and sensitivity to ambient light (Wachowiak and Karas, 2013). These systems are typically chosen to document medium-size and smaller objects in a controlled setting of a museum collection (e.g. Kai-Browne et al., 2016) and have a reputation of being rather complex to operate (Hassani et al., 2015). Nevertheless, structured-light scanners may also be used in the field, as long as all the operational constraints are addressed.

3. Scanning with a *smart*SCAN Duo

Beginning in 2008, the Corpus of Maya Hieroglyphic Inscriptions of the Peabody Museum of Archaeology and Ethnology at Harvard University initiated a 3d scanning program that relied on a structured light system *smart*SCAN Duo to record ancient Maya monuments and building sections in the museum collections and in the field (Tokovinine, 2013a; Tokovinine and Fash, 2008). The scanner consists of a projecting unit and two cameras connected by carbon fiber rods and mounted on the tripod. With a total weight of 4 kg, the sensor is certainly bulkier than an average photo camera. The scanner's cameras are at a 30-degree angle to each other, so the visibility of documented features varies substantially if they are parallel or perpendicular to the plane of the cameras. The scanner has to be connected to a laptop and a projector control box and needs a continuous and stable power supply. There are several sets of projector and camera lenses, which enable larger scans in lower resolution or smaller scans in higher resolution. The design is robust, but it is somewhat vulnerable to moisture, heat, and dust. It is also sensitive to ambient light and works best in complete darkness. A periodic re-calibration using a dedicated plate is required for each set of lenses. The scanner comes with its own proprietary Optocat software for capturing and processing 3d data.

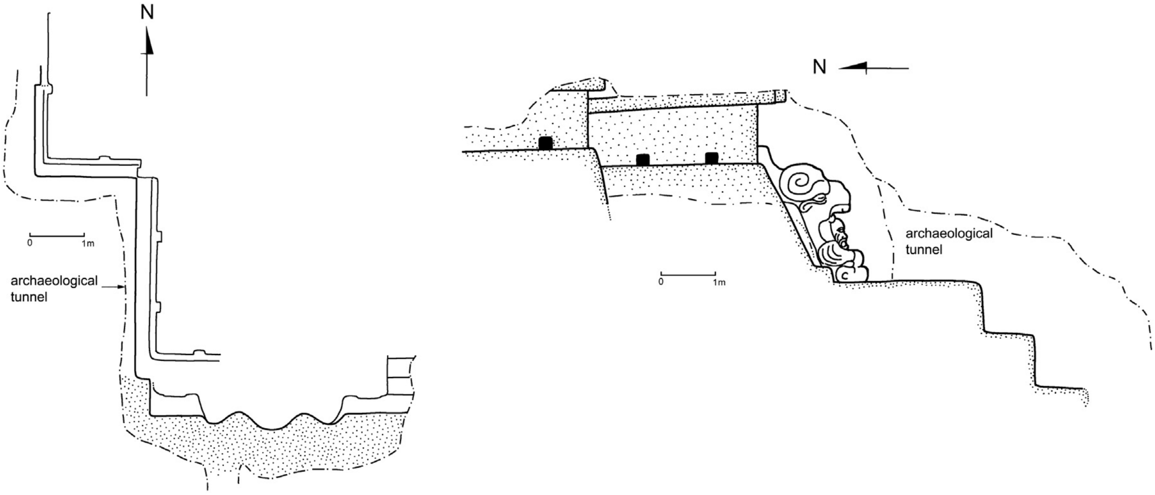
A typical documentation workflow consists of positioning the sensor at a distance of 73 cm from the scanned surface. The software operator adjusts the camera settings (if necessary) and initiates the capture that takes 1–10 s. The software generates a sub-sampled mesh that may be used to assess the quality of the scan. Successive scans must overlap and are aligned by manually indicating at least three shared points. The software then refines the alignment automatically. After that, the scanner may be repositioned for the next capture. If the crew consists of a skilled scanner/tripod manager and a well-trained software operator, the whole sequence usually takes between one and five minutes. Although some of the steps outlined above may be automated (Kai-Browne et al., 2016), field conditions tend to be too diverse and unpredictable for automation.

The present article discusses two cases of using *smart*SCAN Duo to document large sections of stucco-covered building facades inside archaeological tunnels at the archaeological site of Holmul in the department of Petén, Guatemala (Fig. 1a). Initially investigated by Merwin of Harvard University (Merwin and Vaillant, 1932), the ancient Maya city has become the focal point of a new regional archaeological project directed by Estrada Belli (Estrada Belli, 2002, 2004, 2016). Archaeologists working at Holmul today deal with the consequences of the extensive looting of the site during the second half of the twentieth century. The project exemplifies all the standard difficulties of conducting excavations in a relatively remote location. It takes between two and eleven hours to reach the nearest town depending on the state



a b

Fig. 1. Case study maps: a) Holmul and its location in the Maya area (map by Alexandre Tokovinine); b) Holmul site core (map by Francisco Estrada Belli).



a b

Fig. 2. The location of the Building-B ‘mask’ in the archaeological tunnels: a) plan view; b) profile view (drawings by Alexandre Tokovinine).

of the roads. A week or two of sustained heavy rains may cut the site off entirely. Given the roads, exposing and restoring buildings for tourism has not been a priority. Most surface excavations and tunnels were backfilled once the investigations had been completed.

The architectural core of Holmul is defined by three massive platforms known as Group I, Group II, and Group III (Fig. 1b). Much of Merwin's original research was centered on Group II, especially the Proto-Classic and Early Classic phases of Building B (Merwin and Vaillant 1932:20–40). Merwin's project did not identify the earliest construction stages in Group I and Group II, which occurred in the early Late Formative period, as well as the sixth-century phases of some structures (Estrada Belli, 2016). Whereas Merwin and his team relied primarily on extensive surface excavations, the dominant approach of the modern project was to tunnel, often exploiting as entry points the tunnels and trenches left by the looters.

3.1. Case 1: the stucco ‘mask’ of Building B-1st

Building B is one of the temples occupying the platform of Group II of Holmul. The discovery of multiple superimposed burials in the structure by Merwin's team laid the groundwork of the regional ceramic chronology (Callaghan and Nievens De Estrada 2016; Merwin and Vaillant 1932). However, despite extensive excavations, which exposed an entire Early Classic version of the structure, its core remained unexplored. In 2005, an investigation of the looters' trench on the western side of Building B revealed a Late Formative foundation and a

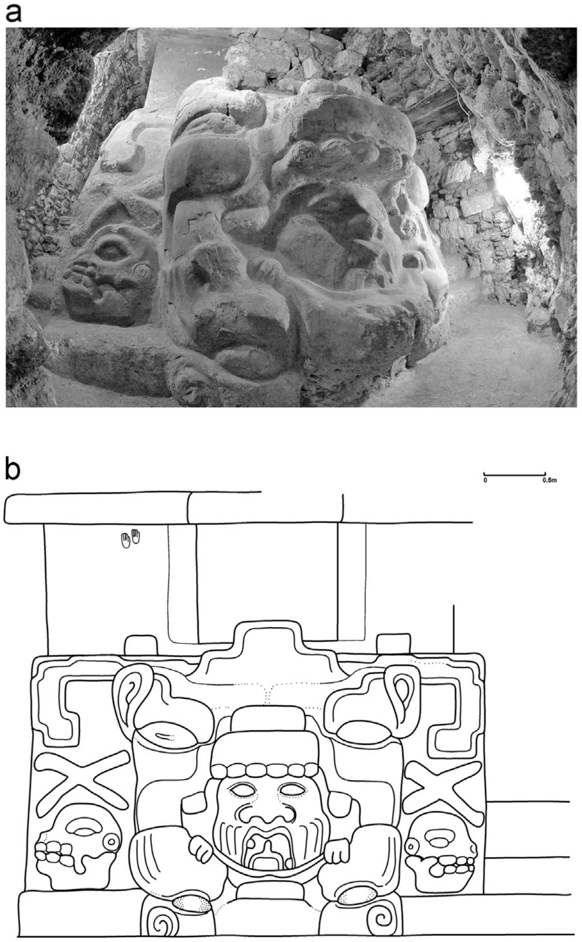


Fig. 3. Documenting the Building-B 'mask': a) wide-angle camera (photograph by Francisco Estrada Belli); b) line drawing (drawing by Alexandre Tokovinine).

T-shaped superstructure that was almost completely preserved within the base of the temple excavated by the Harvard project (Estrada Belli, 2006:4–5). Subsequent tunneling around the building's foundation in 2007 revealed nearly intact stucco reliefs or 'masks' flanking the central stairway on the topmost terrace on the southern side of the temple (Estrada Belli, 2007:12–20).

Once the western 'mask' had been fully exposed, it became apparent that it represented the earliest known constellation of several key concepts, which structured the indigenous landscape, including ancestral worship, caves, living mountains, and fertility (Estrada Belli, 2011:92–96; Tokovinine, 2013b:54–55). However, documenting the 4 m × 3 m × 1.4 m frieze located at the end of a narrow (1 m or less) tunnel (Fig. 2) winding around the top terrace of the structure was a considerable challenge. There was not enough space to make photographs without a substantial distortion (Fig. 3a). The sculpture was also too three-dimensional to be adequately rendered with conventional line drawings (Figs. 2b and 3b). Moreover, although the tunnel around the 'mask' had been consolidated, its roof reinforced, parts of the carving were at risk of losing sections of the stucco surface (as seen in Fig. 3a). Consequently, there was a need for a more comprehensive documentation without touching the stucco, especially the areas at risk of further surface loss. A full-scale digital replica was also seen as the only way of making the monument more accessible to researchers and the public. The idea to use *smart*SCAN Duo was initially deemed unfeasible, because the top of the frieze was inaccessible, whereas scaffolding was considered too risky and impractical because of the bell-like shape of the tunnel. In 2012, the 3d scanning team successfully trialed a setup with a tripod-mounted 2.4 m-long camera crane. It was estimated that the crane could fit inside the tunnel, so the project went ahead.

In the absence of any on-site room with controlled dust, temperature, and humidity conditions, it was decided that the tunnel itself would be the most stable environment for the scanner and that documentation had to be completed as quickly as possible, whereas moisture and dust contamination of the electronic equipment would be addressed upon return from the forest. Moreover, the road between the project camp and Group II was too rough and could cause small adjustments of the scanner's cameras. Therefore, the scanner had to be calibrated inside the tunnel. A couple of instances of minor impact of the scanner against the tunnel walls meant that there were subsequent re-calibrations. It was a painstaking process because of space constraints: the scanner's container had to be used as a table for the calibration plate, and the whole system had to be disassembled and reassembled to switch between calibration and scanning modes. All the equipment remained inside the tunnel for the duration of the project. The width of some access tunnel sections was just barely enough to move the scanner's container, the tripods, and the disassembled crane, so keeping all the equipment inside had an additional benefit of reducing the chances of damaging the building. Only the power generator remained outside.

The team used smaller tripods and a customized stand on a square

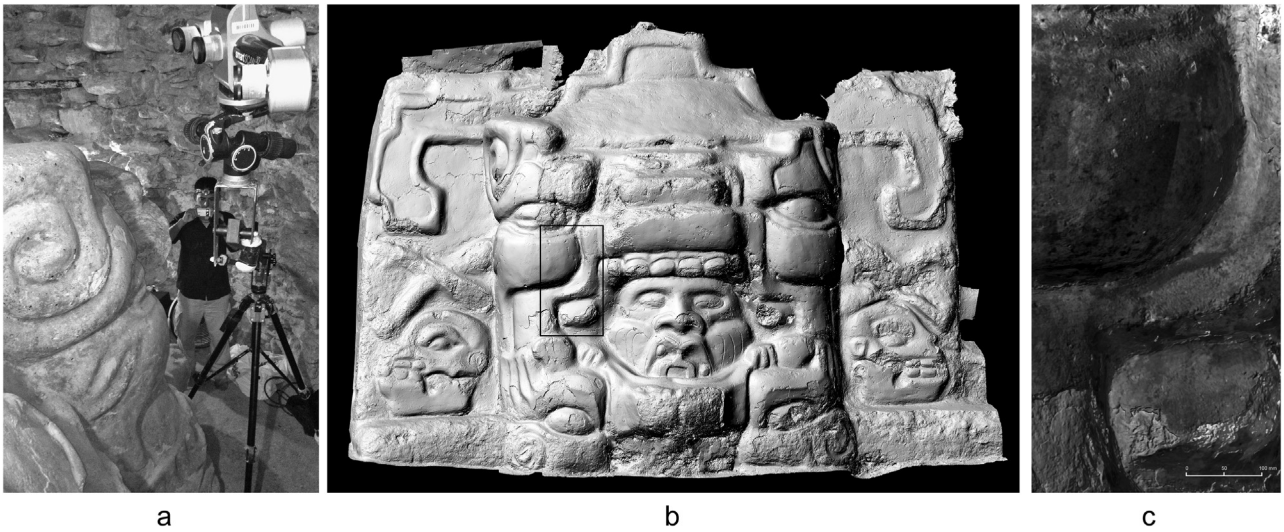


Fig. 4. 3d scanning of the Building-B 'mask': a) the scanner mounted on a camera crane inside the tunnel (photograph by Alexandre Tokovinine); b) texture-free screenshot of a full-resolution 3d model (rendering by Alexandre Tokovinine); c) detail of a colored screenshot of a full-resolution 3d model (rendering by Alexandre Tokovinine).

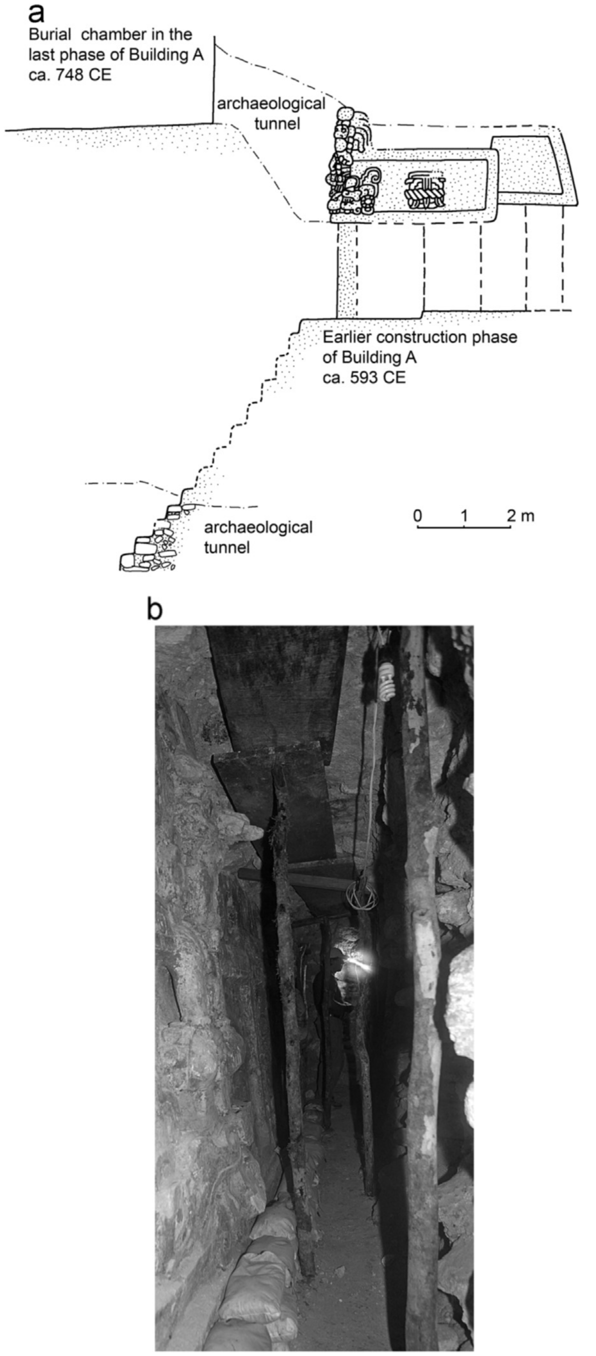


Fig. 5. The location of the Building A stucco frieze: a) profile drawing of the excavated tunnels; b) photograph of the tunnel in front of the western section of the frieze (drawings by Alexandre Tokovinine).

base to scan the lower half of the frieze. Then the camera crane was assembled and provided access to the top sections (Fig. 4a). Given the large size of the 'mask', it was scanned with a set of lenses for a field of view of 600 mm and the XY resolution of 0.36 mm. A set with a smaller field of view and higher XY resolution (300 mm and 0.18 mm respectively) was deemed unfeasible, because the scanning would have taken too long, and the resulting dataset would have been unmanageable. The system made 394 captures of a million points each. With that much data, the biggest challenge was to ensure in the real time that the successive scans aligned properly and that there were no gaps in the record. The triangulated meshes of the scans could be subsampled only up to a certain point, but then the addition of new scans would progressively increase the computation times for aligning and rendering. The issue was resolved by periodically merging the scans and using the merged meshes for inspection and alignment. Moreover, scanning was undertaken in continuous sections, so that upon merging the scans, only the edges of the merged mesh would be kept for alignment with subsequent captures. These procedures kept computation per scan to a minimum at a cost of additional amount of time for the merge operations. It was determined empirically that, for the current system configuration, the optimal cycle was to merge every 40–50 scans. It took three and a half days to scan the frieze. A heavily subsampled 3d model was available immediately.

A more powerful desktop workstation was used to triangulate and realign the scans without subsampling, and then merge them into a single mesh (Fig. 4b). The automatic fine alignment of the full-resolution scan meshes was the most processing-heavy operation and took a couple of days. The completed mesh had to be manually edited to fill some holes with complex edges, which could not be closed by the software. That stage took five days, primarily because of rendering time between the editing steps. The finished mesh had 126 M triangles with an average size of the triangle around 0.4 mm – a considerable reduction from the original dataset, due to several masks and filters, as well as overlaps between the scans. It could be used for making a realistic real-size replica and for monitoring future conservation of the frieze. However, the mesh was still too big to be viewed on an ordinary computer. Therefore, several optimized versions were created, offering a compromise between visibility of certain feature and the size of the mesh. One of them (7 M faces) was subsequently posted on the Sketchfab online platform (see Supplement 1).

One of the advantages of the *smart*SCAN system is its ability to simultaneously capture color and topography. The colored 3d model of the frieze could facilitate the identification of the areas with surface loss (they appear lighter). There were also some traces of paint, which had to recorded. However, assuring consistency of texture information between the scans was difficult. Although the system could be set to operate with external light sources, the option with multiple external light stands seemed to be impractical in the field, especially in a tunnel. The scanner was set to use its own projector as a light source. However, there was no way to adjust the exposure of color shots to changes in the angle between the scanner and the frieze. Consequently, a straight view exposure was set as a default value. As for the oblique views, some areas of those captures appeared underexposed, whereas others were overexposed. If an area in question was captured from multiple viewpoints, its color would still be close to the optimal exposure due to averaging between several captures. Flatter areas with fewer overlapping scans showed some linear brightness variations on the boundaries between the captures (Fig. 4c). Because of the per-vertex texture record, the resolution of the color data matched the resolution of the mesh. Any subsampling would entail loss of color information, unless it were separated into a texture file to be re-mapped onto the simplified 3d surface (for example, using Geomagic Wrap or Geomagic Studio).

3.2. Case 2: the painted stucco frieze of Building A-2nd

Building A occupies the eastern side of the same Group II platform as Building B. The structure received relatively little attention from the Harvard project (Merwin and Vaillant, 1932:18–20). The looters subsequently targeted the building and dug several tunnels and trenches into its substructure. A new investigation of Building A in 2012 and 2013 explored those illegal excavations and tunneled deeper into the mound to reveal a well-preserved 6th-century funerary temple with a spectacular painted roof frieze (Díaz García, 2012; Estrada Belli, 2013). The iconographic program of the frieze offered important insights into the ancient Maya religious beliefs (specifically, the king's rebirth as the sun), whereas a lengthy inscription provided key details of the local dynastic sequence and the regional political history (Estrada Belli and Tokovinine, 2016).

The discovery of the frieze also meant that it had to be properly

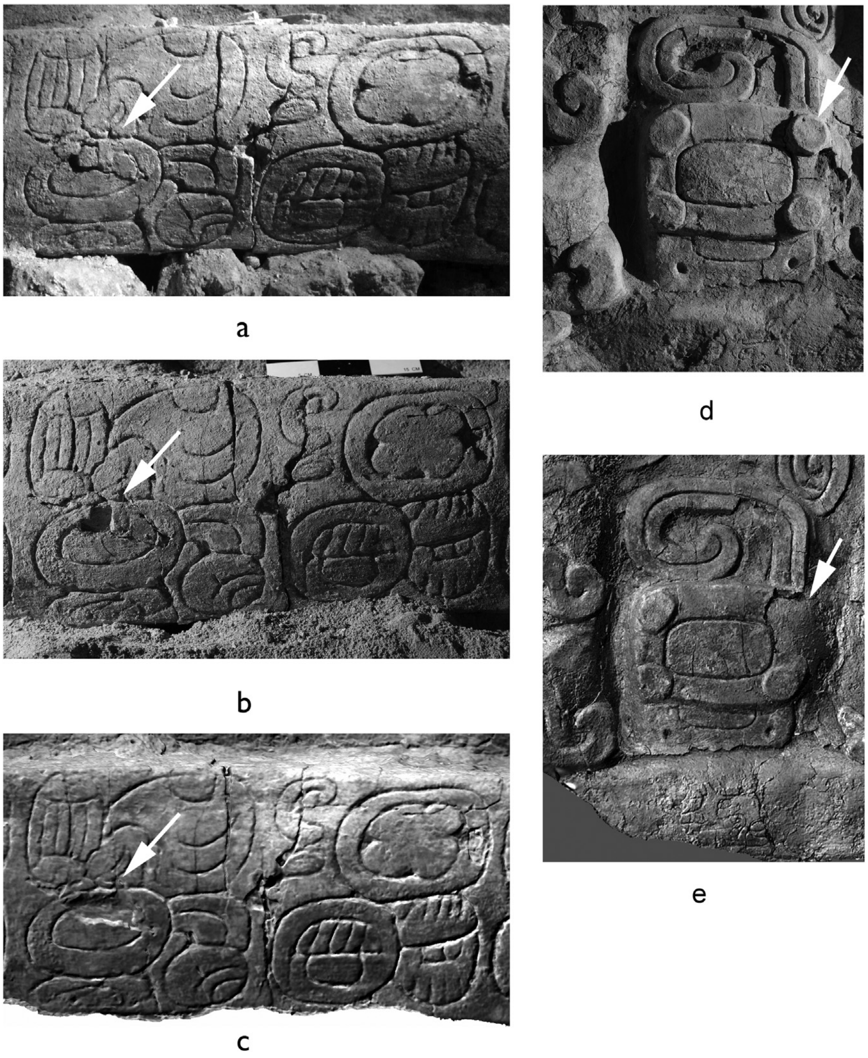


Fig. 6. Building A stucco frieze surface loss (arrows indicate the areas of surface loss): a) detail of a glyph shortly after excavation (photograph by Francisco Estrada Belli); b) detail of a glyph one month after excavation (photograph by Alexandre Tokovinine); c) detail of a glyph one year after excavation (rendering by Alexandre Tokovinine); d) detail of the mountain one month after excavation (photograph by Alexandre Tokovinine); e) detail of the mountain one year after excavation (rendering by Alexandre Tokovinine).

documented. After the initial exploration of the northwestern corner, the main access to the frieze was tunneled near its southwestern corner, connecting it to a vaulted chamber from the last construction episode of Building A (Fig. 5a). The main 8 × 2.4 m relief on the western side of the roof and the glyphic emblem on the southern side were exposed in a narrow tunnel, its width varying from 1.2 m to 0.6 m (Fig. 5b). A field drawing of the reliefs was undertaken immediately upon the excavation (Estrada Belli, 2013: figures 8.4 and 8.7). A composite high-resolution photograph was also produced using Canon 5D Mark II camera with an EF 24–70 mm f/2.8 L USM lens; it was subsequently used for an epigraphic line drawing (Estrada Belli and Tokovinine, 2016:Fig. 4). However, because of the narrow width of the tunnel, especially towards the top of the frieze, some shots could only be taken from an oblique angle. The result was that the top section of the composite photograph appeared distorted.

The tunnel was too narrow to set up consistent lighting for a photogrammetric shoot with the equipment at hand. The remote light source had to be moved along with the camera. 268 overlapping shots taken for the composite photograph (see above) were subsequently used to generate a structure-from-motion 3d model with Agisoft PhotoScan Pro. However, the result failed to include about 0.5 m of the northernmost section of the frieze and one small area of the main inscription because of lighting differences in some overlapping shots. Moreover, scaling the 3d model using scale bars in the photographs produced an error estimate of 43 cm. Consequently, the model was too inaccurate for scientific record.

The conservation of the frieze was of major concern. Its northwestern section was in greater danger, probably because looters' pits breached the protective stucco floors, which sealed the later substructure above the temple. Water and tree roots penetrated the space between the stucco molding of the frieze and the roof wall masonry. Once the frieze had been exposed by the archaeologists, the lateral pressure of the construction fill against the stucco of the relief was removed, whereas the pressure on the wall of the frieze increased. Consequently, the most compromised stucco sections started to detach and fall almost immediately. A comparison between the images taken during the excavation, one month later, and in a year later shows the surface loss. For example, a glyph in the main inscription lost its central element (Figs. 6a, 6b, and 6c). In another case illustrated here, one of the images of living mountains lost a section of its earflare (Figs. 6d and e). Unfortunately, the frieze was discovered at the end of the field season. The roads became impassable shortly after. It was too late to organize a conservation intervention or to do the necessary paperwork to bring a 3d scanner. It was, therefore, imperative, to create a detailed digital replica of the frieze at the beginning of the field season of 2014. The 3d documentation was preceded by an emergency conservation intervention and assessment (Gámez and Zúñiga, 2014), although it still reflected the state of the frieze before more comprehensive conserva-

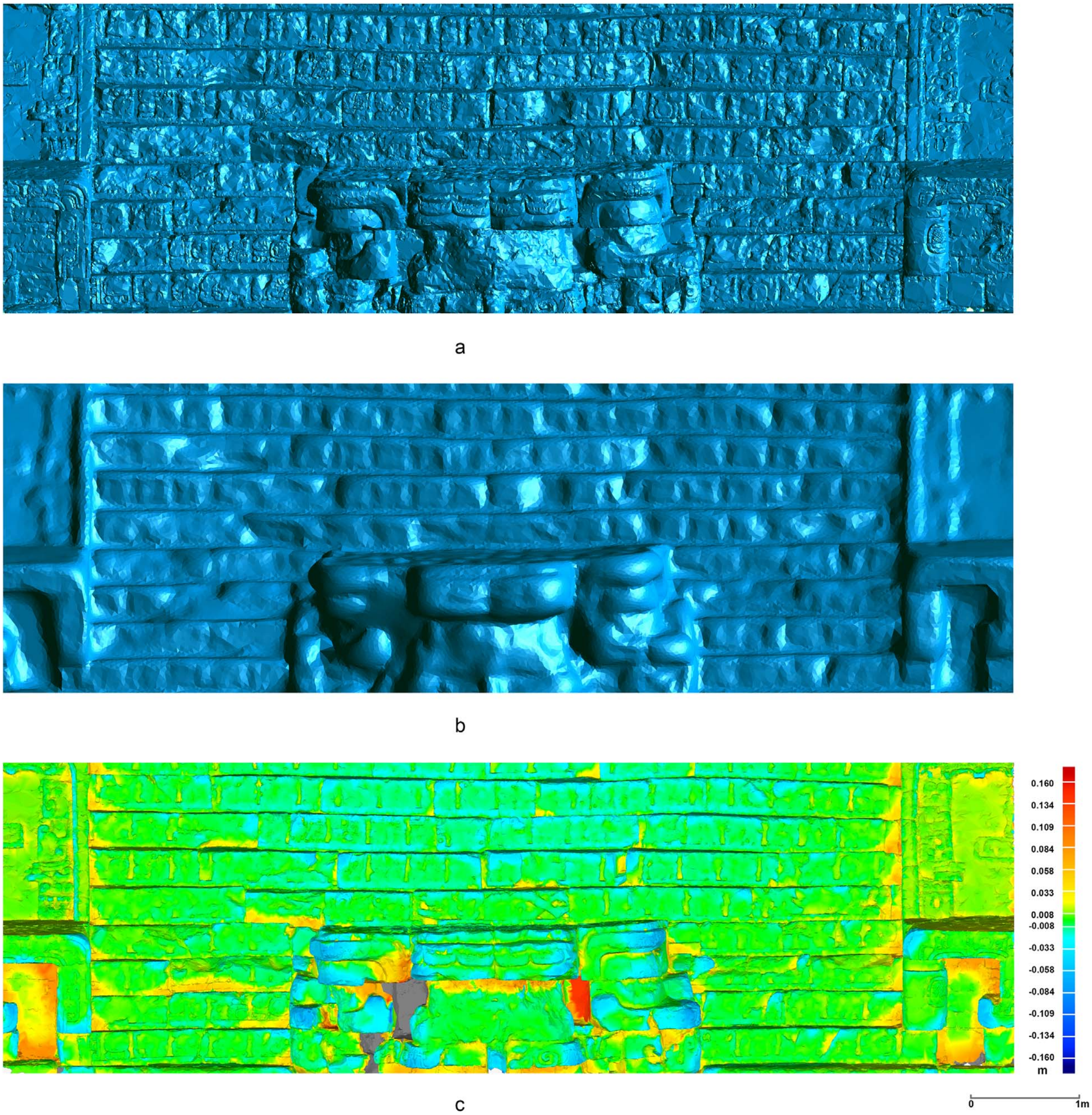


Fig. 7. Comparing laser and structured light scans of the Copan Hieroglyphic stairway: a) screenshot of the 50 mm-resolution 3d model based on the structured light scans (Breuckmann *smart*SCAN Duo); b) screenshot of the 50 mm-resolution 3d model based on the laser scans (Leica HDS3000); c) deviation map for the 3d models in a) and b) (renderings by Alexandre Tokovinine).

tion efforts during the same field season and in the following year (Gámez, 2015; Gámez and Zúñiga, 2014).

Given the large size of the frieze, the relatively small field of view of the structured light scanner meant that close to a thousand individual captures would be required, leading to some concerns about accuracy, just as with the photogrammetry attempt described above. An earlier project centered on the documentation of the Copan Hieroglyphic Stairway (Fash, 2012:463–466; Tokovinine, 2013a:7–9) enabled a direct accuracy assessment for a large-scale object, because the same stairway was also documented with a Leica HDS3000 laser scanner by Massimo Brizzi and his team (Fash and Fash, 2011:8–9). A down-sampled 3d model from nearly two thousand *smart*SCAN Duo captures (Fig. 7a) was compared to a 50 mm-resolution 3d model generated from the HDS3000 point cloud captured primarily from two stations in front of the stairway (Fig. 7b). The deviation map for the two models (Fig. 7c) showed no systematic differences apart from those generated by gaps in the laser scan point cloud due to limited view angles. Therefore, there was no reason to doubt the accuracy of the Holmul frieze scans.

The overall procedure built upon the experience of documenting the ‘mask’ of Building B (see above) with some differences. The same set of lenses for the 0.36 mm XY resolution was used. The tunnel in front of the main, western section of the frieze was even narrower than in the case of Building B, so all the documentation had to be undertaken with a scanner mounted on tripods or placed directly on the floor of the tunnel. Some areas of the tunnel were too narrow to capture with straights shots. It was impossible to achieve the nominal XY resolution and accuracy values across the entire surface of the relief. There was no access to the space above the frieze. Relatively well-preserved green, yellow, and blue paint on a dark-red background covered parts of the frieze surface. Combined with the lighter spots of recent surface loss, there was too much contrast. Therefore, some areas had to be re-

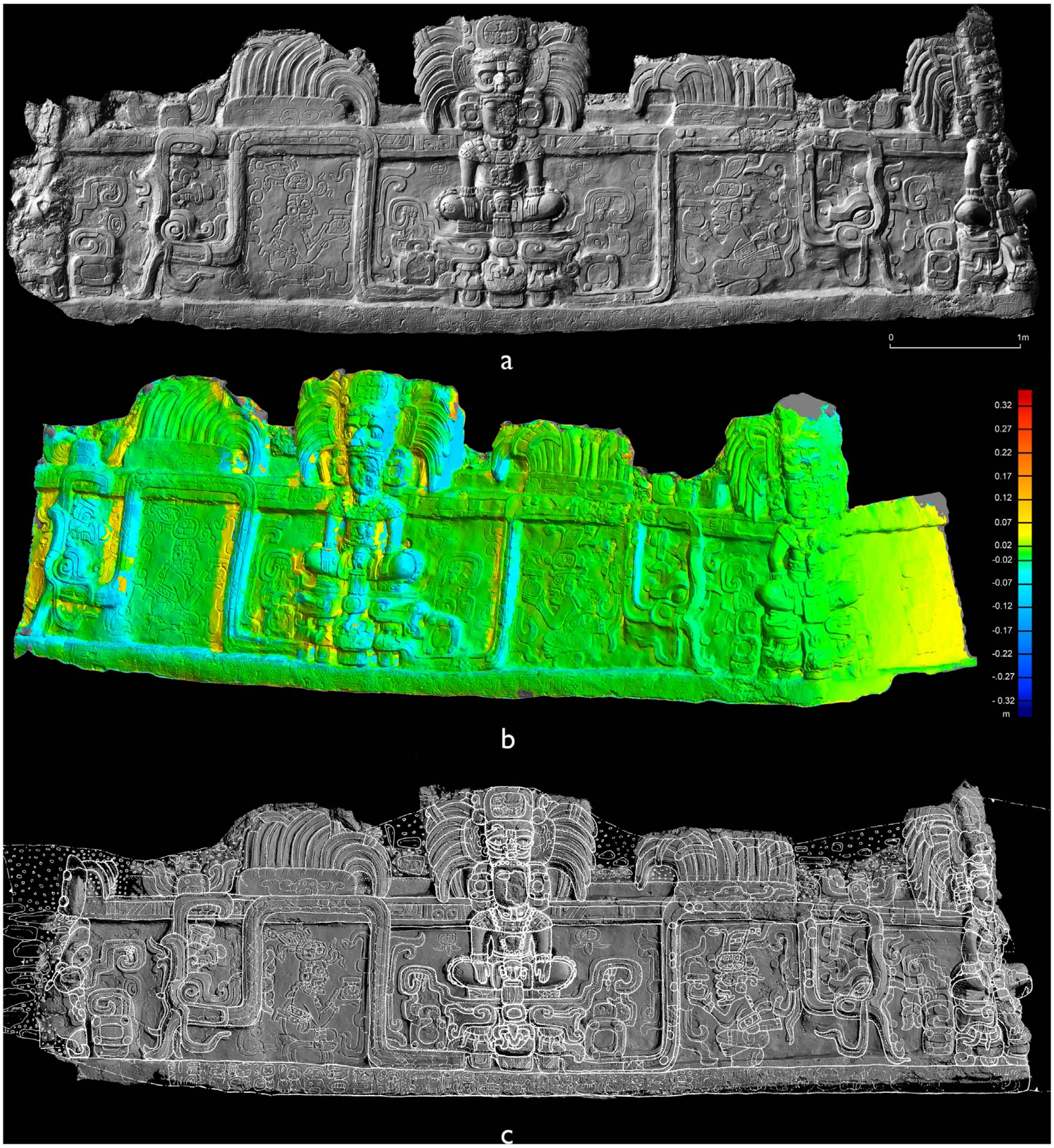


Fig. 8. 3d scanning of the Building A stucco frieze: a) texture-free screenshot the 3d model (0.36 mm resolution, 322 M faces); b) deviation map of the downsampled 3d model based on structured light scans vs. a 3d model based on structure-from-motion photogrammetry (Agisoft PhotoScan Pro); c) overlay of the structured-light 3d model and a field drawing of the frieze (drawings and renderings by Alexandre Tokovinine).

captured with different exposure and averaging settings. Additional scan overlaps of the painted elements were required to address the variable exposure problem (see Case 1).

The total surface area of the documented sections of the frieze was three times as large as the ‘mask’ of Building B. It was decided to split the scanning into the western and the southern sections, which would only be merged as complete models. The larger western sections took 868 captures to document, whereas the southern section took only 77 scans. While the scanning-proper took only six days, the data set was incredibly hard to process because of its sheer size. The fine alignment step, for instance, took over a week of processing time. The merged full-resolution mesh (Fig. 8a) consisted of 322 M triangles and could not be viewed or manipulated in most 3d software packages except for the proprietary Optocat 2013. Therefore, although the goal of creating a comprehensive 3d record of the frieze had been achieved, the practical necessities of using that record meant that several optimized and subsampled versions had to be created.

One of the immediate applications of the 3d scan was verifying previous records of the frieze. For example, a deviation map for the *smart*SCAN Duo 3d model and the photogrammetry-based 3d model (Fig. 8b) showed a systematic difference along the north-south axis of the frieze. In other words, the photogrammetry-based model appeared ‘squeezed’ along its horizontal dimensions, which was consistent with its high error estimates based on the scale bars positioned on the same axis. An overlay of the field drawing of the frieze (hand measurements with a tape, a string with a level, and a weight) and a 3d model screenshot positioned in a way to match the view plane of the drawing (Fig. 8c) revealed a much closer correspondence apart from minor discrepancies and a curious systematic deviation in the southwestern corner of the frieze. The latter could be speculatively attributed to human error, because that section of the field drawing contradicted both 3d models: the one based on *smart*SCAN Duo scans and the one

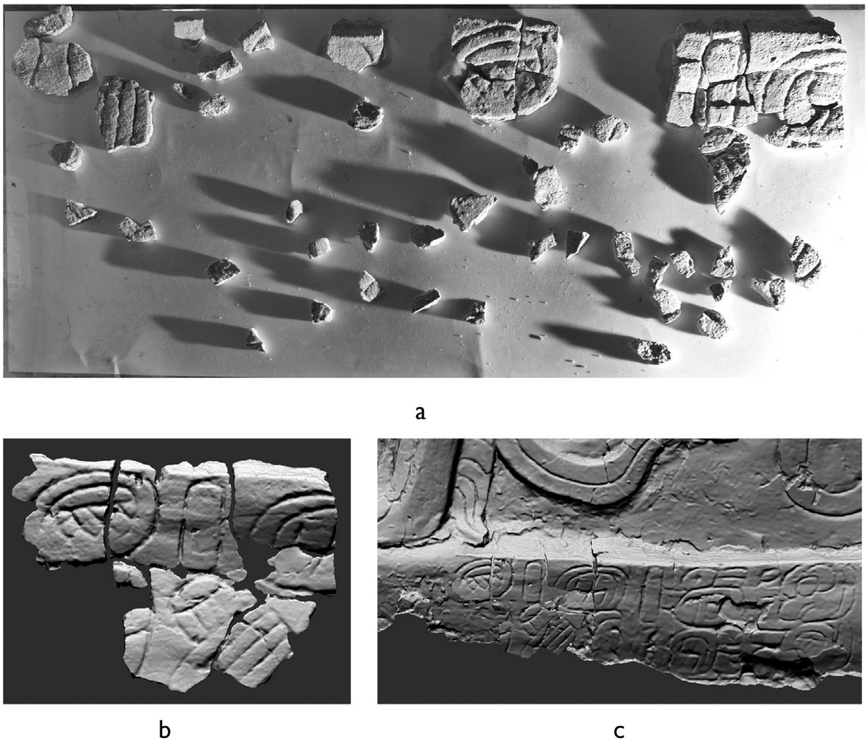


Fig. 9. Using 3d scans for a virtual reconstruction: a) fragments of the main inscription; b) a 3d scan of the re-assembled fragments; c) a virtual reconstruction of the frieze with the scanned fragments (renderings by Alexandre Tokovinine).

based on photogrammetry. Various authors previously commented on a tendency to represent ancient Maya buildings as more regular and rectilinear than they actually are (see Hutson, 2012). The difference between the field drawing and the 3d scan of the Holmul frieze seemingly reflected that kind of error.

A small section of the main inscription on the frieze detached and fell into several dozen fragments during the excavation (Fig. 9a). In 2014, the fragments were re-fitted together and 3d-scanned (Fig. 9b). Instead of physically attaching the fragile pieces to the frieze, a digital reconstruction was attempted using a subsampled 3d model (Fig. 9c). The virtually restored section added a key passage to the inscription and clarified the spelling of *Wiinte' Naah*, the most significant place name in the Early Classic Maya inscription, refuting previous translations and interpretations (Estrada Belli and Tokovinine, 2016:159–161).

The publication of the subsampled model of the frieze on Sketchfab (Supplement 2) had to follow a different procedure compared to the 'mask' of Building B. Given the abundance of painted detail, a strong simplification of the mesh with a per-vertex texture was not an option. The first step of the procedure was creating an optimized 3d model so that it could be operated in Geomagic Studio (from 322 M to 65 M faces). That mesh was then used to create a separate texture file, which was subsequently re-applied to a dramatically simplified mesh (from 65 M to 3.9 M faces). However, even that file turned out to be too bulky, when an online version of a National Geographic article (Vance, 2016) needed to feature an interactive and annotated 3d model of the frieze. The goal was to create a model hosted on Sketchfab that could be quickly uploaded and manipulated on an average portable device. After some trial-and-error, an optimal combination of texture resolution and mesh triangle size (from 3.9 M to 0.35 M faces) was accepted for publication (Supplement 3).

4. Conclusion

The two cases discussed above demonstrate the overall viability of high-resolution (0.36 mm) documentation of sections of ancient Maya buildings using a structured light system. It was possible to overcome the logistical and operational hurdles and complete the documentation within a reasonable time frame. The quality of the data could be assessed during scanning. The resolution and accuracy of the resultant meshes was adequate for conservation-level measurements and potentially even for creating full-size replicas. It was also possible to manipulate and add new data to the models sparing the real buildings from potential damage.

That said, the results raise several important issues. The first challenge is that our ability to generate highly accurate and detailed 3d data vastly outstrips our ability to use it. Newer *smart*SCAN models may produce five times more points per scan, but even with an older 2007 model in our case studies, the resulting meshes exceeded the processing capacity of most personal computers. An average scholar in our field is generally unprepared to spend over $10,000 on a professional workstation and an equal amount on the required software (and then keep spending the same amount of money to upgrade it all every 3–4 years). We are not aware of any accessible cloud-computing solution that would address the present shortcomings. Moreover, it seems that the bulk of the on-going innovation affects the portable devices, which remain vastly inadequate when it comes to visualizing 3d data. There is a clear gap between the potential research and conservation uses, which require highly detailed copies, and the actual quality that may be delivered to an average device and/or posted on a specialized 3d platform like Sketchfab.

The second major issue is the absence of standards and established practices for storing 3d data. It is reasonable to assume that the raw scanning data generated with proprietary software would have a short life span. However, the fate of the meshes saved into common formats such as the Polygon File Format is not secure. Most research institutions do not have a long-term policy to store or commitment to migrate 3d data, primarily because it requires substantial and continuous investments in human resources, hardware, and software. The national institutions in the countries with ancient Maya ruins also lack policies and resources to preserve 3d data. The implication is that data may be lost, an especially unsettling possibility when dealing with a unique record of transient objects such as recently excavated stucco friezes. One of the authors of this paper witnessed how records on Maya monuments stored in a major national archaeological facility were lost twice over the last decade. Those records were successfully recreated because the physical monuments were still there and could be re-identified based on published illustrations. Had the monuments existed solely in digital form, the loss would have been complete and irreversible. Therefore, the paradox of creating a digital record of Maya heritage is that, presently, the only way to really secure its long-term preservation, despite shifting priorities of US academic institutions and lack of resources in the countries of origin, is to make physical replicas. Yet the current cost of reproducing the Holmul frieze at 1:1 scale would be no less than $100,000 (full production cycle outsourced to a dedicated 3d printing studio), exceeding a typical archaeological budget. Physical replication also undermines the key advantages of the digital record, notably, that it can be easily copied and shared. Our only hope here is that the growing amount of 3d data would eventually lead to new standards and established ways of storing and maintaining the accessibility of digital replicas.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.daach.2017.04.004.

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