

UC San Diego

Data Reports

Title

SCANNING THE STONE SEPULCHER: MULTIMODAL DIGITAL DOCUMENTATION OF ACTUN
TUNICHIL MUCNAL

Permalink

<https://escholarship.org/uc/item/4kd7b7ts>

Authors

Rissolo, Dominique

Moyes, Holley

Mcavoy, Scott Patrick

Publication Date

2025

18 SCANNING THE STONE SEPULCHER: MULTIMODAL DIGITAL DOCUMENTATION OF ACTUN TUNICHIL MUCNAL

Dominique Rissolo, Holley Moyes, and Scott McAvoy

Actun Tunichil Muknal (ATM) is among the most visited archaeological caves in the Maya area and is well known for its striking physical characteristics and remarkably intact cultural deposits. Though well surveyed and studied, the cave and its many fragile and at-risk ritual offerings and features had not been digitally documented. A collaborative program of scanning was conducted in the summers of 2023 and 2024 using complementary imaging modalities across scales and resolutions. These included mobile LiDAR – which was ideally suited to the complex, partially flooded passageways and high, narrow chambers of the cave – as well as high-resolution structured-light scanning (of individual objects and features) and photogrammetry. Particular attention was given to the human skeletal remains and ceramic vessels that lie within close proximity to visitor routes within the cave. The result of this integrative approach is a fused multi-resolution digital twin of ATM that will not only serve as an accurate geometric record of the cave and its contents but will enable researchers to better visualize spatial contextual relationships and facilitate taphonomic analyses. An accessible, online, interactive version of the digital twin is being developed for guides and the interested public as well.

Introduction and Background

Located in western Belize (Figure 1), on a tributary of Roaring Creek near Teakettle village, Actun Tunichil Mucnal (ATM) is an unlooted ancient Maya cave site dating from the Preclassic to the Late Classic period (100-900 CE). Flowing through 5 km of subterranean passageways is a perennial stream that sumps and then continues through high-walled chasms and breakdown-choked tunnels, ultimately culminating in a deep blue pool at the eastern entrance of the cave (Figure 2). Cultural remains were found in four major loci: the Main Entrance Chamber, the Sinkhole Tunnels, the Stela Chamber, and the Main Chamber (Awe et al. 1997).

Based on ceramic cross-dating with Gifford's Barton Ramie collection, material from the Main Entrance Chamber and the Sinkhole Tunnels suggests that the cave may have been used from the Early Classic (AD 300-600) to the Late Classic Period (AD 700-950) (Griffith 1998; Moyes 2001). Three AMS assays from charcoal recovered from a hearth and beneath the flowstone in the chamber confirmed these results (Moyes and Awe 2021).

The Main Chamber was the use-area located farthest from the cave entrance and was the area used most extensively and intensively. Its secluded location left it undisturbed by looters. The chamber is located 500 m from the eastern cave entrance where a high-level passage splits from the main passageway. The total surface area is approximately 4,450 m². It measures 183 m in

length, 35 m at its widest point and 5m at its narrowest with the long axis oriented in an east/west direction. The Main Chamber was divided into nine areas to better facilitate archaeological mapping and recording: The Creek, Boot Hill, Passage, Burial Chamber, Ransom Chamber, Cathedral, Angel's Room and Stone Sepulcher, and West Wall (Figure 3). Much of the floor of the Main Chamber is covered by rimstone or travertine dams that fill with water intermittently during extraordinarily heavy rains. They cover the central portion of the floor area and descend gradually toward the eastern entrance, indicating that in the past the chamber experienced wetting and drying events.

The chamber contains approximately 1,500 unique artifacts as well as the remains of 18 reported individuals (see Gibbs 2000; Moyes and Awe 2021:147-148). The site was recorded by archaeologists between 1996-1998 and was then directly opened for tourism. The cave system was originally surveyed by geomorphologist Dr. Thomas Miller who produced a map in 1989 (Figure 4). The first archaeological investigations by the Western Belize Regional Cave Project (WBRCP), under the direction of Dr. Jaime Awe, were conducted between 1996-1998. The project produced detailed maps of archaeologically rich areas, made excavations, and analyzed human remains. Working with the Belize Cave Research Project (BCRP), Holley Moyes undertook the recording of artifacts, took photos, completed the map, and conducted a spatial analysis of the Main Chamber of the cave from 1997-1998. These

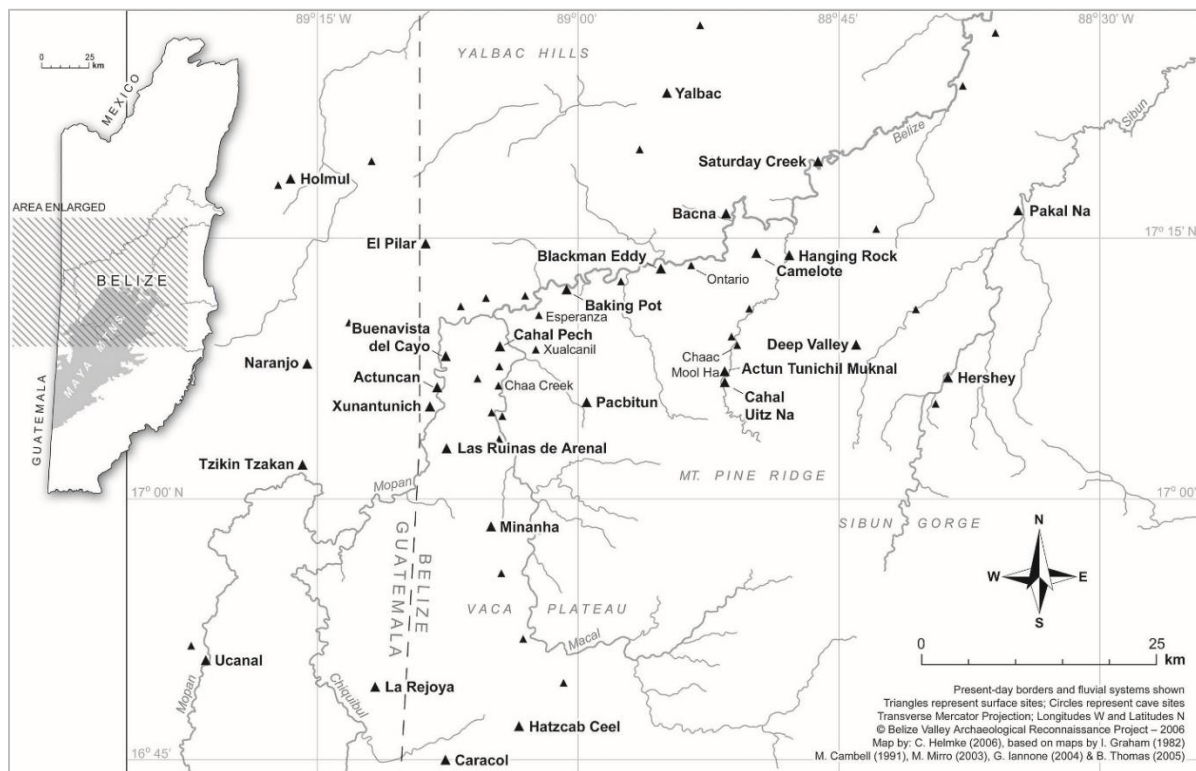


Figure 1. Map of Western Belize showing location of Actun Tunichil Muknal.

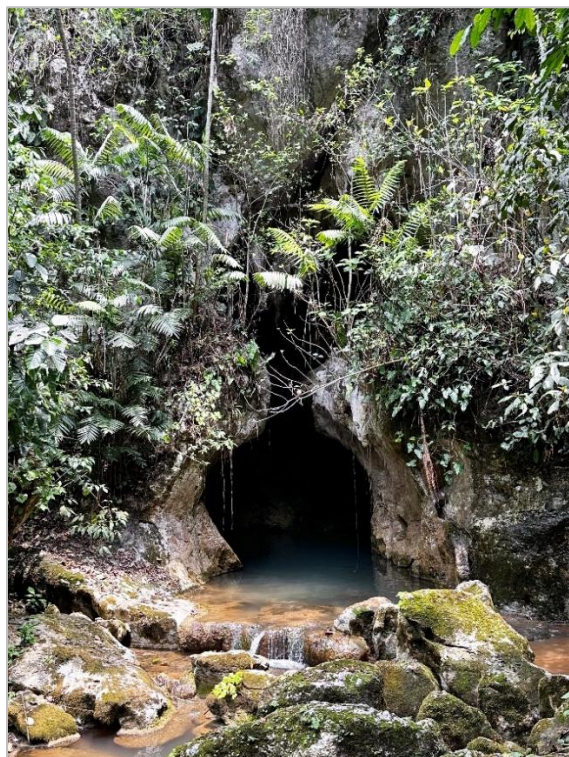


Figure 2. East entrance of Actun Tunichil Muknal (ATM). (Photo by H. Moyes).

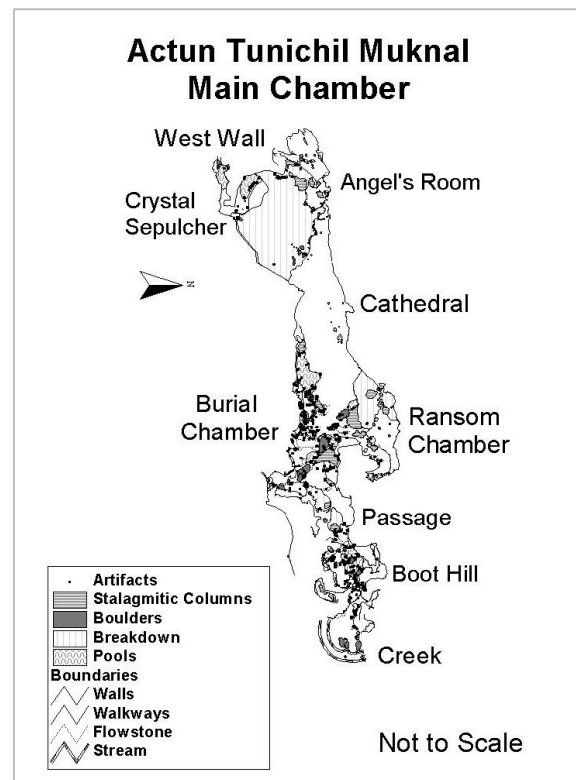


Figure 3. Map of the Main Chamber.

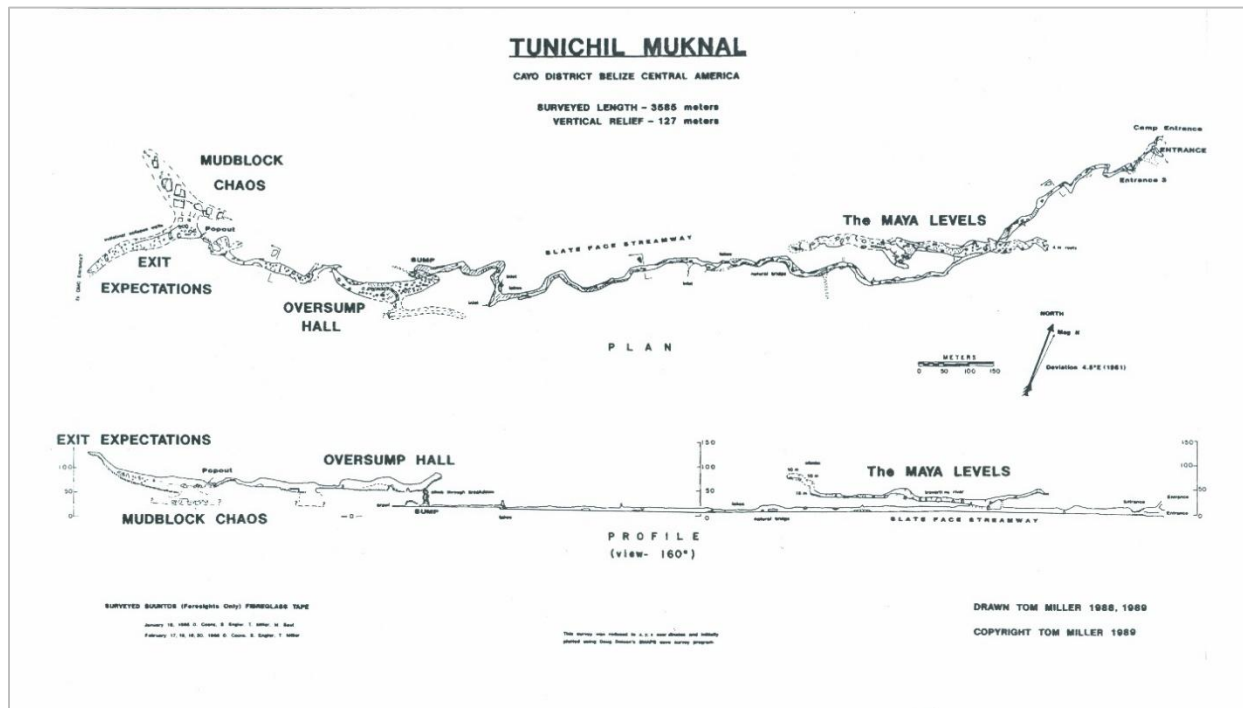


Figure 4. Map at Actun Tunichil Mucnal produced by Thomas Miller in 1989.

investigations are available in various site reports, MA theses, and publications (Moyes and Awe 1998; 1999a; 1999b; Moyes 2001; 2005).

Because of its excellent preservation and public interest, ATM is one of the most visited tourist sites in Belize. The cave has been featured in numerous, world-class television documentaries and magazines such as National Geographic Explorer, the History Channel, Discovery Channel, the BBC, NBC, and on Australian, Austrian, French, German, and Taiwanese television stations to name a few, and most recently in an “Off the Fence” documentary for Curiosity Stream entitled “Underworld: Belize.”

Conservation and Management

The site is unique in that it is being preserved as a living museum. With the exception of excavated materials, the BCRP collected few artifacts or samples while conducting archaeological fieldwork. Artifacts were carefully handled during recording and replaced in their original positions. Prior to opening the

cave for tourism, the Belize government required special training for guides that included cultural

information as well as conservation and safety practices. A relatively small group of guides are licensed for the site and the number of tickets per day are currently limited to 125. Tours are limited to eight people per guide so that guest activities can be closely monitored. The tourist route through the cave is marked and access is limited to only a few areas in the Main Chamber, where visitors can see concentrations of artifacts including partially intact ceramic vessels, grinding stones, jade celts, jewelry, and human remains.

Because the floor is covered by rimstone dams consisting of a thick layer of calcite or flowstone, to protect the deposit no shoes are allowed in the chamber, and socks are required. Tourists may not enter the chamber with cameras, pouches, water bottles, or any other items that can be easily dropped. Some areas have been cordoned off so that they may be only viewed from a distance. For instance, a wire barrier and signage are placed in the room that contains the Stone Sepulcher (also known as the Crystal Maiden), which is a complete human skeleton that has become encrusted in sparkling calcite crystals (Figure 5). The wire barrier prevents tourists from approaching the fragile remains but

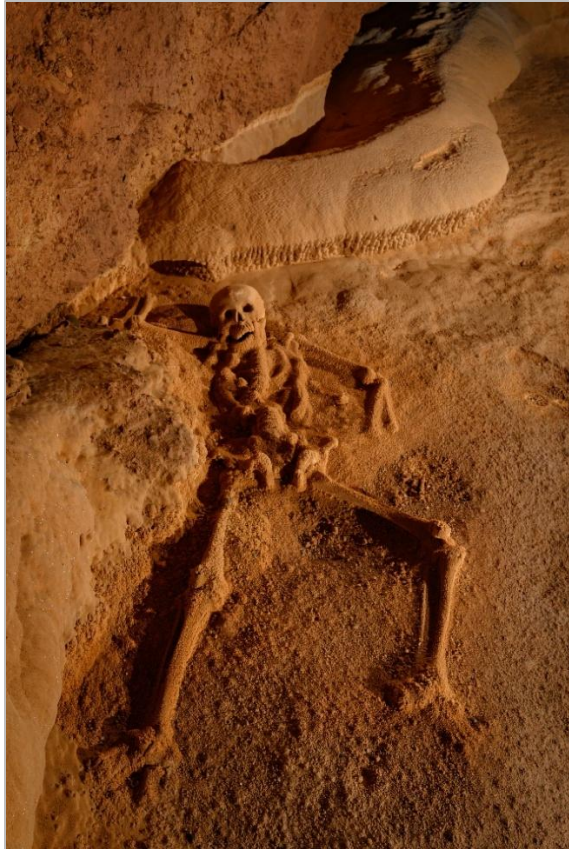


Figure 5. The Stone Sepulcher (“Crystal Maiden”). (Photo by M. Burkey).

does not impair viewing. Although this remarkable find was mapped, analyzed and photographed by the WBRCF, 3D digital documentation had not been performed prior to the 2023 and 2024 field efforts (reported here).

Though minimal, some damage and alterations to the site have occurred. Prior to the opening of the cave for tourism, many artifacts were handled so that they could be measured and photographed during the archaeological documentation. Because the research was conducted before the advent of digital cameras, Polaroid photos were taken of artifacts in situ so that they could be carefully replaced in their original positions. However, the project was not entirely without incident. For instance, a vessel lying on the chamber floor was broken during the 1997 field season. More damage has occurred after the introduction of tourism to the site including vessel breakage and impacts on natural features, such as the fragile calcite formations. Although tour guides are well trained, and



Figure 6. Gonzalo Pleitez scanning with the Hovermap 100 in the partially flooded breakdown tunnels near the east entrance. (Photo by D. Rissolo).

walkways for tourists have been demarcated on the cave floor using flagging tape, both tourists and guides have been known to occasionally deviate from marked trails resulting in damage to artifacts lying near walkways.

Some incidents caused damage to skeletal remains. Responses by the Belize Institute of Archaeology were swift and policies quickly enforced, yet as non-renewable resources, archaeological materials could not be replaced. Unfortunately, given the amount of tourist traffic, accidents were bound to occur no matter how diligently guides monitor guest activities. These kinds of events remind us of how fragile the artifacts and human remains are, and that it is necessary – in fact imperative – to digitally document objects, features, and other cultural deposits using appropriate tools and techniques prior to site wear and tear.

Had 3D documentation techniques been available at the time, archaeologists would have certainly deployed them during their initial investigations. Fortunately, the site is still in remarkably good condition, with most of the artifacts, features, and human remains still intact. Areas of the cave such as the Upper-Level Passages are off-limits to tourists, and these have been the least impacted. Despite controls put in place by the Belize government on tourism and development of ATM, as well as efforts by tour guides to monitor visitors, a degree of risk remains. Tourism is integral to livelihoods in Belize, and 15% of the Belize GDP is from the tourism industry. Tourism must be balanced with



Figure 7. Rumari Ku scanning the Stone Sepulcher with the Artec Leo structured-light scanner. (Photo by H. Moyes).



Figure 8. Dominique Rissolo scanning the Olla Altar with the Artec Leo structured-light scanner. (Photo by K. Vilchis).

site preservation, and 3D digital documentation serves to mitigate impact by recording the current state of site to meet future management and interpretation priorities.

Techniques and Methodology

Mobile LiDAR scanning is well suited to the complex, multilevel morphology of caves and has been used to survey and document subterranean sites around the world (Zlot and Bosse 2014; Konsolaki et al. 2020; Ullman et al. 2023; Lozano Bravo et al. 2023; see also Di Stefano et al. 2021). Traditional cave survey and cartography have real interpretive value, but much can be missed (or left unrevealed) in terms of morphology and potentially meaningful spatial-contextual relationships.

Two-dimensional cartographic representations of caves often emphasize idealized floor environments along with sample

transverse and longitudinal sections. However, the use of caves by humans, cross-culturally, involves niches, shelves, alcoves, walls, and ceilings. The ability to better capture the geometries of these surfaces – in 3D – can be of great interest to the archaeologist. Terrestrial laser scanning (TLS) can be useful in this regard and can be complementary to standard techniques (e.g., Disto and compass) or photogrammetry (when and where ample light can be provided). However, in certain subterranean environments TLS is not practical whereas mobile LiDAR systems can be deployed with relative ease and speed.

In addition to enabling analytical reasoning and interpretation, a cave-scale 3D model (derived from the mobile LiDAR data) provides an opportunity for diverse audiences to virtually explore caves like ATM – both up to and beyond the boundaries of physical tour routes. Ultimately, a 3D “digital scaffold” (created via the processing and alignment of mobile-LiDAR generated point data) can support the integration of data from complementary imaging modalities.

For the ATM digital documentation project, mobile LiDAR was selected as the primary imaging modality. Unlike with tripod-mounted TLS units, cave surveyors can crawl, climb, scramble, rappel, wade, or float with handheld mobile LiDAR scanners – enabling them to access and digitally capture portions of a cave with unprecedented speed, accuracy, and completeness. These systems are able to record trajectories and register scan data to local coordinates in real-time via the implementation of multi-sensor SLAM (simultaneous localization and mapping) solutions. Essentially, the surveyor holding the scanner is free to move through the cave in a more natural way, ensuring greater coverage, especially of harder to reach portions of a cave, including partially flooded passageways (Figure 6).

Mobile LiDAR (like TLS or other LiDAR-based scanning systems) does not require visible light to capture geometry. This has certain advantages, as large or deep spaces viewed by the scanner do not need to be illuminated. This also means that the corresponding point data will be devoid of color. Certain mobile LiDAR systems do have integrated cameras for point cloud colorization, but of course, this would require



Figure 9. Mobile LiDAR point cloud of the Main Chamber (looking east). Note the coverage and level of detail using the Hovermap ST-X (32 channel sensor).

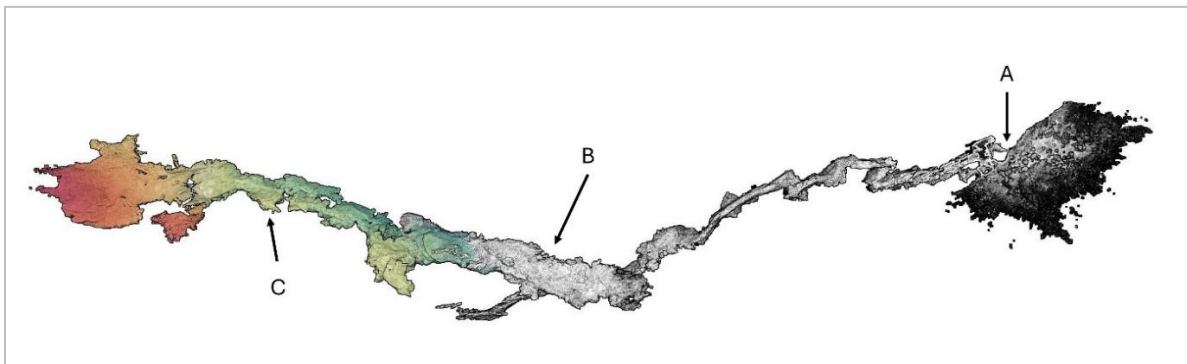


Figure 10. Aligned mobile LiDAR scans of Actun Tunichil Muknal from east entrance (A) to the western reaches of the upper chamber (based on 2023 scan data). The dark and diffuse cloud east of the entrance represents the forest captured in the scans. The western-most river passage, though scanned in 2023, is not included in this illustration. (See Figure 15 for a plan view of all aligned 2023 scans). The grayscale areas are those included in the tour, with the Main Chamber indicated (B). The areas of the cave that appear here in color represent the passages and chambers beyond (west) of the Main Chamber (as scanned in 2023). The location of cultural material (an intact olla) farthest from the entrance (C) is also indicated.

adequate illumination (which can be difficult to achieve in certain cave environments). As discussed below, the decision was made to not pursue camera-based implementations for LiDAR-based point cloud colorization, but rather to focus on rapid and thorough mobile LiDAR data capture to create the comprehensive digital scaffold and to deploy structured-light scanning and photogrammetry to provide photorealistic detail where needed.

Of the SLAM-enabled mobile LiDAR mapping systems currently on the market, we deployed a Hovermap 100 and a Hovermap ST-X. Hovermap, manufactured by Emesent, was an early arrival in this space. Its SLAM solution is considered robust and reliable, and it drew the interest of researchers at UC Merced and UC San Diego due to its autonomy capability when paired with a UAV (or drone). The original concept was to task the drone-mounted Hovermap payload

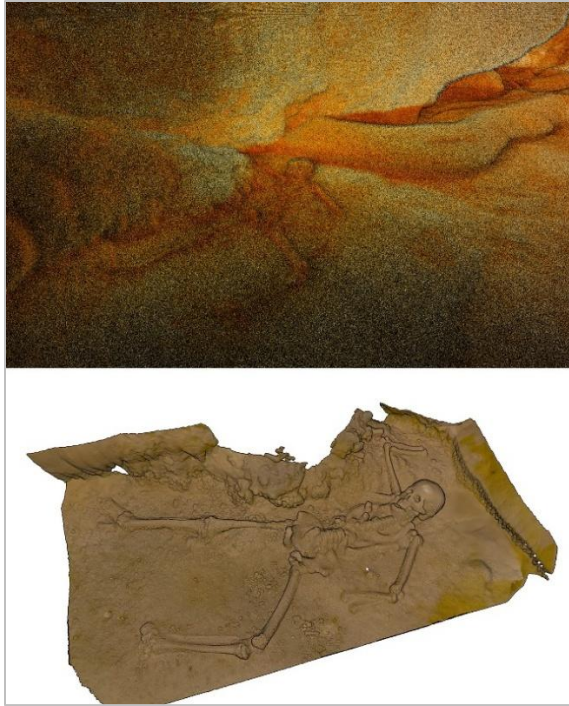


Figure 11. The Stone Sepulcher as it appears in the mobile LiDAR (Hovermap ST-X) point cloud (top). Below is one of the structured-light (Artec Leo) scans of the skeleton.

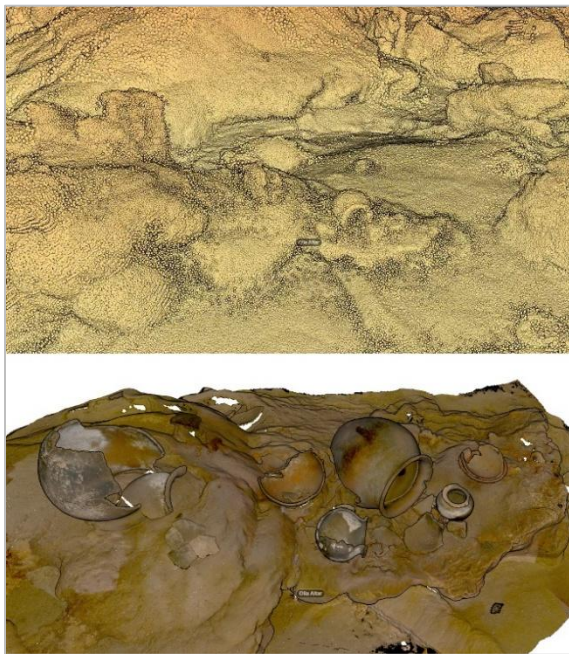


Figure 12. The Olla Altar as it appears in the mobile LiDAR (Hovermap ST-X) point cloud (top). Below is one of the structured-light (Artec Leo) scans of the Olla Altar.

with “exploring” large cave chambers and tunnels – affording archaeologists better views of hard-to-reach upper spaces within caves. (The

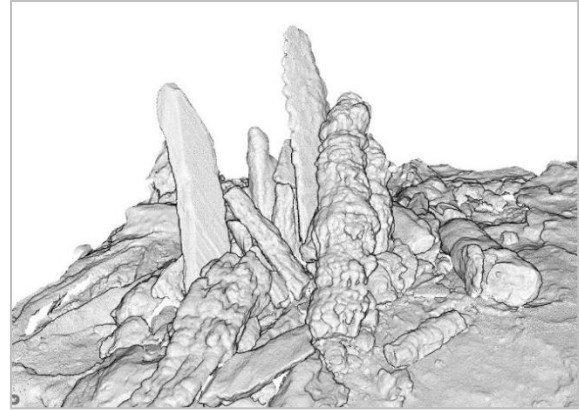


Figure 13. A structured-light (Artec Leo) scan of the Stela Altar (without the RGB data visualized).

Hovermap system was in fact designed to serve the underground mining industry). In 2021, Moyes and Rissolo acquired a Hovermap 100 via an NSF Major Research Instrumentation (MRI) grant and trialed the system at Las Cuevas in 2022 (Lozano Bravo et al. 2023; Moyes et al. 2023).

The Hovermap 100, equipped with the Velodyne VLP-16 Lite LiDAR (16 channel) sensor, produces noisier point data than the Hovermap ST-X, which uses the Hesai XT32M2X (32 channel) sensor. Generally, higher point density and less noise are preferred, especially in more natural (e.g. non-architectural) environments, where cloud-to-cloud alignment can be problematic. For our purposes, scan data should be of sufficient resolution to visually detect or locate archaeological features (in the point cloud) and manually coreference those higher resolution models produced by structured-light scanning and photogrammetry. The Hovermap 100 was adequate in this regard; although, the ST-X, with its denser and cleaner point data and integrated ground control point (GCP) workflow, was an ideal system for scanning the majority of ATM.

The primary technique for digitally documenting the objects, features, and deposits – especially the human skeletal remains – in ATM was structured-light scanning (Figures 7 and 8). We used an Artec Leo to capture extremely high-resolution geometry and texture data of these elements in the caves. The 3D resolution and point accuracy of the Leo are sub-millimeter. Although the RGB values may not be as accurate as those captured via photogrammetry (if well executed), the recording of the surface geometry

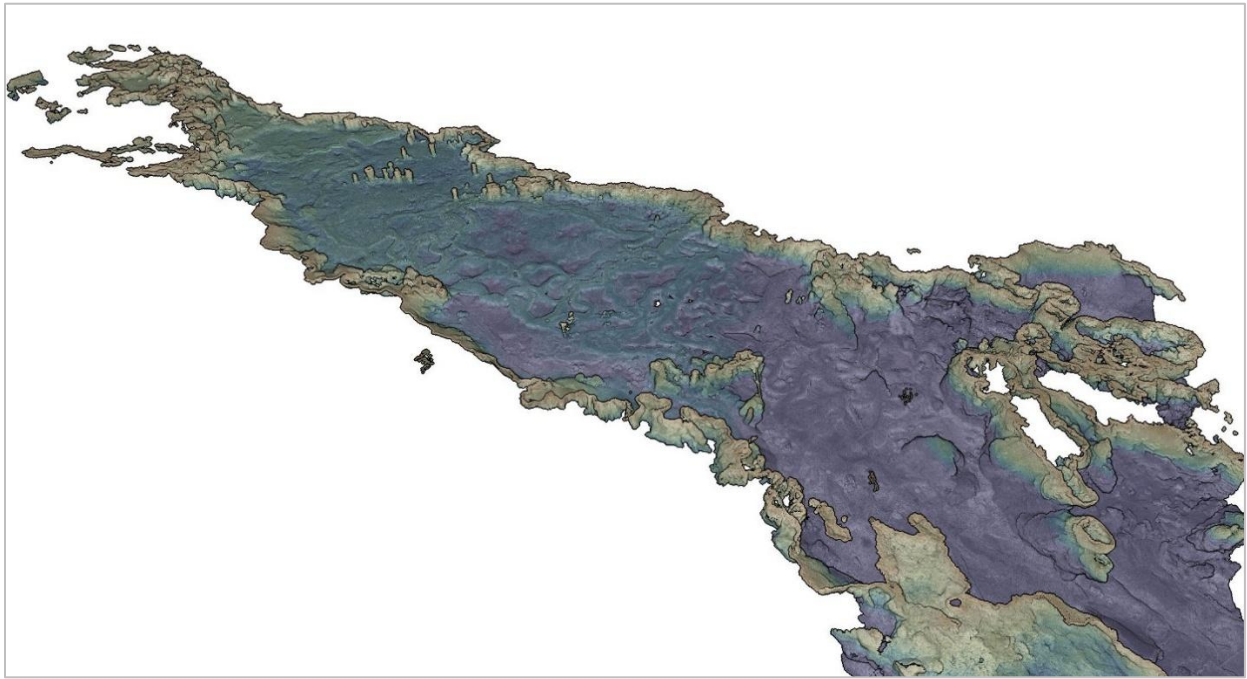


Figure 14. Oblique view of the floor of the Main Chamber. In this visualization, the portions of the mobile-LiDAR point cloud that correspond to the upper walls and ceiling have been removed.

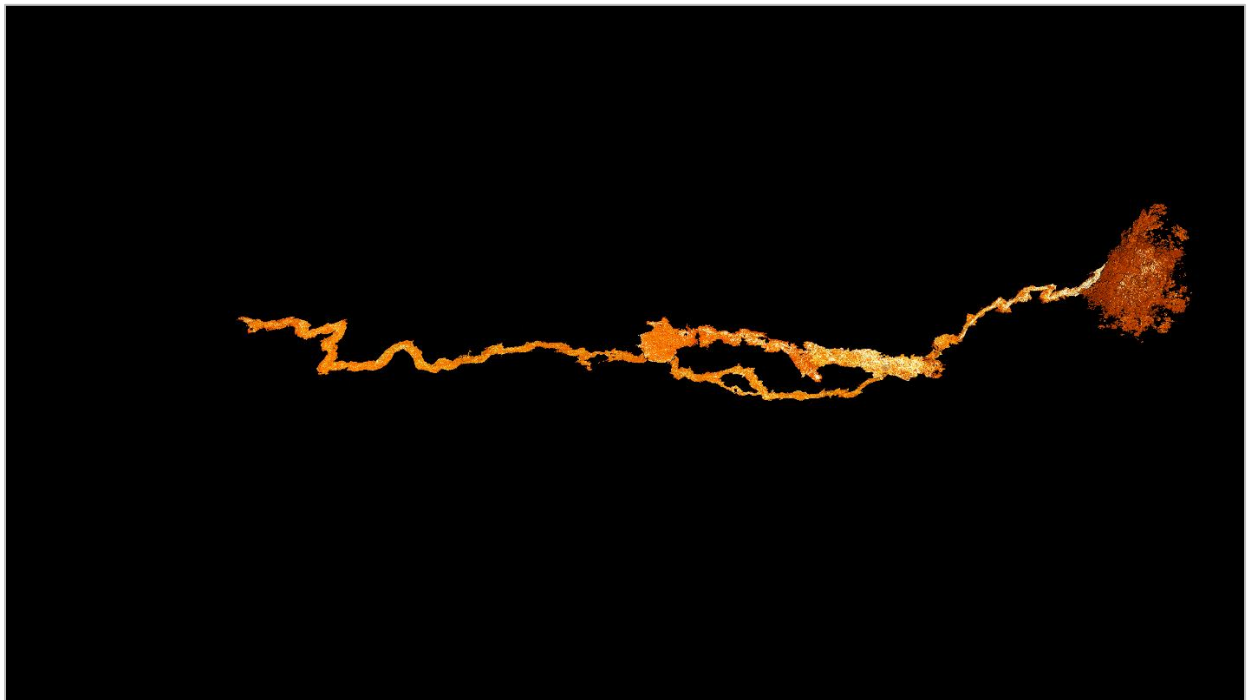


Figure 15. The aligned mobile LiDAR scans of cave from the east entrance to the western sump, including the upper passages (based on 2023 scan data).

is rapid and reliable (and the processing workflow can be more straightforward). The Leo is a portable, standalone scanner with an

integrated display (which helps guide the user and assures optimal coverage). In short, structure-light scanning is the ideal modality for

documenting critical deposits, like the Stone Sepulcher, and fragile features.

Image acquisition for photogrammetry followed standardized techniques and guidelines. The cameras used were Sony a7RIV bodies with Sony FE 16-35 mm/f2.8 GMII lenses and a Nikon D750 with a Nikkor 35 mm lens. Cage mounted lights provided up to 3000 Lm with a CTT of 5000 K. Though the focus was on specific features, such as ceramic vessels or human skeletal remains, care was taken to capture portions of the surrounding area or cave context to facilitate eventual co-referencing with the mobile LiDAR-generated point cloud. Since wider areas can more reasonably be captured via photogrammetry (rather than structured-light scanning), the technique served as a “middle space” (in terms of scale and fidelity) between mobile LiDAR and structured light.

Fieldwork and Results

During the 2023 field effort in ATM, the 100 and ST-X versions of the Hovermap were deployed in tandem. Areas of the cave that are part of the visitor experience were captured using the ST-X, including areas of the cave with the highest concentrations of objects, deposits, or features (Figure 9). Since the ST-X produces “cleaner,” higher resolution point data, we could more readily locate and identify those specific objects or features in the point cloud that would also be captured via structured-light scanning and photogrammetry. This enabled us to coreference or match the models produced via the latter two modalities with the digital scaffold produced by the Hovermap ST-X. Ultimately, 48 scans were performed with the Hovermap ST-X during the 2023 field effort. Concurrent with this capture, Gonzalo Pleitez and Dominique Rissolo performed 16 scans with the Hovermap 100 in the remote upper passageways beyond the Main Chamber and beyond the last known cultural deposit in the cave (Figure 10).

Mobile LiDAR scanning was initiated outside the cave – capturing exterior geometries (e.g. cliff-face, driplines, pools, and waterfalls, etc.). Scanning would then proceed or extend into the cave following a <20-min roundtrip or circuit loop-closure protocol (to reduce drift and improve the performance of the system’s SLAM solution). It was necessary for the individual

moving through the cave to be mindful of the scanner’s field of view, while adjusting rate and position based on the cave’s unique morphology. To reduce occlusions and ensure more accurate localization, efforts were made to present “familiar” scenes or geometries to the scanner while scanning new portions of the cave. This proved more important during loop-closure circuits where – unlike roundtrips, which involve retracing one’s path – the scanner may not view a scene opposite the direction of travel unless the individual carrying the scanner turns around frequently during the scanning procedure.

Since ATM could in no way be captured via a single scan, multiple scans were necessary. All scans subsequent to the initial acquisition required sufficient overlap to ensure more accurate cloud-to-cloud alignment. This was essential in portions of the cave that were separated by low or narrow restrictions (offering the scanner only a limited view or range of features). In such cases, the scanner might pass through the same restriction four times (over two roundtrips). For a long and narrow or anastomosing cave (like the river portion of ATM) the acquisition strategy may be described as daisy chaining, while the trajectories associated with scanning a large chamber might resemble more of a Venn diagram.

In 2024, we returned with the Hovermap 100 to scan areas of the cave beyond the last massive chamber explored by Pleitez and Rissolo. Over the course of a single day, the team added 16 new scans to the project – pushing the upper reaches of ATM even farther west. Leads beyond this point were not obvious, though there is consensus among the group that the cave continues.

With the morphology of the cave (and its many passages and chambers) captured by mobile LiDAR, we relied on structured-light scanning and photogrammetry to provide the resolution and visual fidelity needed for the documentation of specific archaeological features and human remains. This allowed us to economize time and effort. Our rapid, unconstrained approach meant that GCPs were not used for the photogrammetry component. However, scales and a color chart are associated with each photogrammetry project.



Figure 16. An example of how the cave, in its entirety, can be viewed by the public (prior to the creation of a more “realistic” VR experience).

As noted above, use of the Artec Leo structured-light scanner was reserved for objects, features, and deposits. In all, 23 scans were performed. The features captured in detail include the following: the Stone Sepulcher, the Olla Altar, and the Stela Altar (Figures 11, 12, and 13). All known bone clusters, including all crania, were scanned. In areas such as the Ransom Chamber, care was taken to capture the cave floor between and around the individual skeletal elements (to better facilitate future taphonomic or spatial studies).

To assure coverage and redundancy, with respect to 3D documentation, all priority features (again, including the Stone Sepulcher and the altars) were imaged for photogrammetric reconstruction. Since it was unclear as to whether the reflective facets of the calcite crystals (which cover many of the deposits) would prove problematic for the structure-light scanner, the photogrammetry had additional utility. Still, the main focus of the photogrammetry campaign in ATM was to capture the entire floor of the Main Chamber. This was an ambitious task, to be sure, but the scale was far beyond what could be captured via structured-light scanning, and

mobile-LiDAR scanning cannot yield photorealistic textures. Since the field of view (or area of the floor that comprised each exposure) could be easily illuminated by the photographer’s rig, it was an achievable goal.

The structured-light models have been co-registered or fused with the aligned mobile LiDAR point clouds. However, the voluminous image data for photogrammetry (collected in 2023 and 2024) is currently being reorganized and reprocessed. These photorealistic reconstructions of the floor of the Main Chamber will be fused with the corresponding mobile LiDAR “base map” (Figure 14).

Concluding Remarks

The result of our integrative, multimodal approach is a fused multi-resolution digital twin of ATM. These 3D data not only serve as an accurate geometric record of the cave and its contents but will enable researchers to better visualize spatial contextual relationships and facilitate taphonomic analyses across scales. The comprehensive mobile-LiDAR mapping campaign has allowed us to visualize and appreciate, for the first time, the size and complex

morphology of the cave itself – in 3D (Figure 15). Our methodology has essentially made possible a degree of immersion that reveals or communicates certain phenomenological aspects of the cave as well.

We are currently working towards an accessible, online, interactive version of the digital twin, which will be tailored for guides and the interested public. Most readily deliverable, in the short term, is an experience that looks much the way the data appear now – an environment of false-color point clouds (Figure 16) populated with more realistic and higher-resolution models. Users would navigate through this space along prescribed paths, flying or jumping to points of interest. The 3D data that we collected also make possible the future creation of a VR experience in which the point clouds are meshed and artificially textured to look like “real” cave environments. This may not serve scientific objectives, per se, but it would virtually open access to the cave to diverse audiences in ways that both inform and convey the majesty of this remarkable place.

Acknowledgements We are grateful to the Institute of Archaeology for the opportunity to digitally document ATM Cave. Our efforts benefited from the guidance of Dr. Melissa Badillo, Rumari Ku, and Josue Ramos. As well, we enjoyed the enthusiasm of Dr. Jaime Awe. Funding was provided by the Alphawood Foundation and the Strauss Family Fund for Mesoamerican Studies. This project would not have been possible without the support of the GIS Center, the Academic Senate, and the Center for the Humanities at UC Merced and the Qualcomm Institute at UC San Diego. The Hovermap 100 system was acquired via a National Science Foundation (NSF) Major Research Instrumentation (MRI) Grant (#2117877), and use of the Hovermap ST-X system on this project was provided by Emesent. We were fortunate to have an extraordinarily skilled and spirited field team in ATM in 2023 and 2024. Our deepest gratitude goes to Gonzalo Pleitez, Graham Goodwin, Kay Vilchis Zapata, Mark Robinson, Paul Smith, and Denis Martinez. Justin Simkins led the Hovermap ST-X survey, processing, and alignment effort. Thank you also to Falko Kuester at UC San Diego. Finally, we are indebted to the gracious, dedicated, and knowledgeable members

of the Belize Tour Guide Association. The promising future of ATM cave is ensured by their commitment and passion.

References Cited

- Awe, Jaime, Cameron S. Griffith, and Sherry A. Gibbs
2005 Stelae and Megalithic Monuments in the Caves of Western Belize. In *In the Maw of the Earth Monster: Mesoamerican Ritual Cave Use*, edited by James E. Brady and Keith M. Prufer, pp. 403-411, University of Texas Press, Austin.
- Di Stefano, F., A. Torresani, E.M. Farella, R. Pierdicca, F. Menna, and F. Remondino
2021 3D Surveying of Underground Built Heritage: Opportunities and Challenges of Mobile Technologies. *Sustainability* 13, 13289.
- Gibbs, Sheryl A.
2000 An Interpretation of Human Remains from the Caves of the Southern Maya Lowlands. MA Thesis, Department of Anthropology, Trent University, Peterborough, Ontario, Canada.
- Griffith, Cameron
1998 Excavations and Salvage Operations in Actun Tunichil Muknal and Actun Uayazba Kab, Roaring Creek Valley, Belize. In *The Western Belize Regional Cave Project: A Report of the 1997 Field Season*, edited by Jaime J. Awe, pp. 39-70. Department of Anthropology Occasional Paper No. 1. University of New Hampshire, Durham.
- Konsolaki, A., E. Vassilakis, L. Gouliotis, G. Kontostavlos, and V. Giannopoulos
2020 High Resolution Digital 3D Modelling of Subsurface Morphological Structures of Koutouki Cave, Greece. *Acta Carsologica* 49/2-3:163-177.
- Lozano Bravo, Hilda, Eric Lo, Holley Moyes, Dominique Rissolo, Shane Montgomery, and Falko Kuester
2023 A Methodology for Cave Floor Basemap Synthesis from Point Cloud Data: A Case Study of SLAM-Based LiDAR at Las Cuevas, Belize. *ISPRS Annals of the Photogrammetry, Remote Sensing, and Spatial Information Sciences* Volume X-M-1-2023:179-186.
- Moyes, Holley
2001 The Cave as a Cosmogram: The Use of GIS in an Intrasite Spatial Analysis of the Main Chamber of Actun Tunichil Muknal, and Maya Ceremonial Cave in Western Belize. MA Thesis submitted to Florida Atlantic University.
- 2005 Cluster Concentrations, Boundary Markers, and Ritual Pathways: A GIS Analysis of Artifact Cluster Patterns at Actun Tunichil Muknal, Belize. In *In the Maw of the Earth Monster*:

- Mesoamerican Ritual Cave Use*, edited by James Brady and Keith Prufer, pp. 269-300, University of Colorado Press, Boulder.
- Moyes, Holley and Jaime J. Awe
- 1998 Spatial Analysis of Artifacts in the Main Chamber of Actun Tunichil Muknal, Belize: Preliminary Results. In *The Western Belize Regional Cave Project: A Report of the 1997 Field Season*, edited by Dr. Jaime Awe, pp.22-38, Department of Anthropology, Occasional Paper No. 1, University of New Hampshire, Durham.
- 1999a Ritual Pathways in the Underworld. Paper presented at the New Directions in Field Research in Maya Cave Studies Symposium, 64th Annual Meeting of the Society for American Archaeology, Chicago.
- 1999b Cultural Constructs and the Binding of Space: Ritual Pathways at Actun Tunichil Muknal, Belize. In *The Western Belize Regional Cave Project: A Report of the 1998 Field Season*, edited by Dr. Jaime Awe and David F. Lee, Department of Anthropology, Occasional Paper No. 2, University of New Hampshire, Durham.
- 2021 Sacrifice of the Maize God: Re-creating Creation in the Main Chamber of Actun Tunichil Muknal, Belize. In *The Myths of the Popol Vuh in Cosmology, Art, and Ritual*, edited by Holley Moyes, Allen Christenson, and Frauke Sachse, pp. 136-169. University Press of Colorado, Boulder.
- Moyes, Holley, Dominique Rissolo, Hilda Lozano Bravo, Eric Lo and Shane Montgomery, and Amy Newsam
- 2023 Maps and Imagery: A Hybrid Model for Analyses and Interpretation of Archaeological Cave Sites. *Research Reports in Belizean Archaeology*, Vol. 18, pp. 91-102. Institute of Archaeology, NICH, Belmopan, Belize.
- Rissolo, Dominique, Scott McAvoy, Helena Barba Meinecke, Holley Moyes, Samuel Meacham, Julien Fortin, Fred Devos, and Falko Kuester
- 2024 A Multimodal Approach to Rapidly Documenting and Visualizing Archaeological Caves in Quintana Roo, Mexico. *The International Archives of the Photogrammetry, Remote Sensing, and Spatial Information Sciences* Volume XLVIII-2-2024:349-354.
- Ullman, M., B. Laugomer, I. Schicht, B. Langford, S. Ya'aran, I. Wachtel, A. Frumkin, and U. Davidovich
- 2022 Formation processes and spatial patterning in a late prehistoric complex cave in northern Israel informed by SLAM-bases LiDAR. *Journal of Archaeological Science Reports*, 47 (2023) 103745. doi.org/ 10.1016/j.jasrep.2022.103745.
- Zlot, R. and M. Bosse
- 2014 Three-Dimensional Mobile Mapping of Caves. *Journal of Caves Karst Studies*, 76(3):191-206. doi.org/ 10.4311/2012EX0287.