A Multimodal Approach to Rapidly Documenting and Visualizing Archaeological Caves in Quintana Roo, Mexico

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Abstract

Clearing and construction activities related to the Maya Train (Tren Maya) project resulted in potential and inevitable impacts to archaeological caves sites in largely undeveloped areas of Quintana Roo. An effort coordinated by Mexico’s National Institute of Anthropology and History (INAH) involved accelerated digital documentation of two caves – via SLAM-enabled mobile LiDAR scanning and targeted photogrammetry – to facilitate prompt visualization and evaluation of terrestrial and subterranean geospatial relationships. Mobile LiDAR is well suited to the challenges of capturing the complex, multilevel morphology of caves and was readily deployed across and through priority environments. Specific archaeological features – such as ancient Maya rock art and masonry shrines – were documented via photogrammetry, and the resulting higher-resolution models co-referenced with the georeferenced mobile LiDAR-generated point clouds of each cave and the surrounding topographic context. This integrative approach contributed to a more informed decision-making process, with respect to conservation and construction, and provided baseline data for future monitoring of the affected cave sites.

1. Introduction

1.1 The Maya Train Project and Archaeological Cave Sites

The documentation and mitigation of potentially impacted cultural heritage sites associated with the Maya Train (Tren Maya) project (Figure 1) was conducted by the National Institute of Anthropology and History (INAH) in accordance with established federal regulations and best practices. A portion of the 1,550km Maya Train route cut through undeveloped and largely unpopulated areas of dense tropical forest within the central coastal region of the state of Quintana Roo, Mexico. Clearing efforts in 2021 and 2022 revealed numerous archaeological caves and cenotes, which necessitated investigations by INAH. Rapid survey techniques were required to both document the caves and to visualize their geospatial relationships with the planned right-of-way above. These data (and associated derivatives) informed decisions regarding the conservation of archaeological cave sites.

Figure 1. Maya Train route (Trainspotting34).

Evidence of the ceremonial use of caves by the ancient Maya of this region is ubiquitous and may include ceramic offerings, rock art, and architectural features. Detailed studies of masonry temples, shrines, and altars in caves demonstrate stylistic and possibly functional similarities with Postclassic religious architecture at sites such as Tulum, Tancah, Xelha, Xcaret, Xamanha, and others (Rissolo et al., 2017; see also Rojas Sandoval et al., 2023). These fragile structures, like the miniature temple in Ocho Balas Cave (Figure 2), are at risk of direct or indirect impacts related to the construction of transportation infrastructure and regional urban expansion. Readily deployable tools and techniques for rapid capture of 3D data, combined with data-fusion workflows for didactic visualization, are appropriate given the dynamic nature of the Maya Train project.

1.2 The Case for Using Mobile LiDAR in Caves

The complex, multilevel morphology of caves can offer an ideal environment for the use of SLAM-based mobile LiDAR systems for the survey and documentation of subterranean sites (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 has significant interpretive value, but much can be missed (or left unrevealed) in terms of morphology and potentially meaningful spatial-contextual relationships. Cartographic representations of caves often emphasize idealized floor environments along with sample transverse and longitudinal sections. However, use of caves by humans (cross culturally) involves niches, shelves, alcoves, walls, and ceilings. The ability to better capture the geometries of these surfaces is often 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

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compass) or SfM 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.

Differing levels of accuracy notwithstanding, a major benefit of mobile LiDAR systems (either handheld or UAV-based) is the ability to scan cave environments more rapidly than tripod-mounted laser scanners. Moreover, the varied terrain of caves lends itself to scanning technologies that can be used while crawling, climbing, abseiling down vertical shafts, or floating across cave pools – all offering improved line-of-sight opportunities and greater overall coverage. To meet the requirements of the Maya Train project, SLAM-based mobile LiDAR mapping (using the Emesent Hovermap 100) was chosen as the primary cave scanning modality.

Figure 2. Scanning the miniature Postclassic temple in Ocho Balas Cave with the Hovermap 100 (photo by D. Rissolo).

1.3 A Multimodal Approach

Since archaeological features, such as rock art, may not be captured in LiDAR scans, images for photogrammetry were acquired in select portions of the caves – with the resulting point clouds later co-referenced or fused with the mobile LiDAR data. Additionally, available existing 2D cave survey data (including georeferenced maps) were co-referenced with the aligned scans of each cave. In the case of Ocho Balas, an abbreviated TLS and photogrammetry campaign was conducted in 2014, with a focus on the prominent miniature temple inside the cave (Rissolo et al., 2016). These data were also integrated into the current study.

For Las Manitas, aerial photogrammetry flights (using a DJI Mavic 3) were conducted in concert with mobile LiDAR scanning of areas outside the cave entrance and across the surrounding landscape. Once georeferenced, these datasets provided complementary views of the cave relative to the then-cleared areas of the Maya Train right-of-way above. An aerial LiDAR-derived DEM, provided by Mexico's National Institute of Statistics and Geography (INEGI), was ultimately translated into a point cloud to be used as an additional basemap (see sections 3.2 and 3.3).

2. Cave Sites

2.1 Ocho Balas

Our rapid 3D data capture and visualization efforts were focused on two archaeological caves, Ocho Balas (Figures 2, 3, and 4) and Las Manitas (Figures 5, 6, 7, and 8), which were adjacent to, or extended below, the Maya Train right-of-way. Ocho Balas Cave (also known as Oratorio) represents the NW entrance to the 12.7km-long Zumpango Cave System, located west of present-day Puerto Aventuras. A program of exploration and comprehensive survey of the cave system was directed by Peter Sprouse, who provided the authors with a detailed map of the cave.

The miniature temple in Ocho Balas was originally registered with INAH by Miguel Covarrubias Reyna and separately digitally documented (via TLS and photogrammetry) by Rissolo et al. (2016). The building is remarkably well preserved and exhibits architectural details characteristic of the regional Late Postclassic style (roughly AD 1200-1500). The walls of the masonry structure are thickly plastered, and the beam-and-mortar roof is intact (see Rissolo et al. 2016 for a more detailed description). In comparison to cave shrines in the region, the building is unique in its refinement and quality of construction

The 2022 effort reported here involved a total of 11 mobile LiDAR scans (over two short days) – capturing the temple and chambers to the northeast and the extensive passages to the southeast. (The cave system continues significantly further to the southeast, though our efforts where focused on areas of the cave in close proximity to the planned Maya Train route and the approaching cleared right-of-way). Fusion with terrestrial 3D data and corresponding global coordinates revealed the location of the right-of-way relative to the subterranean spaces below (Figure 3).

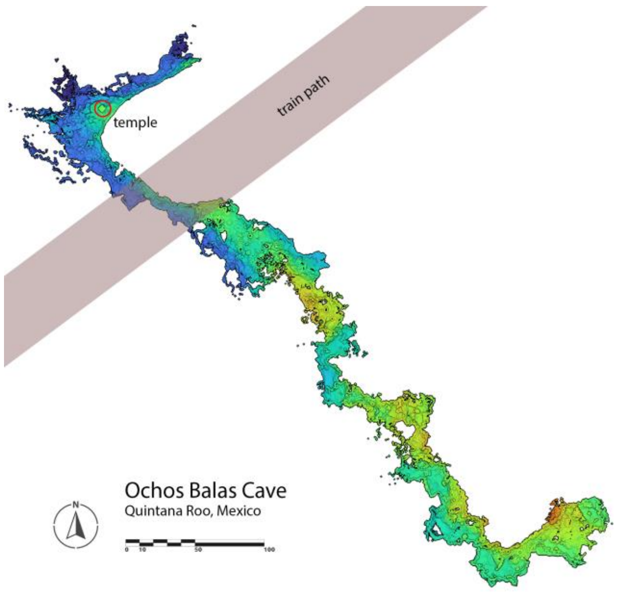

Figure 3. Aligned mobile LiDAR scans of Ocho Balas. Note the location of the miniature temple inside the cave and the planned train route above.

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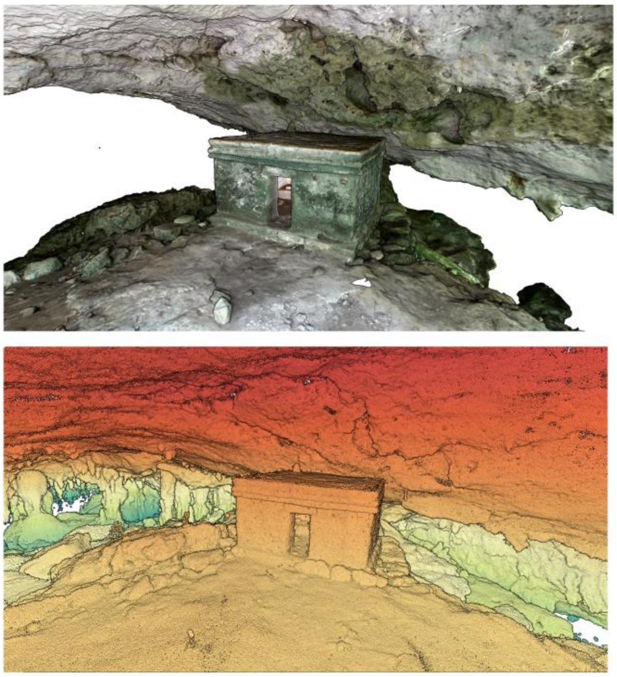

Figure 4. Miniature temple inside Ocho Balas. Top image: 2014 TLS and photogrammetric model. Bottom image: 2022 Hovermap 100 mobile LiDAR model.

2.2 Las Manitas

The cave of Las Manitas – so named because of the ancient ochre handprints found inside – was directly adjacent to (and ultimately determined to extend beneath) the Maya Train right-of-way. Like Ocho Balas, the cave is located west of present-day Puerto Aventuras. Four Hovermap scans were conducted within the cave, while a fifth scan captured the cave interior, dripline, open collapse area, and the already-cleared right-of-way above and to the east (Figure 5 and 6). Present here was a recently exposed Maya surface site (situated above the cave). The contours of the collapsed platform and mound structures were captured both in the mobile LiDAR scan and via aerial photogrammetry. The positioning or siting of civic-ceremonial architecture above or adjacent to caves is not uncommon in the Maya area and its symbolic significance has received considerable attention from scholars (e.g. Brady, 1997). A regional example of the physical co-association between surface temple and cave can be found at El Kisim near Punta Venado (Martos López 2002:228-231).

At least nine negative handprints are clustered on the ceiling above the offertory area in the cave and on adjacent dripstone formations (Figures 7 [bottom] and 8). Additionally, two positive handprints are located on a formation near the east entrance of the cave, while two are visible on the cave wall beyond the water’s edge. Handprints have been documented in ritual caves elsewhere in Quintana Roo (Rissolo, 2003; 2004; 2020) and in neighboring Yucatan (see Strecker, 1982; see also Tec Pool, 2012; Tec Pool and Krempel 2016). Both the positive and negative handprints located on the ceiling and walls of Las Manitas were documented via photogrammetry. Viewed together, the mobile LiDAR point cloud and the corresponding photogrammetric reconstruction of the offertory area facilitated visualization of the cave’s morphology and contextualization of its archaeological features.

Figure 5. Aerial view of Las Manitas archaeological site on the right-of-way (as clearing progresses). The image to the right indicates the position of the cave below.

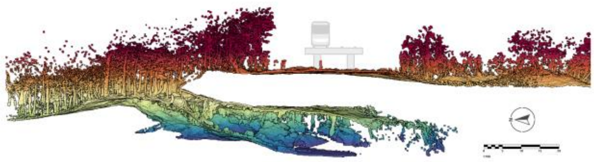

Figure 6. Cross-section of Las Manitas Cave with illustration of the proposed railway above.

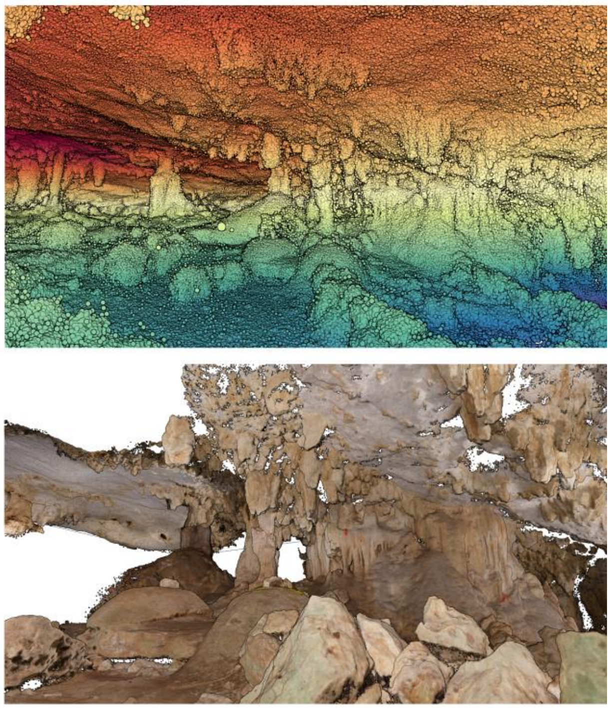

Figure 7. Mobile LiDAR (top) and photogrammetry (bottom) of the offertory area (with handprints) in Las Manitas.

3. Methodology

3.1 Acquisition Strategy

As stated above, SLAM-enabled mobile LiDAR mapping was selected as the primary imaging modality due to the highly complex and physically challenging nature of the cave environment and the project’s requirement for rapid visualization and evaluation of terrestrial and subterranean geospatial relationships. Greater coverage of the cave systems could be attained more rapidly using mobile LiDAR versus

TLS. The objective was not to compare mobile LiDAR to TLS or compare the Hovermap 100 to other mobile LiDAR systems (e.g. those manufactured by Leica, GeoSLAM, Stonex, Kaarta, or Exyn). Rather, SLAM-enabled mobile LiDAR was selected, as a modality, due to its inherent benefits.

It should be noted that the Hovermap 100 (equipped with the Velodyne VLP-16 Lite LiDAR sensor) produces noisier point data than the Hovermap ST-X (which uses the Hesai XT32M2X 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 co-reference those higher resolution models produced by photogrammetry (or in other cases, structured-light scanning). The Hovermap 100 was more than adequate in this regard; although, the ST-X, with its denser and cleaner point data and integrated ground control point (GCP) workflow, would have been an ideal system for this cave scanning project.

For both Ocho Balas and Las Manitas, mobile LiDAR scanning (without the use of GCPs) was initiated outside the cave – capturing exterior geometries (e.g. driplines and collapse margins) that had been surveyed and georeferenced by the INAH team. 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 neither cave in this study could be reasonably 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 Ocho Balas) the acquisition strategy may be described as daisy chaining, while the trajectories associated with scanning a large chamber-type cave (like Las Manitas) might resemble more of a Venn diagram.

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

Image acquisition for photogrammetry followed standardized techniques and guidelines. The camera used was a Sony a7RIV (full-frame sensor) with a Sony FE 16-35mm/f2.8 GMII lens. Cage mounted lights provided up to 3000Lm with a CTT of 5000K. Though the focus was on specific features, such as the handprints in Las Manitas, care was taken to capture portions of the surrounding area or cave context to facilitate eventual co-referencing with the LiDAR-generated point cloud.

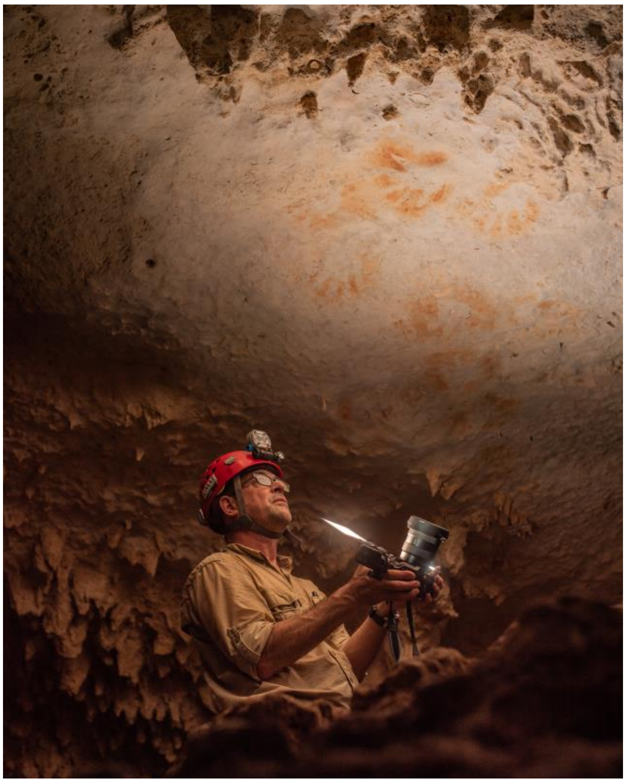

Figure 8. Acquiring images of handprints on the ceiling of Las Manitas Cave for photogrammetry (photo by K. Vilchis).

3.2 Data References and Processing

The study involved acquiring and incorporating the following:

1. Hovermap 100 mobile LiDAR data (up to 3cm resolution) – exported and filtered from Emesent Processor and subsampled at 3cm point spacing. Individual scans were aligned in CloudCompare. (See McAvoy, 2022 for scan inventory).
2. FARO Focus3D X130 TLS data (up to 3mm resolution) – scans aligned in FARO Scene and fused with photogrammetry using RealityCapture.
3. Terrestrial photogrammetry via Sony a7RIV full-frame sensor camera (sub-mm resolution) – processed at maximum resolution in RealityCapture, no control points used.
4. Vector files associated with the survey of Ocho Balas and the Zumpango Cave System.
5. Aerial photogrammetry via DJI Mavic 3 for (5cm resolution) – the system was flown manually; data were processed using Agisoft Metashape.
6. Satellite imagery (3m resolution) provided by Planet.
7. LiDAR-derived regional hydrological DEM provided by INEGI (5m resolution) – data reprojected and translated into a point cloud using GDAL and CloudCompare.

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Drone survey, satellite imagery, and the INEGI DEM provided the geospatial references to which all other datasets were aligned. Each dataset followed its own individual processing pipeline, and all data were unified within a single projection, UTM 16N WGS84, and exported as LAZ point cloud files. Cave scans were manually segmented using Agisoft Metashape to classify cave floors, ceilings, and water.

3.3 Alignment, Fusion, and Georeferencing

Data fusion was performed with octree-sorted point clouds within the Potree (Schütz 2016) WebGL architecture allowing for real-time full resolution visualization of 3D and 2D inputs within a geospatial context (see Campiani et al., 2023). Various data sources were converted into point clouds and aligned within a geospatial context using manual offset and rotation (when global positioning was not baked into the data). Full resolution datasets are transposed, and can be toggled on and off at will, streaming detail as needed. Each dataset was nested within its lower resolution counterpart, as such the spatial accuracy of the Las Manitas survey is expected to be accurate to within 1m (using drone-based GPS), and the Ochos Balas survey is expected to be accurate to within 5m, using only the INEGI data for spatial reference, and having no visible features within the forest-covered satellite imagery.

3.4 Visualization and Dissemination

Data were delivered via an interactive online WebGL point cloud viewer, and video. All 3D cave scans were simplified as 2D raster images and vectorized contour maps (for practical use by Mexican government partners). All raw data assets were saved and archived anticipating future reuse requiring re-processing and integration with external data.

4. Future Work

The deployment of a handheld SLAM-based mobile LiDAR system in concert with image capture for photogrammetry met the temporal and logistical constraints of the Maya Train project, while the rapid processing and post-processing workflow facilitated visualizations (for stakeholders) that were intelligible, relatable, and ultimately usable. Speed is certainly not essential in all cave documentation or mapping projects, offering opportunities for more systematic approaches and experimentation with different data acquisition strategies and techniques. This might involve more rigorous comparison of the results of separate scans of the same environments and evaluation against existing datasets from different scanning or surveying modalities. A goal of this case study was to inform the coordinated use of mobile LiDAR and photogrammetry in caves while emphasizing the specific objectives or expectations of a given scanning project. In all cases, we would caution against the uncritical embracing of rapid-capture technologies (as benefits and limitations must always be considered).

Though TLS could have proved a more reliable ground-truth, the aligned and georeferenced mobile LiDAR scans nevertheless serve as valuable baseline data for future monitoring of Ocho Balas and Las Manitas as the Maya Train construction project continues. Regionally, the pace and scale of development – and the associated impact on subterranean heritage sites – warrants the ongoing use (and refinement) of rapid documentation and visualization strategies and techniques.

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