PRACTICAL EXPLORATION OF LOW-COST YET HIGHLY ACCURATE 3D MAPPING TECHNIQUES FOR DOCUMENTATION AND CONSERVATION OF AN EGYPTIAN TOMB (THEBAN TOMB 45)

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ABSTRACT:

This research presents the initial endeavour to perform geo-referenced 3D reconstruction of an ancient Egyptian tomb located on the West Bank of the Nile in Luxor, evaluating low-cost techniques. This study uses low-cost equipment in conjunction with simple geodetical principles to accurately map a tomb in 3D to empower archaeological teams with limited budgets to efficiently and effectively map their projects. Emphasizing the project goals of both high detail and high accuracy, one of our chosen techniques is photogrammetry with a standard system camera. Additionally, 3D mapping with a modern smartphone was explored in the tomb and was compared with results from the photogrammetry process. Geo-referencing the underground map in a global grid was also part of the project goals. This research shows that, within certain reasonable constraints, the chosen low-cost techniques successfully achieved all goals of producing a highly detailed, highly accurate, and georeferenced 3D map of the selected tomb (Theban Tomb 45). In this first season of mapping the tomb in 3D, various mapping methods were used and tried and where possible compared. Digitally mapping an ancient, underground Egyptian tomb requires a planned approach. In order to better plan when using low-cost scanning equipment, preliminary research was done for mapping a mostly underground, relatively small but complex to survey ancient Egyptian tomb. Data have been collected with the use of both devices and also with a total station, a laser distance meter and a GNSS (Global Navigation Satellite System) datalogger.

1. INTRODUCTION

1.1 Theban Tomb 45

Since 2018, the Leiden University Mission to the Theban Necropolis has carried out a fieldwork and research project in Theban Tomb 45 (TT45), directed by Dr. Carina van den Hoven. Theban Tomb 45 dates to ca. 1400 BCE and is situated in the Theban necropolis, a UNESCO World Heritage Site on the West Bank of Luxor. The Theban necropolis is one of the largest ancient burial sites in Egypt, comprising the famous royal tombs of the Valley of the Kings and the Valley of the Queens, as well as hundreds of private elite tombs, memorial temples, remains of royal palaces, and domestic communities.

Theban Tomb 45 is a so-called classical inverted T-shaped tomb (Figure 3), of which only the first room (the so-called transverse hall) has been decorated with painted figures and hieroglyphic texts (Figure 1). The second room (the so-called longitudinal hall) has remained undecorated and leads to a third room that has been cut to the left, which leads in turn to a sloping passage and burial chamber.

One of the most interesting aspects of Theban Tomb 45 is its reuse: the tomb was constructed and partly decorated around 1400 BCE (18th dynasty; Amenhotep II) for a man named Djehuty and his family. Djehuty was charged with overseeing the estate of a high priest of Amun, and he was chief of the weaving workshop at Karnak temple. He is depicted on the tomb walls with a woman whose name is not mentioned in the accompanying texts (probably his wife), as well as with his mother.

Figure 1: Theban Tomb 45, decorated transverse hall. © TT45 Project, Matjaž Kačičnik.

Several hundred years later, in the Ramesside period, the tomb was reused by a man called Djehutyemheb. Like the first tomb owner, he was also a chief of weavers. Djehutyemheb and his parents, children, and grandchildren are all depicted on the tomb walls.

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The practice of tomb reuse may call to mind images of tomb robbery, usurpation, and destruction, but Theban Tomb 45 was reused with consideration for the memory of the first tomb owners. The second tomb owner did not replace the original decoration with his own, but instead left most of the existing decoration in its original state. He added his own paintings and texts to wall sections that had been left undecorated by the first tomb owner. In addition, he also retouched and partially repainted some of the original paintings. For example, some of the garments, wigs, and furniture depicted on the tomb walls were changed in order to update them to contemporary (Ramesside) style, and some new texts referring to the second tomb owner and his family were added to the existing texts.
The reuse of Theban Tomb 45, and in particular the way in which the second tomb owner dealt with the existing decoration, forms the starting point for a research project which investigates the mechanisms and motives behind tomb reuse in ancient Egypt, carried out by Carina van den Hoven at The Netherlands Institute for the Near East, Leiden University (Hoven, C. van den, 2019; Hoven, C. van den, 2021).

1.2 Main aims and objectives of the TT45 Project

The international team carries out a wide range of activities, including conservation and restoration, documentation and publication, analysis of the painted decoration, archaeological study, preventive conservation, and site management activities.

1.2.1 Conservation: After its discovery in the winter of 1903–1904, the tomb was left without a protective door, and as a result it has been damaged. Although some emergency repairs have been made in the past, no active, practical conservation work has been done in the tomb until 2018. One of the main goals of the TT45 Project is to carry out a full conservation programme for the tomb, in order to preserve it for future generations. The team also undertakes various measures in preventive conservation and site management, aimed at protecting the tomb against flash flooding.

1.2.2 Digital documentation and publication: Another key objective of the TT45 Project is to record the tomb as precisely as possible, using the most recent technological tools and developments, including high-resolution digital photography, photogrammetry, 3D technology, digital epigraphy, and digital reconstruction. The aim is to produce a highly detailed digital record of the tomb, which not only documents its architecture and decoration, but which also functions as a digital research tool enabling future generations of scholars to (interactively) study the tomb without the need for physical access. In this way, the team aims to make a significant contribution to the development and application of non-invasive digital technologies in documenting, publishing, and providing (digital) access to ancient material culture.

1.2.3 Art historical and non-invasive material analysis of the painted decoration: Another main aim of the TT45 Project is to systematically study the painted decoration of the tomb. To this end, a combination of art historical visual analysis and non-invasive material analysis is used. A detailed visual examination of the paintings is carried out aided by raking light and UV light inspection. The material analysis of the painted decoration comprises the non-invasive analysis of the ancient materials used: mortars, pigments, binders, coatings, etc., as well as their techniques of application. This analysis is done through various techniques: photography in flat, raking, and ultraviolet light; X-ray fluorescence (XRF); infrared photography; and multi-spectral imaging techniques. The material analysis of the wall paintings is carried out with multiple purposes in mind: 1) the identification of particular pigments, coatings and binding agents provides useful information for the conservator in determining the best conservation approach and techniques; 2) the identification of particular pigments, coatings and binding agents helps to distinguish between the original paintings and the ancient retouchings and repaintings; 3) to digitally enhance ancient pigments that have deteriorated and faded over time and are now barely visible with the naked eye, in order to improve the legibility of some of the texts written on the tomb walls that are currently illegible.

1.2.4 Preventive conservation, site management activities and archaeological study: The team carries out preventive conservation measures and site management activities around Theban Tomb 45, with the aim of protecting it against flash flooding and preserving it for future generations.
The condition survey of the tomb carried out by the team's conservator in 2019 showed that flash flooding forms the main external threat to the stability of the tomb. In fact, the tomb already shows evidence of previous flooding and resulting damage. The tomb is extremely vulnerable to flash flooding due to its position at the lower part of the Theban mountain, as well as the fact that it has a deep and narrow courtyard. Flooding of the tomb poses a risk not only to its painted decoration, but also to the stability of the tomb, given the marl content of the tomb structure. For this reason, the area surrounding the tomb will be re-landscaped in order to direct the drainage paths of flash flooding away from the tomb and nearby monuments. In order to make space for the various preventive conservation measures, the modern retaining wall around the courtyard will be removed and ca. 15m of sand will be cleared from around the tomb. This gives the team the opportunity to carry out for the first time a full archaeological study of the tomb, which will provide new insights into its usage history and its position within the lower area of Sheikh ʿAbd el-Qurna, of which currently very little is known.

1.3 Mapping Theban Tomb 45

The most recent fieldwork season of the TT45 Project took place in two parts, in March and in November–December 2022. In March, the team continued work on the practical conservation of the wall paintings. The main aims of the November–December season were to continue the documentation and art historical analysis of the tomb decoration, as well as to continue the preventive conservation, site management activities, and archaeological study of the tomb. The documentation work involved making a highly accurate plan and 3D model of the tomb.
To this aim, the tomb was completely emptied, except for some lamps and electric cables to provide lighting. Theban Tomb 45 forms part of an important UNESCO World Heritage Site, and considering its age and its fragility (the mountain into which the tomb is cut is made up of sedimentary limestone, marl, shale, and chalk), the process of mapping had to be done is such a way that no damage or changes were made to the underground environment of the tomb. The dimensions of the tomb are slightly irregular: ceiling heights vary between 1 and 2m and the width between its walls varies between 70 cm and 2m. The first room (transverse hall) is decorated with paintings being executed on a series of layers of mortar and plaster applied to the underlying rock-cut structure. All other rooms have been rock-cut only. The door which gives access to the tomb from its courtyard is the only connection to the outer world and hence the only source of daylight in the tomb.

1.3.1 Main goals of the mapping work and research question: In mapping Theban Tomb 45, the aim was to make a detailed, accurate and geo-referenced map of the tomb combining the following 4 sub goals:

1. to accurately map ancient cultural heritage (CH), in this case an ancient Egyptian tomb;
2. to map the tomb as precisely as possible, in order to enable future generations of scholars to investigate the tomb without the need for physical access;
3. to connect the map of the (partially) underground parts of the tomb to the above-ground situation by using a global grid for both;
4. to use “low-cost” equipment and open-source software where possible, and to share our experiences and findings with other archaeological teams.

The overall research question for this preliminary research is:

“How accurate and how detailed can an ancient Egyptian underground tomb be mapped while geo-referencing the results with low-cost equipment?”

In this case this research was done with specific choices on equipment and in a specific environment, i.e. Theban Tomb 45 at the West Bank of Luxor.

With the following circumstances the plan for mapping was set up:

1. Underground mapping;
2. Connected only in one location to the outer world;
3. Artificial lighting in place but in small numbers;
4. No geo-referenced points available nearby;
5. Narrow passages connecting relatively narrow rooms;
6. Very rough walls and ceilings that cause shadows;
7. Windblown sand dust on the floors (at least when the mapping work started).

1.3.2 Preliminary work on the temple of Taffeh: Preliminary research was done on most parts of the mapping methods to be used in Theban Tomb 45. In preparation to the work in Egypt, another ancient Egyptian monument was mapped: the temple of Taffeh (Voûte et al, 2023), which is currently located at the National Museum of Antiquities, Leiden, The Netherlands. The most important differences were 1) that the temple is completely above ground, which made it easier to access all its outer parts, and 2) that it is located inside the museum, which made geo-referencing in a global grid impossible. This is because GNSS receivers do not give reliable results in buildings and transferring the outdoor grid to indoor by means of terrestrial surveying techniques was not allowed at that time by the museum. Similar equipment was used in mapping the temple of Taffeh as well as of Theban Tomb 45, namely a mirrorless camera for photogrammetry, an iPhone with LiDAR, a wooden ruler for scaling, and a laser distance meter for validation.

2. METHODOLOGY

2.1 Choosing methods

Starting with the limitation of using low-cost equipment it was decided to look for practical methods. Many (Remondino, 2011) (McCarthy, 2014) (Jalandoni et al., 2018) have shown multi-image photogrammetry is a well-suited method for cultural heritage mapping.
Current developments show that smartphones that have a low-cost LiDAR built in can give fast and promising results (Leutzenburg et al., 2021; Teppati Losè et al., 2022).
Mapping underground brings complexities. Since entry is sometimes limited to only one location while mapping, drift will occur. This needs to be prevented or corrected as much as possible. A strong internal network (i.e. many independent tie points) will help. Geo-referencing underground assets is possible but since GNSS devices do not give results underground, the reference needs to be transferred from outside to underground. Both total station measurements (triangulation) or photogrammetry can solve this. For underground mapping also Ground Penetrating Radar (GPR) can help. For this research that proved both to be impossible (too deep underground) and too expensive.
(Weeks, 2000) described a method to map underground tombs in Egypt, in this case in the nearby Valley of the Kings, but at a time when GNSS measurements were not available. Traversing and using theodolites and measuring tapes were the only options at that time.
To achieve the above-mentioned 4 goals the method selections had to be made based on the method of mapping and the used hardware. The starting point was the low-cost and small footprint goal, but more expensive alternatives were chosen when the other goals required as much.

2.2 Photogrammetry

Photogrammetry became the preferred method of scanning the tomb because of the lower cost compared to both terrestrial and mobile laser scanning. The preliminary research of the temple of Taffeh (Voûte et al., 2023) showed negligible differences in 3D model quality between our photogrammetry setup and a ZEB Horizon mobile laser scanner.
Photogrammetry 3D models can be created using any basic camera. Research shows a camera as simple as found in smartphones can be used to reconstruct accurate 3D models (Shan et al., 2023). However, due to the object of interest being underground and presenting challenging lighting conditions, a modern camera with a full frame sensor was chosen because of its low-light capabilities and high dynamic range. The camera used was the Canon EOS R6 with in-camera HDR enabled, combining 3 images of different exposure levels to maximize dynamic range.
The lens was chosen on similar features, because of low-light situations a wide aperture was preferred and because of the tomb dimensions a wide angle of view decreased the minimal distance to the wall given the overlap between images. The chosen Canon RF 16mm F2.8 STM achieves both and also complies to the low-cost goal.
The photogrammetric 3D model acquired with this setup is the result of 2901 images with 70% overlap in both vertical and lateral direction. These photos were processed to a point cloud using Reality Capture 1.2.0 on a HP Zbook G5 x360 workstation. The point cloud consists of 261,233,600 points.

2.3 Referencing

Three methods were selected to scale the photogrammetric point cloud to real-world dimensions. The first two, a wooden plank painted as a ruler and a laser distance meter, comply with the low-cost goal. The third method, a total station, was used to access the accuracy of the first two.

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2.3.1 Ruler: In order to get as low-cost as possible, the first method of referencing used was a simple wooden plank which was purchased locally and then prepared as ruler. It consists of a plank with a length of 2.00 meter precisely divided in 0.10-meter sections using a black permanent marker. The result of which can be seen in Figure 2. The corners of each section were manually selected within RealityCapture as control points. These were then used to scale the point clouds. The rulers were placed in the narrow corridors of the tomb in order to provide RealityCapture additional matching points between the various rooms.

2.3.2 Markers: The laser distance meter and total station measurements both required repeatable measurements between static points. Therefore 22 markers were placed on surfaces throughout the tomb. The markers used were QR-code markers which each have a unique ID coded in them. These are automatically detected and processed by RealityCapture and are then assigned coordinates in the point cloud.

Using the laser distance meter, distances were estimated between markers with a direct line of sight. A Bosch GLM 250 VF Professional was used with a specified accuracy of 0.05 mm/m. Each measurement was repeated 3 times to eliminate user error.

The total station measurements covered all markers using the station setup in various locations throughout the tomb. This resulted in a list of coordinates of all markers in a local grid. For comparison the distance between each marker was calculated using these coordinates.

2.3.3 Georeferencing: The three methods of referencing mentioned in this section are able to scale the 3D-model to real-world dimensions, but georeferencing is required to achieve the third goal of placing the model a world grid. The method chosen to geo-reference the model was to estimate the location of exterior markers visible in the point cloud with the help of a GNSS receiver.

The GNSS receiver used is a combination of an ELTEHS board with a u-blox ZED-F9P GNSS chip and an Ardusimple Multiband antenna. Previous research has shown low-cost GNSS receivers like these are capable of centimeter level accuracy measurements. (Wielgocka et al., 2021; Bose et al., 2021) These low-cost receiver chip and antenna made it possible to obtain raw dual frequency data measurements for multiple GNSS constellations. The data was then processed and stored using a python script developed for this project. The script ran on a Raspberry Pi 4b, which together with the GNSS components was powered by a 20.000mAh power bank.

This setup was configured to obtain raw GNSS data with a frequency of 1Hz for 12 hours. During this time, it recorded L1/L2 carrier phase data from the GPS, Galileo and GLONASS constellations and stored this in the u-blox proprietary ubx-format. After recording, the data in this file was processed to RINEX format using the RTKLIB RTKCONV software. An adapted version of the software was used to be able to process the dual-frequency data of the ZED-F9P chip (Everet, 2019).

This RINEX file with per-satellite measurements was processed using the Precise Point Positioning (PPP) technique. PPP removes errors from GNSS measurements using calculated corrections and models in order to get a high-accuracy position without the need for two separate GNSS stations as used in techniques like Real Time Kinematic (RTK).

Errors corrected by PPP are satellite orbit and clock deviations as well as atmospheric deviations caused by the troposphere and ionosphere. The corrections for these errors are calculated using ground stations spread around the world and final results are only available after multiple days.

Figure 2: Wooden rulers.
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PPP processing for the mapping work at Theban Tomb 45 utilized a service provided by the Natural Resources department of the Government of Canada: The Canadian Spatial Reference System Precise Point Positioning (CSRS-PPP) (Natural Resources Canada, 2019). It provides a service where one can upload RINEX GNSS data, apply corrections and deliver the result in a specified mailbox. This result contains an estimate of the GNSS location given in the ITRF2014 reference frame, standard deviation for this location and a report with the applied corrections and measurements.

2.4 iPhone LIDAR

Together with the photogrammetry model a separate 3D model using an Apple iPhone 12 pro was acquired, utilizing the iPhone's built-in LiDAR sensor and the iOS app 3D Scanner App version 2.0.8.

Because of software limitations, Theban Tomb 45 was scanned in 4 separate sessions. Each session covered part of the tomb with additional overlap between sessions. After data acquisition the different models were manually aligned in the open-source software CloudCompare version 2.13 using the markers mentioned in section 2.3.2. The 3D Scanner app calculates a textured 3D mesh of the scanned object instead of the point cloud constructed by the photogrammetry process. As opposed to a camera sensor, the LiDAR sensor in the iPhone provides depth information in meters. Therefore, the resulting model is already scaled and no reference method is required.

2.5 Comparison

Because there is no ground-truth model of Theban Tomb 45, an absolute error cannot be quantified. To compare and discuss the quality of the selected methods different combinations of reference methods were applied in the photogrammetry process, resulting in separate models. A series of relative comparisons between these models were done to determine their quality as reference method.

2.5.1 Reference methods: Three combinations of (geo)-reference methods were selected for comparison:

- ruler
- ruler, laser distance meter, GNSS
- ruler, laser distance meter, total station, GNSS

These selections were chosen to quantify the differences for each added method of referencing, starting with the ruler as it is the most low-cost option. Each reference method has a set of constraints as explained in section 2.2. Using RealityCapture, these constraints were applied to the photogrammetry model as control points, which resulted in a separate point cloud per combination.
For each point cloud the coordinates of all markers were exported. These were in a local grid for the first combination: just the ruler, and in a global grid for the other two combinations.
For all markers then the distance was calculated, which was compared between models as well as with the input reference measurements.

2.5.2 Camera – iPhone: The comparison between the camera photogrammetry models and the iPhone LiDAR model is focussed on the relative precision between both methods. For this the iPhone model was aligned with the photogrammetry model, which was scaled by the ruler and laser distance measurements.
First both models were aligned in CloudCompare. An initial alignment was done by selecting all markers in both models and transforming the iPhone model. The transformation only included a translation and rotation to preserve the scale already present in both models. After the manual transformation, an additional alignment was applied using CloudCompare's Iterative Closest Point algorithm.
With the aligned models three sections were selected for closer comparison: burial room, decorated room and ruler. For each section the cloud-to-mesh distance was calculated using the built-in CloudCompare function. This function calculates the orthogonal distance of each point in the section of the photogrammetry point cloud to the corresponding polygon in the section of the LiDAR mesh.
As can be seen in Figure 3, 22 markers were placed on walls and ceilings to help the photogrammetry process. All markers had a unique QR code, enabling automatic identification within the photogrammetry software. Some of the distances between mutually visible markers were measured (at least twice and until differences were less than 3 mm) with the laser distance meter. The two wooden rulers were put in place in narrow passages and lying flat on the floor, to ease the connection between rooms for the photogrammetry. Both rulers had two markers attached to them. To check if the rulers were disturbed during the process very precise top-down photos of the rulers and their surrounding soil were made and paper tape was attached to the ground on the four corners to make re-alignment possible during the process.

3. RESULTS

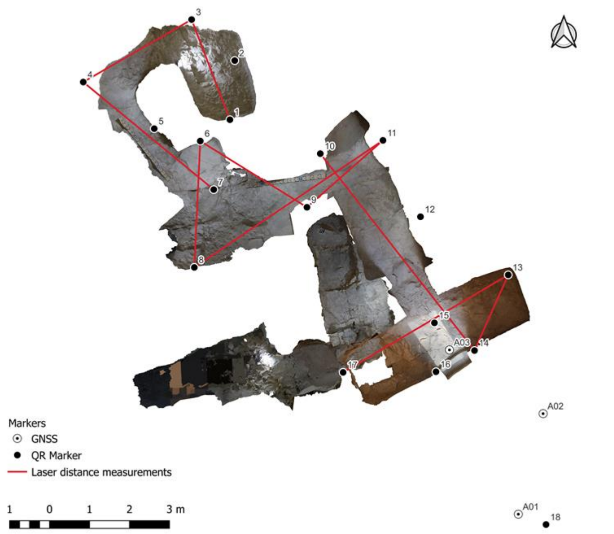

Figure 3: Map of Theban Tomb 45 showing all markers, GNSS points and measurements with the laser distance meter. © TT45 Project.

Based on an old map of the tomb a photo plan was made up front to get 80% overlap in all directions and enough sharpness with the 16 mm lens. This meant taking around 2000 photos with an average of 1m distance to the objects. In the end 2901 photos were used for the photogrammetry.

3.1 Total Station

Georeferencing the total station measurements with the collected GNSS data showed that unexpected differences had occurred with errors over 60 meters between these two, where a few centimetres should have been expected. The GNSS measurements on the 3 points closest to the tomb were repeated, showing that these were accurate with less than 1 cm deviation in the X, Y, and Z directions between the two attempts. Therefore, all total station data was left out of comparisons for this first season of surveying. Distances calculated from the total station measurements between all targets within the tomb showed that the average difference with the same distances in the photogrammetry model is 7 mm on average.

3.2 Detailed map

The photogrammetry software allows different levels of accuracy. The RealityCapture software that was used for the photogrammetry resulted in a model that was first aligned and then rendered. In all cardinal directions of the tomb and from all the walls and the ceiling in the decorated room orthographic photos were generated. In this case this resulted in a resolution of 1 mm per pixel for the undecorated parts and 0.2 mm per pixel for the decorated walls and ceiling. This denomination is to be compared with a GSD (ground sampling distance).
The photogrammetry software generated 10,163,915 tie points in 2901 photos. The model was generally scaled by the use of the two wooden rulers that were left in place simultaneously during the capturing of the photos.

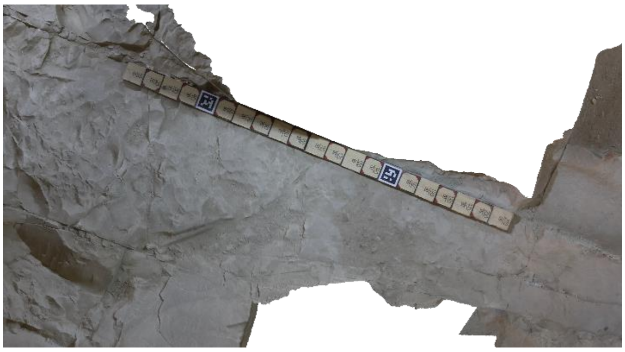

Figure 4: Part of orthophoto of floor with ruler.
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Figure 5: Orthophoto of detail of NE wall of decorated room.
© TT45 Project.

Figure 6: Original photo detail of NE wall of decorated room.
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3.3 Accurate map

In this phase of the research no real geodetic equations could be done due to a lack of raw measurements i.e. from the total station, so only comparisons are shared here. To be able to assess the accuracy of the map, distances measured with different methods were compared.

3.3.1 iPhone: The iPhone LiDAR model created with the 3D Scanner app is a combination of four separately scanned parts which were aligned and combined to a single mesh. The final model has 814,492 vertices and 1,268,922 faces.
A visual and statistical comparison was made based on three sections of the 3D models. The mean and standard deviation of the cloud-to-mesh distance found between the iPhone LiDAR model and the photogrammetry model is shown in Table 1.

Section	Mean distance	Standard deviation
Burial chamber	0.025 meter	0.017 meter
Decorated room	0.030 meter	0.023 meter
Ruler	0.045 meter	0.019 meter

Table 1: Cloud-to-mesh distances per section.

These results show the mean distance between both models is on the order of centimetres. The burial chamber section is visually the best scanned section without artifacts. The iPhone LiDAR model misses details which are well captured in the photogrammetry model, creating a more smooth surface on the walls. This translates in larger distances between both models on the numerous edges and features found on the walls of the burial chamber of Theban Tomb 45 as can be seen in Figure 7. The ruler section shows similar results in a feature-rich area.
The decorated room has flat walls with few geometric features. Nevertheless, the mean distance found does not show an improvement on the other sections. The spread in distance values indicates a shift or bias might cause the larger mean distance, but further research is required.
The iPhone registration with the used app showed that the results are not as detailed as needed but for quick results and potentially showing progress during the work it needs to be tried further.

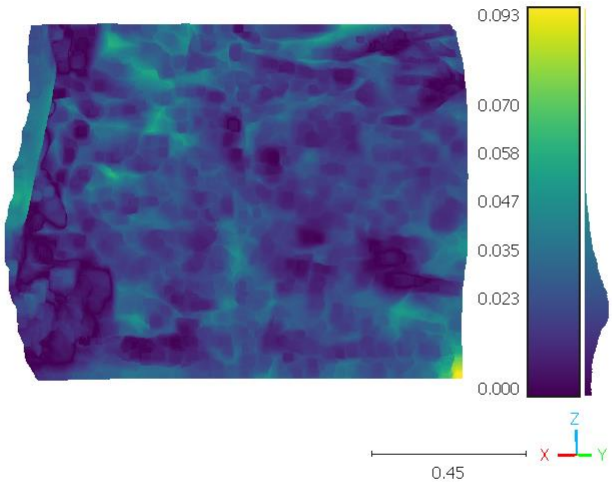

Figure 7: Detail of the cloud-to-mesh distance on a wall of the burial chamber of Theban Tomb 45.
© TT45 Project.

3.3.2 Photogrammetry: Lighting turned out to cause issues with regard to the influence of daylight falling into the single entry of the tomb. With the opening of the tomb facing south, the very early morning hours were not useful because the lighting of parts of the floors and walls that had direct lighting changed very rapidly. The hours in the afternoon were also less useful because of the changing of the colours in the tomb due to the daylight entering from outside (parts turned orange). This effect was not helping the reproduction of the real colours for study afterwards. The first effect actually influenced the photogrammetry, resulting in re-takes of parts of the tomb.
Some windblown dust on the floor of the tomb resulted in the floor not being reconstructed due to inconsistent features between. The removal of the dust resolved this issue.
Rulers were used for three reasons, to scale the model, to serve as location for markers to be recognized automatically and to try to help the photogrammetry in narrow parts of the tomb.

Two rulers were put on the floor and left there for the entire capturing of photos. The results show that in the model that only had the rulers as constraints and no geo-referencing, the distances between markers that also were captured with the laser distance meter the maximum difference was 24 mm with an average of 7 mm. This is the same difference that was achieved by comparing it with the distances calculated from the total station measurements in the tomb.

To assess the accuracy of the photogrammetry model, distances between control points were calculated in this model and were validated with distances measured by other means. 12 distances between mutually visible markers were measured with a laser distance meter, at least twice or more often until two measurements with a difference of less than 3 mm were reached. These distances were used for validation.

In the tomb distances could also be extracted from the laser distance meter measurements. 8 of these distances also were used for validation. Finally, the 3 outdoor points (A01, A02 and A03) captured with the GNSS receiver were used to generate 3 distances for validation.

The 3 above-mentioned outdoor GNSS points had coordinates in a global reference grid, and by adding them as ground control points in the model it was possible to geo-reference the entire model. The same equation and validation on distances was done after geo-referencing the model and shows that results are less good.

	Average distance error	Maximum distance error	Distance error per distance measured
	mm	mm	
Not geo-referenced	09	25	0.00013%
Geo-referenced	09	30	0.00015%

Table 2: Distance errors between model and validation.

3.4 Geo-referenced map

The geo-referencing required fixed points in the direct vicinity of the tomb with coordinates in a global grid. None of these were available so they had to be made. This can be done in many ways, but to prevent dependence on other data or unavailable equipment 3 points were fixed in the ground with survey nails, two in the bedrock of the courtyard and one on top of the modern wall surrounding the courtyard. On all 3 points the GNSS receiver/data logger was put up for 12 hours and that repeated a second time for points A01 and A02. This resulted in coordinates that were used for geo-referencing and validation.

Point	Latitude degrees	Longitude degrees	Height meters
A01	25.72999656	32.60869879	97.8545
-STD (meters)	0.007	0.006	0.034
A02	25.73002170	32.60870496	97.6545
-STD (meters)	0.006	0.007	0.033
A03	25.73003798	32.60868188	101.6925
-STD (meters)	0.003	0.003	0.014

Table 3: Base points captured with GNSS.

Data is in latitude, longitude (both in degrees with decimals) and height (in meters) related to ITRF14 epoch 2022.9. STD means Standard Deviation.

4. CONCLUSIONS

The overall research question for this preliminary research was:

"How accurate and how detailed can an ancient Egyptian underground tomb be mapped while geo-referencing the results with low-cost equipment?"

4.1 Low-cost equipment

Being a prerequisite for this project it is needed here to evaluate the results. The GNSS receiver uses easily available components that are all produced in abundance. The total price of a set was approximately 300 EURO at the time of the research. The software was built by the team and open for use.

For the PPP process an open-source service of the Canadian Government was used. The iPhone 12 Pro has a price tag of approximately 1000 EURO and the mirrorless camera and lens together were the most expensive, namely 2500 EURO. In comparison to standard indoor mapping equipment, like terrestrial laser scanners (with a value of a few ten thousand EURO) both are valued as low-cost. The photogrammetry software is free to use for academic usage. The wooden rulers were made of simple planks of 3 EURO per piece.

4.2 Accurate mapping

4.2.1 GNSS: The GNSS points had a STD of max. 7 mm in X and Y direction and max. 34 mm in Z direction (while in a narrow courtyard).

4.2.2 Total Station: The measurements outside the tomb could not be correlated with the GNSS measurements at the same spots, while these turned out to be reliable. The distances between points in the tomb turned out to be within 7 mm of the same distances in the photogrammetry model.

4.2.3 Scaling and ruler: The scaling of the photogrammetry model with the self-made wooden rulers compared against the measurements of the total station gave differences in the distances of 7 mm.

4.2.4 Photogrammetry: With over 10 million tie points in a space of less than 10 x 10 m wide and 4 m deep the photogrammetry process delivers a model, that was scaled with two rulers and validated with both the laser distance meter, the total station and the GNSS points. The errors in distance are between 7 mm (total station) and 9 mm with the laser distance meter.

4.2.5 iPhone: The results with the iPhone were less accurate than with the photogrammetry as expected but were fast and also possible in dim light conditions.

4.3 Detailed mapping

In the results of the photogrammetry a GSD of 0.2 mm (in reality) per pixel (in the orthophoto) was achieved. The orthophotos will be used to produce digital epigraphic tracings of the painted decoration of the tomb, using graphic design software and a Wacom Cintiq Pro 16 drawing tablet.

The results depend on the distance between lens and object and also on the ISO setting of the camera. The GSD with the iPhone has not been measured.

4.4 Underground mapping

Extending the photogrammetry data collection to the outdoor world made it possible to include the 3 points measured with the GNSS receiver and so referencing the underground parts. Scaling underground was done with the rulers.
Combining all these things the research question is answered positively with the numbers mentioned above. A digital 3D map is possible with low-cost equipment. These numbers are specific for the chosen equipment and way of working.

5. FUTURE WORK / RECOMMENDATIONS

In the next step of this research it is important to improve the workflow to make mapping of change possible. Mapping every week will have to be made possible. This can be done by working with fewer photos and adding GNSS points with more ease. For example, using a Realtime Kinetic (RTK) setup that can also be made by the team. For this the iPhone mapping also needs to be looked at again, because apps rapidly improve and acquisition times are low.
To test the accuracy in a more geodetic way the measurements with the total station need to be changed in such a way that the primary measurements (angles and distances) are collected.
For improving the quality of the rendered model for epigraphy it needs to be found out how to collect photos much closer to the objects. For this the work probably needs to be split up into a fast process (see above) and a more detailed one.

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The list of all the control points in this geo-referenced model will be made available at the TT45 Project website: www.stichtingael.nl.

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