



Integrated TLS-UAV Surveying for Risk-Aware Conservation at the Jupiter Temple in Baalbek Castle: Policy Application and Evidence for Resilience

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Abstract

Information about cultural heritage resources is archived and documented through data collection, including measuring results. The capacity of these measures to represent all the object's primary and secondary characteristics accounts for their efficacy. This article investigates the combination of terrestrial laser scanning (TLS) and photogrammetric surveys utilizing unmanned aerial vehicles (UAVs) for the three-dimensional modeling of the Baalbek temple complex, a globally significant cultural heritage site. However, due to their relatively recent introduction into geodetic practice, and especially useful for fixing monuments. There are many questions about the use of this technology for fixing monuments. They basically come down to making sure that accuracy standards are met. To ensure the accuracy of survey points and, more generally, laser scanning and aerial photography, this article uses the geodetic method. Simultaneously, the least-squares approach was used to create the reference network and estimate its accuracy. The accuracy of several supporting network designs was simulated, and the outcomes were compared with real data. (Novel, 2015). This study emphasizes the crucial role of current geospatial technologies in conserving architectural and cultural integrity while addressing urbanization pressures and environmental threats, so directly complementing SDG 11.4 on safeguarding cultural heritage and SDG 13.1 on resilience to hazards. (United Nations, 2015).

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Keywords

Accuracy, cultural heritage, least-squares approach, terrestrial laser scanning (TLS), three-dimensional models, unmanned aerial vehicles (UAVs)

1. Introduction

The survey of cultural heritage monuments is governed by strict normative documentation, such as GOST R 56891.2-2016 (Federal Agency for Technical Regulation and Metrology, 2016a) and GOST R 56905-2016 (Federal Agency for Technical Regulation and Metrology, 2016b). The use of advanced geodetic techniques is required to meet these precision standards, which ensure accurate documentation and cultural site conservation.

Because they provide information about earlier civilizations, their architectural innovations, and their social structures, cultural heritage monuments are essential conduits to the past. Effective documentation, monitoring, and conservation of these sites requires international cooperation and the use of cutting-edge technologies, making their preservation a duty that crosses national borders. In order to ensure that restoration efforts are supported by correct data and to stop additional degradation brought on by environmental and human-induced variables, geodetic technologies are essential for accurately capturing historical structures. (Tapinaki, 2021)

This case study was selected because the Jupiter Temple at Baalbek is a UNESCO World Heritage site of monumental scale and exceptional cultural value. As part of one of the world's best-preserved and most studied ancient complexes, the temple represents a key element of Lebanon's history and heritage, making it an ideal subject for accurate documentation and preservation efforts. This location, which was formerly known as Heliopolis during the Greco-Roman era, is a witness to the excellence of ancient architecture and engineering. There is still interest in and research on the massive limestone blocks that were utilized to build these structures; some of them weigh more than 1,000 tons. Research on construction methods, structural resilience, and precision engineering is still influenced by the advanced methods employed by ancient builders.

High-precision documentation of these structures is essential for assisting archaeological research and digital heritage applications in addition to their protection. Technological developments in UAV-based photogrammetry and terrestrial laser scanning (TLS) have transformed heritage documentation due to the demand for extremely accurate and non-invasive survey methods. High-precision three-dimensional modeling is made possible by these methods, which offer comprehensive reconstructions for applications in virtual heritage, research, and conservation. (Böhler, 2004). Experts may evaluate structural integrity, examine fine architectural details, and produce interactive digital models for repair and education using these techniques.

Sites like the Parthenon in Greece and Machu Picchu in Peru have benefited from similar technologies all over the world. Because these locations may now be digitally preserved, researchers can examine their architecture in great detail without having to physically visit them, causing the least amount of harm to fragile components. By recording millimeter-level information, TLS and UAV photogrammetry enable improved structure analysis, condition evaluations, and even virtual reconstructions in the event of damage brought on by human or environmental forces.

Additionally, these tools provide significant benefits for tracking continuous alterations in historical locations throughout time. Historic buildings are increasingly at risk from urbanization, pollution, and climate change, which calls for constant observation and quick reaction plans. Researchers can follow foundation movements, material degradation, and structural deformations with unparalleled precision by utilizing geodetic techniques like TLS and UAV photogrammetry. By enabling early vulnerability detection, these capabilities minimize irreversible damage and enable prompt conservation responses.

The use of geodetic technologies in the preservation of cultural resources is growing as they develop further. The quality and efficiency of documentation efforts are being further improved by the use of machine learning and artificial intelligence in geospatial analysis. Workflows for heritage conservation are becoming more efficient through the use of automated feature detection, point cloud processing, and predictive modeling. These developments highlight how crucial it is for geodesists, archaeologists, and conservationists to work together across disciplines in order to preserve historical sites for future generations.

In summary, the endurance and validity of historic monuments depend on the use of high-precision geodetic techniques in cultural heritage documentation. The enormous usefulness of these technologies in conserving and comprehending ancient buildings is best demonstrated by Baalbek's Jupiter Temple.

Heritage specialists can achieve unprecedented levels of precision in documentation and conservation by utilizing TLS, UAV photogrammetry, and new digital tools. This will open the door for more robust and knowledgeable preservation techniques around the world.

2. Literature review

The use of geodetic techniques in preserving cultural heritage has been the subject of numerous studies. A comparison of TLS and photogrammetric methods was presented by Böhler and Marbs (2004) (Böhler, 2004) Who also highlighted the benefits of each method. While UAV photogrammetry is superior for large-scale documentation due to its high-resolution aerial perspectives, TLS is especially good at collecting minute details with sub-millimeter accuracy. Nevertheless, there are still difficulties in combining these two methods into a single workflow.

Numerous studies have been conducted on the application of geodetic techniques to cultural heritage preservation. Böhler and Marbs (2004) compared TLS and photogrammetric techniques and emphasized the advantages of each technique. The combination of TLS and UAV photogrammetry offers a more thorough method for extensive and in-depth historical documentation. However, integrating these two approaches into a unified workflow continues to provide challenges.

The effect of scanning geometry on TLS accuracy was investigated by Soudarissanane et al (2011), who found that the angle of incidence has a major influence on data dependability. To reduce mistakes brought on by different scanning angles and target reflectivity, (Cheng, 2016) suggested correction algorithms (Sylvie Soudarissanane, 2011). In order to increase survey accuracy, these studies emphasize the necessity of widely spaced ground control points (GCPs) and geodetic reference networks.

Data collection capabilities have been considerably enhanced by recent developments in sensor technologies. UAVs may now collect more comprehensive topographical and architectural data thanks to the addition of high-resolution LiDAR sensors. To gain a better understanding of material compositions and structural conditions, studies like and (Remondino, 2010) have looked at the combination of multispectral imaging and infrared scanning with geodetic techniques.

In their investigation of geodetic control networks for UAV photogrammetry, (Kompoti, 2023) Showed that accurate ground control improves the spatial alignment of TLS and photogrammetric datasets. In a similar vein, (Sanz-Ablanedo, 2018) Presented empirical data demonstrating how well optimized GCP insertion techniques increase model accuracy. These results emphasize how crucial structured geodetic operations are for documenting cultural resources.

Automated point cloud classification and advanced processing tools can streamline data management by reducing manual effort, while the interpretation of architectural features continues to rely fundamentally on human expertise. For extensive heritage surveys, such advancements also facilitate the integration of UAV and TLS photogrammetry, providing a more comprehensive documentation workflow.

Furthermore, recent research has highlighted the importance of multi-temporal monitoring. Researchers may monitor structural deterioration and changes over time by collecting data at various intervals, which makes predictive modeling and early conservation strategy intervention possible. A complete method for managing cultural resources is provided by combining historical records with geodetic and remote sensing data.

The usefulness of geodetic techniques is further increased by integrating GIS with TLS and UAV datasets. Heritage site visualization across time, structural assessments, and spatial analysis are all made possible by GIS systems. Decision-makers can prioritize preservation efforts and more efficiently allocate resources by integrating geospatial data with conservation strategies.

The effect of climate change on historic conservation has also been the subject of recent studies. According to studies, the stability of historic buildings may be impacted by increased environmental stressors, including temperature and humidity swings. High-resolution TLS and UAV photogrammetry allow researchers to more precisely evaluate the effects of these factors and suggest prompt mitigation strategies.

In conclusion, even though TLS and UAV photogrammetry offer extremely accurate recording capabilities, their effective use requires precise ground control, organized workflows, and ongoing technological development. The increasing use of AI, multispectral photography, and multitemporal analysis will improve geodetic techniques' ability to preserve cultural heritage locations across the globe. Furthermore, future heritage management plans will be greatly influenced by the interdisciplinary cooperation of geodesists, archaeologists, and conservationists.

3. Methodology

3.1. Design of the survey network

The accuracy assessment of the survey network was performed through modeling. An idealized network scheme is presented in Figure 1. The designed survey network consists of five points (1-5). The reference points are located around the perimeter of the designated area, with a total of four points (ST1 – ST4). The coordinates of all points were determined in the Autocad environment and were subsequently adjusted to account for the nominal accuracy of commonly used total stations, with distance measurement accuracy ranging from 2 mm + 2 ppm to 5 mm + 3 ppm. The distances between the reference and survey points ranged from 70 to 100 meters.

The combination of UAV photogrammetry and terrestrial laser scanning (TLS) for cultural heritage documentation has been well researched, with particular focus given to the effects of distance, geometry, and incidence angles on the quality of TLS data. (Sylvie Soudarissanane, 2011) (Cheng, 2016)

The calculation of the root mean square error (RMSE) of the survey points' coordinates was performed using the least squares method (LSM). The fundamental equation of LSM in matrix form is expressed as follows:

$$V = AX - L \quad (1)$$

$$A = \begin{bmatrix} A_{11} & A_{12} & \dots & A_{1m} \\ A_{21} & A_{22} & \dots & A_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ A_{n1} & A_{n2} & \dots & A_{nm} \end{bmatrix}; X = \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_n \end{bmatrix}; L = \begin{bmatrix} L_1 \\ L_2 \\ \vdots \\ L_n \end{bmatrix} \& V = \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_3 \end{bmatrix} \quad (2)$$

Where: A - design matrix (coefficient matrix of parametric equations), X - matrix of adjusted parameters, L - vector of measured values, V - vector of corrections.

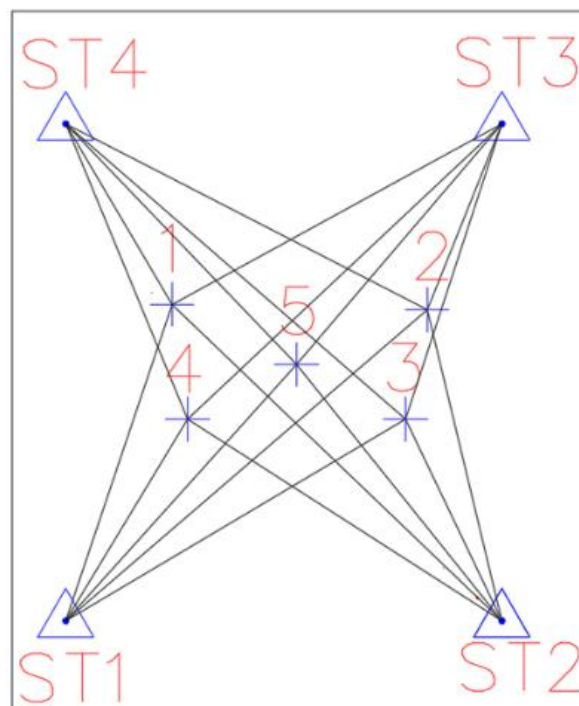


Figure 1. Scheme for modeling the geodetic network (Source: Author, 2025).

The following block diagram (Figure 2) shows how to determine the corrections X and V:

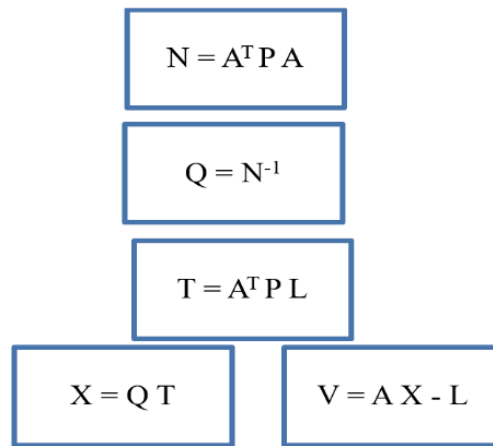


Figure 2. The block diagram of the adjustment and determination of the error in determining points coordinates of the survey network using LSM (Source: Author, 2025).

Where: N - normal matrix, AT - transposed design matrix, P - weight matrix, Q - inverse matrix, T - matrix of coordinate corrections.

The weight matrix is a diagonal matrix, and its off-diagonal elements are zero. The value of the weights is inversely proportional to the variance (σ).

$$P = \begin{bmatrix} P_{11} & 0 & 0 & 0 \\ 0 & P_{22} & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & P_{nn} \end{bmatrix} = \begin{bmatrix} \frac{1}{\sigma_{11}^2} & 0 & 0 & 0 \\ 0 & \frac{1}{\sigma_{22}^2} & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & \frac{1}{\sigma_{nn}^2} \end{bmatrix} \quad (3)$$

The posterior standard RMSE (μ^2) and posterior variance (μ) of the corrected measurements are determined from the following expressions:

$$\mu^2 = \frac{v^T P v}{n-t}; \mu = \sqrt{\frac{v^T P v}{n-t}} \quad (4)$$

Where: n - number of measurements, t - number of unknowns.

The covariance matrix of the variance is given by:

$$\Sigma_{xx} = \mu^2 \times Q_{ii} \quad (5)$$

Where: $Q_{i,i}$ - diagonal elements of matrix Q.

Then the RMSE of the geodetic planar network coordinates ($m_{Network}$) is determined by the expression:

$$m_{Network} = \sqrt{\text{Trace} \Sigma_{xx}} \quad (6)$$

Where: $\text{Trace} \Sigma_{xx}$ - sum of the diagonal elements of the covariance matrix.

$$m = \sqrt{\mu^2 \times Q_{i,i}} \quad (7)$$

Where: m - RMSE of the corrected coordinates.

Finally, the calculation of the RMSE of the point coordinates is performed using the following expression:

$$m_{XY} = \sqrt{m_x^2 + m_y^2} \quad (8)$$

Where: m_{XY} - RMSE of the point, m_x - RMSE along the X-axis, m_y - RMSE along the Y-axis.

Using the LSM algorithm (Figure 2) for the idealized network (Figure 1), calculations were performed, and the average posterior RMSE of the five survey points was determined.

$$m_{Average\ XY} = \frac{m_{xY} + m_{xY(i+1)} + \dots + m_{xY(n)}}{n} \quad (9)$$

Where: $m_{Average\ XY}$ - average RMSE of the survey points, $m_{xY(i)}$ - RMSE of the point coordinates.

The RMSE of the survey points' coordinates was calculated using the given algorithm for various numbers of reference points and the nominal accuracy of total stations (Figure 3).

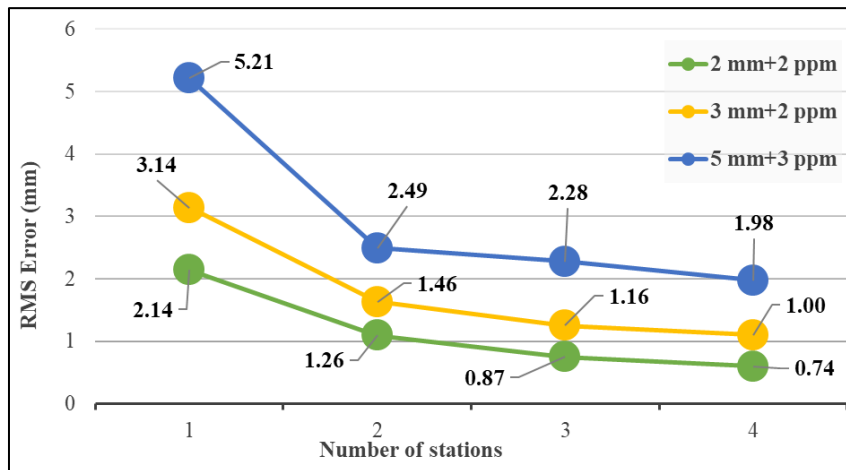


Figure 3. Graphs of accuracy variations of the survey points depend on the number of starting points and the nameplate accuracy of the total station (Source: Author, 2025).

The graphs in Figure 3 show that the number of reference points significantly impacts the accuracy of determining the coordinates of the surveyed points. The influence of the nominal accuracy is also evident. The preliminary calculation allows for selecting the geodetic network scheme (reference + survey network) depending on the specific task (accuracy of the final model construction). The results of these tests formed the basis for designing the survey network for laser scanning and aerial photography of the Baalbek Castle.

The image-based and laser scanning techniques for cultural heritage documentation are complementary, which emphasizes the importance of integrating both approaches to produce high-quality results. (Remondino, 2010)

The effects of combining TLS and UAV technologies on the preservation of cultural heritage have been shown in recent studies, including applications to large-scale archaeological sites. (Kompoti, 2023). These studies validate the strategy used in this project, highlighting the importance of high-precision geodetic networks in making such integrations successful.

3.2. Design of the control (Reference) points network and field measurements on a fragment of Baalbeck castle (Part of the Jupiter wall)

The survey network was initially designed with 15 points located in front of the wall. Considering the preliminary assessment (see Figure 3), three reference points (ST01, ST02, and ST03) were established (Figure 4a).

Next, on the survey site—the castle walls—27 control points were planned and fixed for subsequent laser scanning. Actual linear-angular measurements, targeting the 27 control points (Figure 5), were performed from three survey points (7, 9, and 11) using a total station with a distance measurement accuracy of 3 mm + 2 ppm in reflectorless mode (Figure 4b).

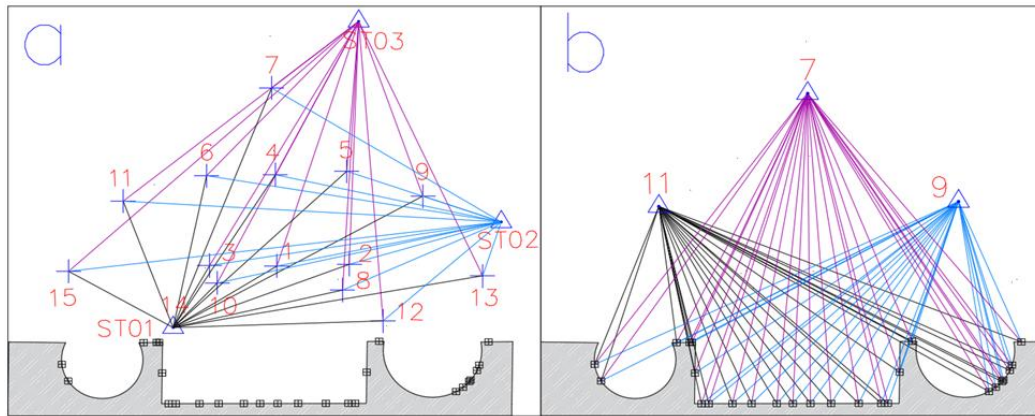


Figure 4. Schemes for the construction of a geodetic network for laser scanning (on the left) and measuring to wall tie points (on the right). (Δ - reference points, + survey points, - tie points mounted on the wall) (Source: Author, 2025).

Jo et al. (2017) demonstrate how TLS and UAV photogrammetry can be integrated into heritage sites, which is like the process used at Baalbek. (Jo, 2017). The use of 3D approaches in Navarino is also documented by Kompoti et al. (2023), who provide a comparative case study to support the selected methodologies. (Kompoti, 2023)

Using the above algorithm (1), a graph was created (Figure 6) showing changes in the average RMSE values of the reference (survey) points (15 points on the ground near the wall) and the RMSE of the control points (27 points on the wall, Figure 5). The first RMSE values were determined based on 1-3 reference points (ST01-ST03). The second RMSE values were obtained from measurements taken from 1 to 3 survey points (a total of 15 survey points) (Figure 4a), located directly in front of the wall, and targeting the control points (tie) points (27) mounted on the wall for use in TLS.



Figure 5. Example of one of the 27 control points attached to the wall (Source: Author, 2025).

Upon examining Figure 6, it is confirmed that the accuracy of determining point coordinates is proportional to the number of observation stations and increases with their number. The graphs in Figure 6 are consistent with those in Figure 3. A comparison shows that actual measurements proved more accurate than the modeled ones. This can be attributed to the increased accuracy due to the number of measurements and their averaging. The use of these points for assessing the accuracy of the wall control points results in only a slight loss of accuracy in determining their coordinates.

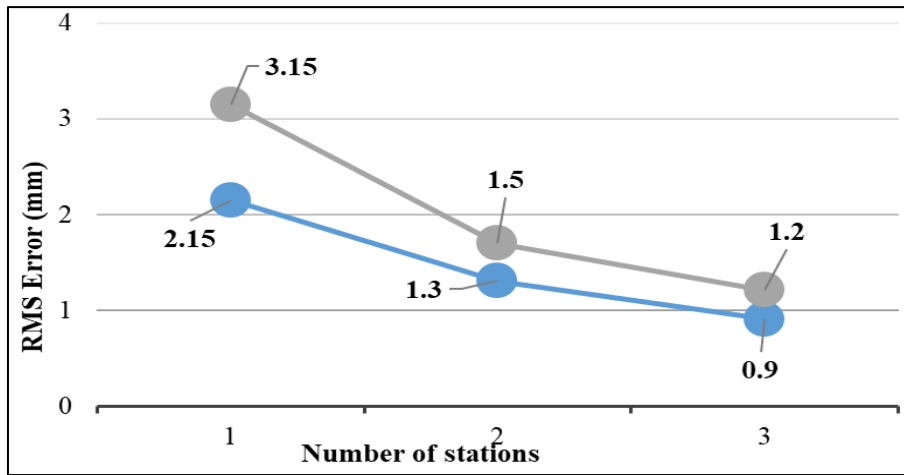


Figure 6. Graphs of the accuracy variation of the laser control points coordinates (blue color) and tie (gray) points on the wall (Source: Author, 2025).

3.3. Laser scanning

After calculating the coordinates of the wall control points and survey points, all conditions were set for TLS. The Leica P30 scanning station was used, with horizontal and vertical angular accuracy of 8 seconds and distance measurement accuracy up to 10 mm within the entire range from 3 m to 50 m.

The scanning was conducted from 15 points (Figure 4a), resulting in the construction of an equal number of point cloud models of the temple wall (Figure 7). The object was scanned from various distances and at different scanning angles.



Figure 7. A point cloud model created using the laser scanner (Source: Author, 2025).

Figure 8 shows the distribution of coordinate errors for the points captured by laser scanning from station 7 (points, Figure 4a), located 50 meters away from the wall. The error was considered in two directions (x, y) and calculated using the following equation:

$$\text{Error} = \sqrt{(x_T - x_{TLS})^2 + (y_T - y_{TLS})^2} \quad (10)$$

Where: x_T & y_T - coordinates corrected using the LSM and x_{TLS} & y_{TLS} - coordinates obtained directly from laser scanner measurements.



Figure 8. The distribution diagram of the relative errors of points coordinates depending on the distances to the laser scanning station (surveyed from station №. 7) (Source: Author, 2025).

The results of the laser scanning analysis numerically demonstrate an increase in survey error with increasing distances to the laser reflection points and the scanning angle.

3.4. Aerial photography with UAV

The equipment used was the DJI Phantom 4 Pro. The photography was conducted from a height of 35 meters with an 80% overlap of images (both longitudinal and lateral). As a result, the collected material fully covers the wall and the area in front of it, where a network of 15 fixed survey (reference) points was established. A point cloud model of the temple wall was constructed (Figure 9).



Figure 9. A point cloud model derived from a survey using a UAV (Source: Author, 2025).



Figure 10. Example of a GCP used for UAV photogrammetry georeferencing (Source: Author, 2025).

The coordinates of the point cloud were corrected by adjusting with five reference points (7, 9, 12, 14, 15) (Figure 4a & 10).

The RMSE resulting from the georeferencing of the model points to the reference points was 1.6 cm. The transformation matrix and scale factor were as follows:

$$\text{Transformation matrix} = \begin{bmatrix} 0.999 & 0.000 & 0.001 & 1.019 \\ -0.000 & 0.999 & 0.001 & 1.164 \\ -0.001 & -0.001 & 0.999 & 1.640 \\ 0.000 & 0.000 & 0.000 & 1.000 \end{bmatrix} \& \text{ Scale factor} = 0.9988 \quad (11)$$

3.5. Unified model construction

After obtaining two point cloud models of the same area (the southern wall of the Temple of Jupiter) using two geodetic technologies (TLS and UAV), both models were combined. The following checks were performed on these models:

1. First step (the same operations are performed after the second step) - the calculation of distances between points of the two point cloud models using the "cloud-to-cloud" comparison algorithm before and after registration (Figure 11). It was found that the models are approximately the same: the maximum point deviations were 0.32 cm, the standard deviation was 1.06 cm, and the average distance between points was 0.74 cm. Figures 11 & 12 show the relationship between the approximate distance (Δ) (in cm) and its quantity (in percentage) across 8 classes between the two point cloud models (the total values of approximate distances are 14,739,059)

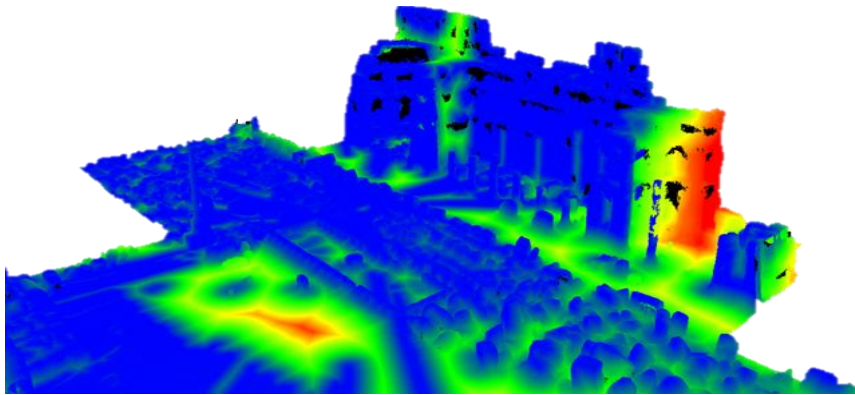


Figure 11 Comparison picture of models constructed by UAV and TLS technology (Source: Author, 2025).

(blue areas are shown: $\Delta \leq 1$ cm / red areas: $\Delta > 7$ cm / yellow areas: $1 \text{ cm} < \Delta < 7 \text{ cm}$ / black areas: gaps)

2. The second step involved the registration (merging) of the two models using the CloudCompare stereo software with the ICP algorithm. The RMSE resulting from the model merging was 11 mm. The transformation matrix and scale factor were as follows:

$$\text{Transformation matrix} = \begin{pmatrix} 1.003 & -0.000 & 0.002 & -2.482 \\ 0.000 & 1.003 & -0.002 & -2.734 \\ -0.002 & 0.002 & 1.003 & 0.274 \\ 0.000 & 0.000 & 0.000 & 1.000 \end{pmatrix} \& \text{ Scale factor} = 1.0028 \quad (12)$$

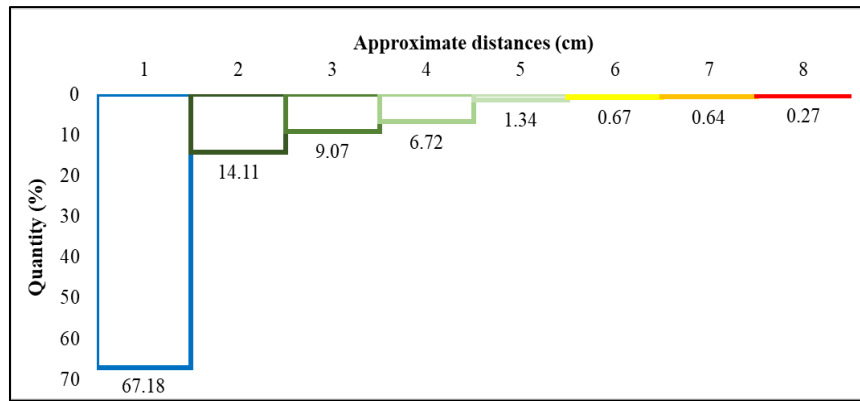


Figure 12. A histogram indicating the percentage of the distances (deviations) between the points (Source: Author, 2025).

After merging the models, the point alignment was performed again using the "cloud-to-cloud" algorithm for cross-sections of the two-point clouds in the blue area (which represents areas with minimal deviations, see Figure 11). Higher deviations, indicated in red and yellow at ground level and on the vertical surfaces close to the entrance pillar, can be explained by the known limitations of both sensors: UAV photogrammetry usually shows greater deviations on vertical surfaces due to image geometry and reduced overlap, while terrestrial laser scanners tend to show increased errors on horizontal surfaces due to incidence angles and occlusions. The following result was obtained: maximum error = 0.06 mm, standard deviation = 0.05 mm, and average distance = 0.03 mm. The total number of approximate matches was 5,951, of which more than 75% had discrepancies of less than 0.045 mm. Figure 13 illustrates the merged TLS and UAV point clouds.



Figure 13. Integrated point cloud model based on TLS and UAV photogrammetry data. (Source: Author, 2025)

As evident from the above calculations, the model construction error was 11 mm. Regarding the research objective: documenting cultural heritage sites, the quantitative value is not as important as the algorithm for creating the geodetic framework, which includes the possibility of achieving a wide range of practically significant accuracies. This approach is particularly relevant for compiling documentation for heritage preservation.

4. Discussion

Significant new information about the potential and constraints of TLS and UAV photogrammetry has been made possible by their integration in the documentation of Baalbek's Jupiter Temple. A more thorough and accurate representation of the location was attained by fusing aerial and ground viewpoints. The development of a highly detailed digital twin of the structure was made easier by the capacity to record both horizontal and vertical features.

The impact of environmental factors on data collection was one of the main difficulties this study faced. Extensive post-processing was necessary to improve the data quality, since noise was introduced into the datasets by lighting conditions, atmospheric disturbances, and variations in the stone surfaces. The TLS/UAV software package's integrated statistical and outlier filtering techniques were used to minimize noise, eliminate isolated points, and increase the final model's overall dependability.

The alignment of the TLS and UAV datasets was another important factor. By establishing a widely dispersed geodetic reference network, disparities between datasets were reduced, and control points were precisely positioned. The spatial alignment was improved by employing least squares adjustment techniques, which decreased systematic errors and raised the overall accuracy of the model.

In addition to spatial alignment, data fusion has become more efficient in recent years due to the incorporation of AI-enhanced processing workflows. Large datasets may now be processed with less manual labor because of the use of machine learning techniques to find discrepancies in point clouds. The efficiency of heritage site recording has been greatly increased by automated error detection techniques, which guarantee that high accuracy standards are upheld without imposing undue computational demands.

The size of documentation projects is a significant determinant of TLS-UAV integration. TLS is particularly effective for capturing precise geometric details at high resolution, whereas UAV photogrammetry is well-suited for documenting larger areas efficiently and giving greater spatial context. An ideal combination of these techniques produces better outcomes in both structural integrity assessments and digital reconstruction projects, according to case studies in heritage preservation.

It is impossible to overestimate the importance of long-term monitoring in historic conservation. Cultural heritage monuments are seriously threatened by natural disasters, human-caused destruction, and environmental degradation. Over time, structural deformations can be detected with the aid of real-time monitoring systems and geodetic sensors. Conservationists can take preventative measures to stop further deterioration by identifying at-risk locations with the use of predictive models that use AI and machine learning.

Researchers have been using multi-temporal analysis more in recent years to evaluate how historic constructions have deteriorated over time. TLS and UAV photogrammetry enable specialists to measure surface changes with previously unprecedented accuracy by collecting data at various intervals. Differential models for deformation analysis have been very helpful in tracking foundational changes in ancient temples, allowing authorities to carry out restoration work before irreparable harm is done.

Additionally, advances in thermal and multispectral imaging have improved the capacity to identify underlying structural problems that are invisible to the human eye. Numerous research has investigated the integration of spectral analysis with TLS and UAV information, showing its efficacy in detecting material degradation, moisture infiltration, and hidden fractures in stone structures.

The integration of geodetic documentation with asset Building Information Modeling (HBIM) is presented as an effective strategy in cultural asset management. HBIM varies from traditional BIM by addressing the irregular geometry and particular situations of heritage sites, which makes modeling complex and often requires extensive manual involvement. Although a complete HBIM model was beyond the scope of this study, the datasets generated through UAV and TLS photogrammetry provide a solid foundation for future HBIM development and digital twin applications.

More community participation in historical recording has also been made possible by the growing accessibility of TLS and UAV photogrammetry technology. Cultural heritage conservation has benefited from crowdsourced geospatial data collection, in which local communities take part in scanning and mapping activities. (Kersten, 2006)

In the end, combining TLS with UAV photogrammetry is a big step forward for the preservation of cultural assets. Even if there are still difficulties in improving data fusion methods and reducing errors, continuous study and technical advancements keep making these approaches more successful. For historic sites like Baalbek's Jupiter Temple to be

conserved for future generations, interdisciplinary cooperation between geospatial scientists, historians, and conservationists will be crucial.

In conclusion, the field of historical documentation has changed because of the combination of modern computing technology and geodetic techniques. Long-term monitoring plans and more informed conservation decisions are made possible by the capacity to create accurate, high-resolution digital reproductions of historic sites. By connecting geodetic accuracy to risk-aware management, these findings support SDG 11.4 on protecting cultural heritage and SDG 13.1 on resilience to environmental hazards while also offering a precise baseline for future restoration efforts and preservation planning, which have immediate practical implications. (United Nations, 2015).

5. Conclusions

This study highlights the revolutionary effects of combining UAV photogrammetry and TLS for the recording and conservation of cultural heritage monuments, illustrating how their integration improves both completeness and accuracy of documentation. The Jupiter Temple at Baalbek serves as an example of how well these cutting-edge geodetic techniques may be combined to produce incredibly accurate and detailed digital reproductions of historical structures. The combination of TLS and UAV photogrammetry offers a thorough method for documenting complex architectural features as well as large site layouts, guaranteeing that priceless historical data is captured with millimeter accuracy.

The study's conclusions emphasize the value of organized geodetic processes, stressing the need for evenly spaced ground control points, exacting accuracy evaluations, and sophisticated computational methods for the best possible data integration. By automating feature extraction and lowering the possibility of point cloud alignment mistakes, the use of AI and machine learning further improves data processing efficiency.

One of the most important aspects of preserving cultural assets is ongoing observation. Conservationists can identify structural changes over time by using multi-temporal geodetic surveys, which allow them to use proactive intervention techniques to mitigate deterioration brought on by human activity, environmental variables, or climate change. By providing cutting-edge instruments for risk assessment and predictive modeling, the combination of remote sensing, multispectral imaging, and GIS platforms increases the focus of conservation initiatives. Future studies should concentrate on improving data fusion techniques, incorporating other remote sensing methods like LiDAR and thermal imaging, and creating real-time monitoring systems as geospatial technologies continue to advance. Opportunities for developing interactive 3D models that support restoration planning and public involvement in cultural heritage awareness are also presented by the potential of Building Information Modeling (BIM) in heritage conservation.

Ultimately, a multidisciplinary strategy combining the knowledge of geodesists, archaeologists, and conservationists is needed to preserve historic sites like Baalbek's Jupiter Temple. In order to preserve cultural heritage and give future generations access to precise, in-depth, and immersive depictions of our common past. TLS and UAV photogrammetry will go further, guaranteeing immersive and accurate documentation of our common history and offering baselines that are important to policy and support SDG 11.4 on preserving cultural heritage and SDG 13.1 on enhancing resilience to environmental threats (United Nations, 2015).

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developments have improved the caliber of this research and offered insightful information about high-precision documentation techniques.

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Ethics approval

This study did not involve surveys, interviews, or questionnaires.

Conflict of interest

I do declare that there is no competing interest

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