GEODETIC TECHNOLOGY FOR CULTURAL HERITAGE MONITORING - THE CASE STUDY OF KLEPSYDRA AT THE ACROPOLIS OF ATHENS

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***Keywords**: Digital recording, cultural heritage, monitoring, terrestrial laser scanning*

ABSTRACT

The aim of this work is to demonstrate the aspects of documentation and recording of a cultural heritage monument in order to study the structural stability of the monument over time. Specifically, the monument of Klepsydra examined in this paper is the oldest water spring of the Athens Acropolis located at the north slope. However, the monument is prone to deformations and the implementation of a permanent monitoring scheme in order to measure the movements over time has been within the priorities of the responsible archaeologists. The paper describes the monitoring network comprising 23 stations that was established in selected parts of the monument. Five measuring epochs of monitoring using conventional surveying were performed and a deformation analysis is provided which indicates that no statistically significant movement was identified in the horizontal neither at the vertical. In addition, terrestrial laser scanning was implemented into the surveying workflow not only for the 3D recording of the monument but also to aid in the monitoring investigation. In this project, scans of two different measuring epochs are studied.

INTRODUCTION

The recording of cultural heritage involves a variety of monuments, buildings, or landscapes of outstanding universal value from the point of view of history, art or science. These sites are often under threat from environmental conditions, structural instability, increased tourism and development. Traditional surveying techniques in combination with other digital documentation techniques such as terrestrial laser scanning provide an extremely useful way to document the spatial characteristics of these sites. This spatial information forms not only an accurate record of these rapidly deteriorating sites, which can be saved for posterity, but also provides a comprehensive base dataset by which site managers, archaeologists, and conservators can monitor sites and perform necessary restoration work to ensure their physical integrity. A digital record of these sites also facilitates their accessibility to a broader audience via the Internet.

The aim of this paper is to demonstrate the aspects of the documentation and recording of a cultural heritage monument under the rationale to study the structural stability of the monument over time. Specifically, the monument of Klepsydra examined in this work is the oldest water spring of the Athens Acropolis located at the north slope. The spring with the surrounding small caves comprise an archaeological site of considerable interest as it dated in prehistoric times (circa

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3500 BC). A brief historic review regarding the site is given in section 2 of the paper. However, the monument is prone to deformations, thus the implementation of a permanent monitoring scheme in order to measure the movements over time has been within the priorities of the responsible archaeologists. The paper describes the monitoring network which comprises 23 stations that were established in selected parts of the monument that were specified by the archaeologists. The site

selection and the instrumentation are described in section 3 in order to provide an understanding of the recording of a heritage site and the specifications so that a repeatable level of geometric precision is achieved. In the same section, the five measuring epochs of the monitoring scheme are presented and a deformation analysis is provided which indicates that no statistically significant movement was identified in the horizontal neither at the vertical.

Further to the conventional surveying measurements, the technology of terrestrial laser scanning was introduced into the surveying workflow not only for the 3D recording of the monument but also to aid in the monitoring investigation. The main advantage of terrestrial laser scanning is the enormous and dense spatial data information that is provided within a short time by the acquired point clouds as opposed to the selected points that are measured by the conventional surveying techniques. In addition, terrestrial laser scanning as a non-destructive technique is ideal for the monitoring of structures as it allows obtaining the geometry of the object (shape, size and dimensions) even if it is inaccessible. In this project, scans of two different measuring epochs are studied. From the scans, the 3D models from selected parts of the monument are given along with metric results regarding the deformation study of the site. The measuring scheme and the processing of the data are presented in section 4 of this paper along with specific examples from the model. Finally, concluding remarks are drawn in section 5, showing that laser scanning can be used as an accurate, fast and cost effective method and recommendations for further study are suggested.

THE MONUMENT OF KLEPSYDRA

The monument of Klepsydra is placed at the western end of the Acropolis, on the North Slope, to the point where the walk meets the Panathenaic Way (or route of the Panathenaic) (shown with arrow in Fig.1). Clepsydra itself was the premier source of the Acropolis (Fig. 2). It is worth noting that it was discovered since several centuries BC, and was formerly named Empedo, after the nymph who was worshiped in the cave of the spring. The name was later changed to Clepsydra (hourglass), because the waters were sometimes obvious and sometimes lost.

Very close to the source of Clepsydra, is an impressive series of caves of great archaeological significance, which give to the North Slope of the Acropolis an imposing character. The caves were originally used as dwellings, but over time turned into shrines and places of worship of the twelve gods, or smaller local goddesses. The most important of these is the cave - temple of Apollo, Zeus cave, the cave of Pan, the cavern Ersi, where the Mycenaeans had formed as a fountain (source exploitable), and the temple of Aphrodite. In conclusion, the greater region of Klepsydra is considered as a universally significant cultural heritage monument, because the specific source, with the surrounding caves, were the most significant reference locations for the detection of prehistoric human presence and action in the Greek area.

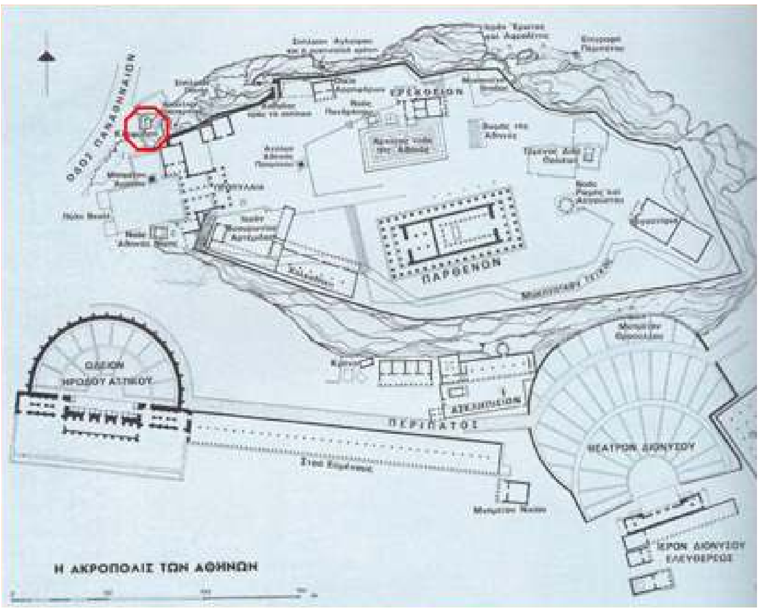


Figure 1: Map of the Athens Acropolis

The historic studies relay that the first signs of human presence in the wider North Slope of the Acropolis were placed in the late Neolithic period (3500-3000 BC), where the northern part of the current position of the Clepsydra had 22 shallow wells. In the early 5th century BC, a manufacturing facility was constructed in Klepsydra for the collection and distribution of water source, shaping it into a fountain. The fountain was a simple rectangular structure, built with river water to depth, next to the source. Between the 10th and 11th century AD, at the position of the source, the Chapel of the Holy Apostles was established. In the middle of the 13th century AD the Acropolis was fortified resulting in the source being buried beneath the rocks and forgotten. The first excavations in the Clepsydra began in 1874 by the French archaeologist E. Bournouf and resumption of work on Clepsydra was in the years 1936-40 by the American archaeologist A.W. Parsons [1].

Figure 2: View of the Klepsydra

RECORDING SCHEME

Traditional surveying techniques in combination with other digital documentation techniques such as terrestrial laser scanning have been used in this work to provide an accurate record of this rapidly deteriorating site. In this way the archaeologists and conservators can monitor the site of Klepsydra and perform necessary restoration work to ensure its physical integrity.

Figure 3: Example of monitoring points

For this reason a monitoring network comprising 23 control points located in the surrounding area of the monument was established for the structural study of the monument. These points were carefully chosen by the archaeologists. Specifically, 9 points are on the stone paved area, 4 are located in the western marble wall, 6 are found in the rocks above the monument and 4 points on the wall by stone slabs on the east side of the monument (Fig. 3). Also, a reference network of 5 points was implemented (Fig. 4). The geodetic measurements were performed by the Leica TDA5005 industrial total station (manufacturer's precision of ±1.5cc in angle measurements and 1mm±2ppm in distance measurements).

In total, five monitoring epochs have been completed (between March 2008 and February 2009). Each monitoring epoch comprises the measurement of the reference station network (angles and scale) and measurements (114 angles and 3 distances) from each of the five reference points to all the 23 monitoring points.

A least squares adjustment of all measurements in each epoch was performed. It must be noted that two approaches were implemented: a unique 3D adjustment and a separate 2D horizontal with a 1D vertical adjustment. The coordinate results in both adjustments were identical and only a small difference in the aposteriori sigma was noticed (σ_0 of 1.1 in the 2D adjustment versus σ_0 of 2 in the 3D adjustment).

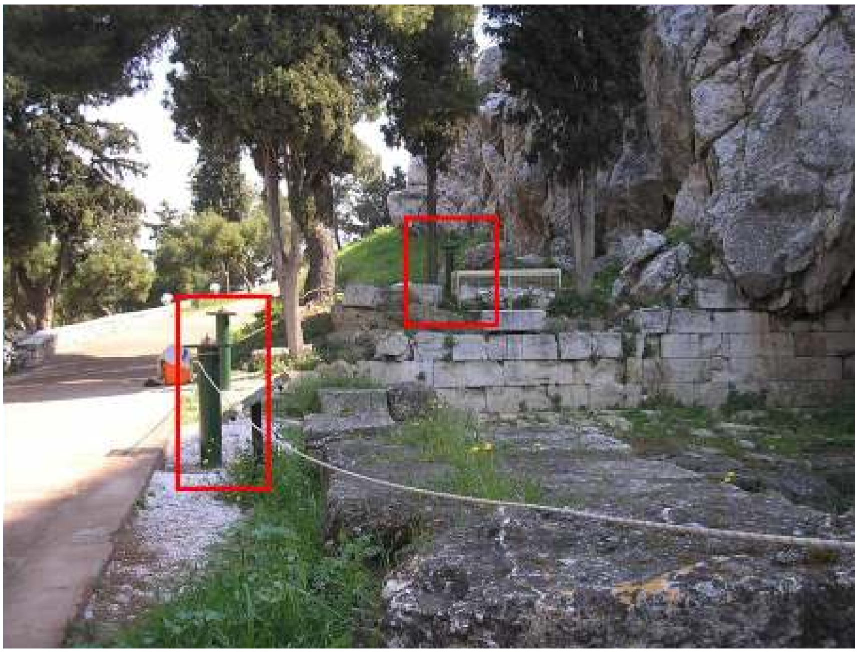


Figure 4: Example of reference control points

Monitoring results

The statistical comparison of the results from the five monitoring epochs revealed for 95% confidence interval that no movement has occurred. The results are given separately for the horizontal, vertical and 3D network adjustments.

(a) Horizontal control network

In each monitoring session, the number of observations, the number of independent parameters and the degrees of freedom are respectively, n = 117, m = 53 and r = 64. The mean redundancy number is 0.461. The aposteriori sigma σ_0 for each epoch is given in Table 1.

In the 2D adjustment, the size of the errors ellipses at the 95% confidence interval varied from 0.002 -0.004m (semi-major axis) and 0.001m (semi-minor axis). The absolute and relative error ellipses also revealed large uncertainty in scale but small uncertainty in orientation (Fig. 5). The displacement vectors from the 2D adjustment between the two measuring epochs 1 and 2 are shown in Figure 5 (in red). Also, the control reference network of the five stations is depicted in the figure.

Table 1: Values for aposteriori σ_0 in 2D adjustment

monitoring epoch	aposteriori sigma
1	0.6359
2	0.3558
3	0.3531
4	0.3513
5	0.3608

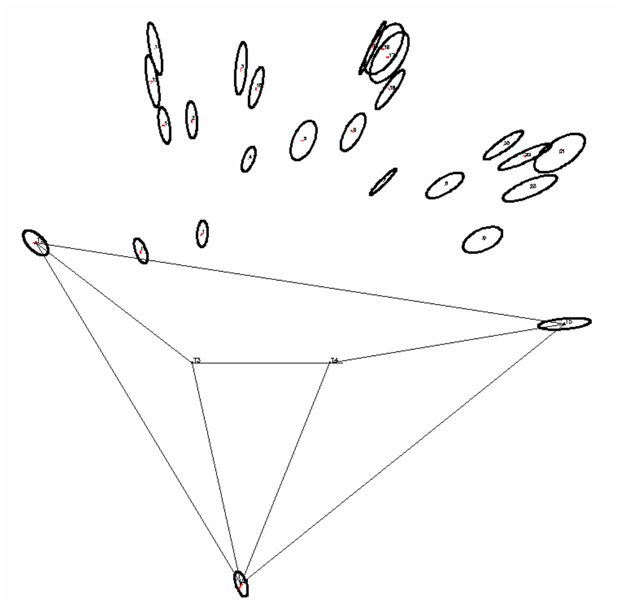


Figure 5: The displacement error ellipses between epochs 1-2

The statistical analysis for possible deformation confirmed that between epochs 1-2 and 1-5 no absolute movement was detected, whilst between epochs 1-3 two movements were detected and epochs 1-4 one movement was detected but were all within the limit of the statistical error at the 95% level. At the 97% level no movement between epochs was detected. Neither relative movement was detected between all epochs at the 95% level.

(b) Vertical control network

In each monitoring session, the number of observations, the number of independent parameters and the degrees of freedom are respectively, n = 117, m = 27 and r = 90. The aposteriori sigma σ_0 for each epoch is given in Table 2. The 1D adjustment gave a mean uncertainty of 0.001m, in all epochs (at the 95% level).

Table 2: Values for aposteriori σ_0 in 1D adjustment

monitoring epoch	aposteriori sigma
1	0.763
2	0.903
3	0.947
4	0.879
5	0.901

The statistical analysis for possible vertical deformation at the 95% level showed that between epochs 1-3 and 1-5 no absolute movement was detected, whilst between epochs 1-2 three movements were detected and epochs 1-4 one movement was detected, but were all within the uncertainty of 1mm. No relative movement was detected between all epochs at the 95% level.

(c) 3D control network

The 3D adjustment did not provide satisfactory results (mean aposteriori σ_0 in the order of 5). This can be attributed to the fact that the number of distance observations was very small within the total number of observations (3 out of 117 observations). In the last two measuring epochs the use of distance observations by reflectorless total station resulted in better aposteriori σ_0 (in the order of 1.5), however the uncertainties of the estimated parameters were greater than the separate adjustments. For this reason, the results from the 3D adjustment were not used further for the deformation analysis.

TERRESTRIAL LASER SCANNING RESULTS

Further to the conventional surveying measurements, terrestrial laser scanning was implemented for recording of the monument but also to aid in the monitoring investigation. The main advantage of terrestrial laser scanning is the enormous and dense spatial data information that is captured as opposed to the selected points that are measured by total station. Scans of the monument were acquired at two different epochs (in mid of 2008 and late of 2009). The first measurement epoch provided an initial state (null deformation) and also to check the verticality of the structure. With this aim, a full and detailed metric digital archive was obtained based on TLS. In both epochs, the terrestrial laser scanner TLS (Leica ScanStation 2) was placed at a mean distance of 20m from the object. Specifically, each scanning session comprised six scans which were acquired at a resolution of 3mm (Fig. 6).

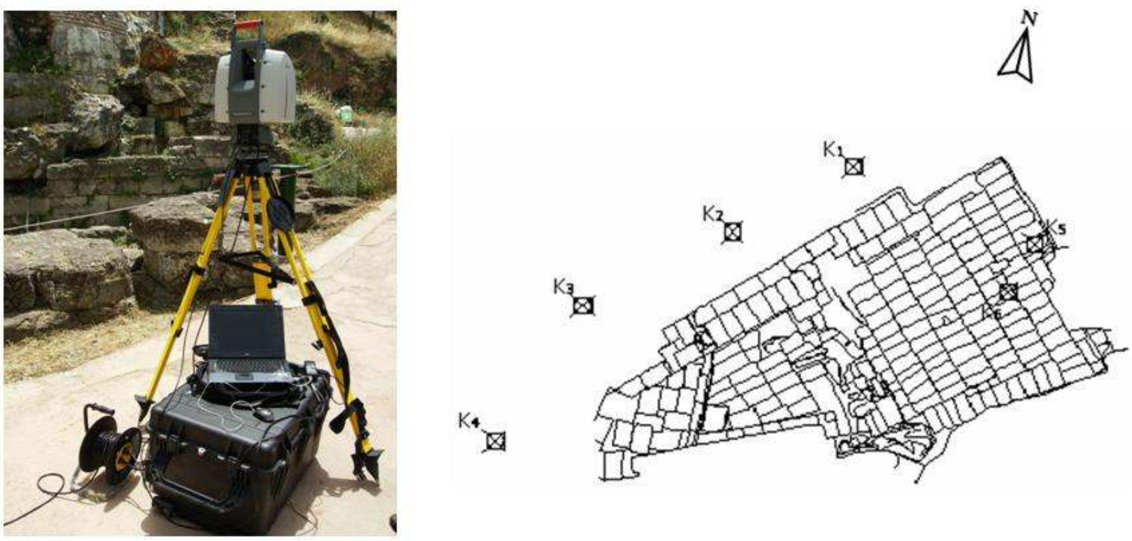


Figure 6: The scanner locations (K_1 to K_6)

Additionally, taking into account that the TLS incorporates an automatic dual axis compensator, the instrument was carefully leveled each time in order to define the vertical direction, providing a geometric constraint to check the vertical direction of the reference coordinate system.

During the scanning process and in addition to the control points discussed in section 3, special HDS retroreflective targets were placed at selected points on the monument and were measured with high accuracy at a level of 1mm. The targets provided the georeference as well as the control for comparison between the two measuring epochs. Also, special spheres recognised by the TLS were also implemented and placed out of the object of study and fixed in stable elements, such as rocks and urban furniture, in order to establish an external reference frame free of possible deformations (Fig. 7).

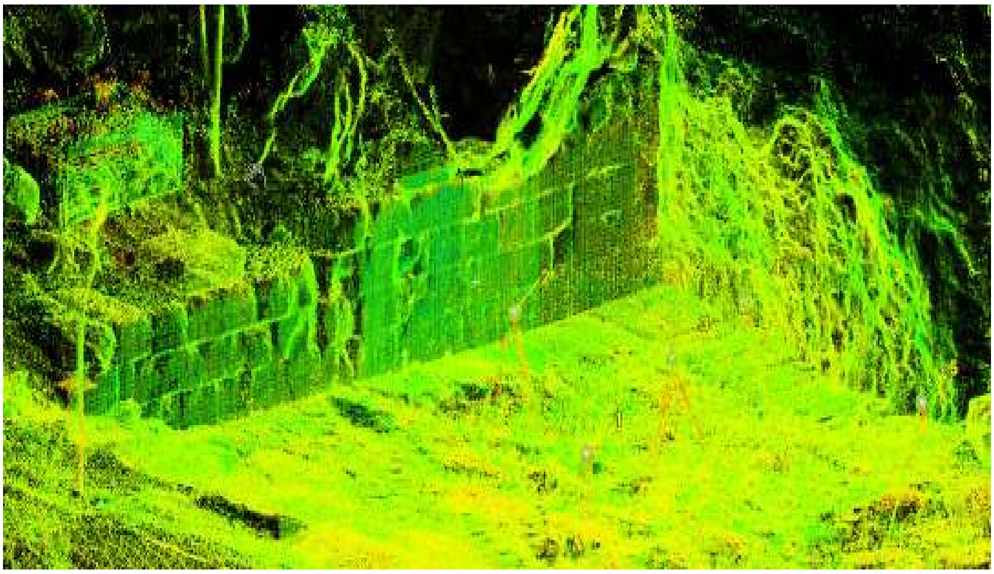
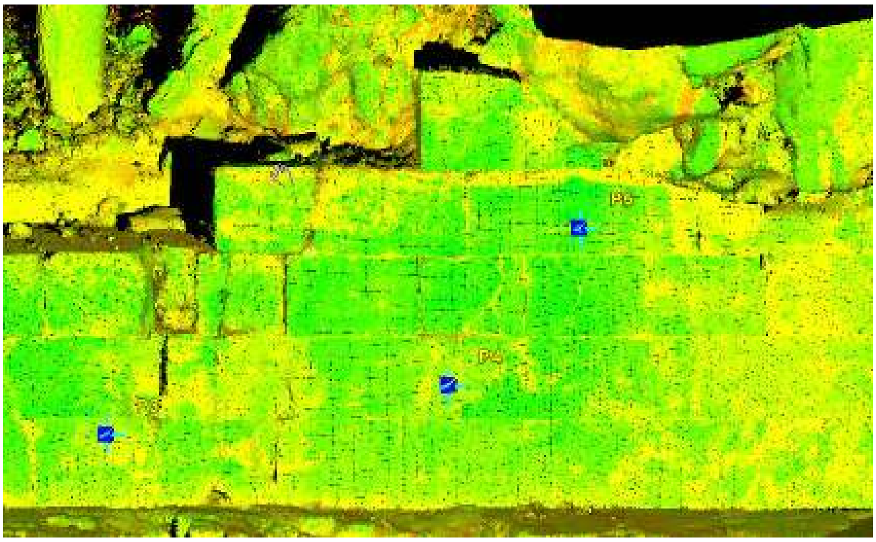


Figure 7: Use of special spheres to establish reference frame

The registration process in each scanning epoch resulted in similar values. Specifically, the RMS of the registration in the first epoch was 2mm and in the second epoch was 3mm. The second stage of the processing involved the georeferencing of both datasets and the establishment of accuracy control with a resulted value of 3mm.

The following stage involved the processing of the registered point clouds. At first, an automatic procedure is applied to remove noise and erroneous data in the point clouds. Then, the triangulation process to create a mesh of the object is performed and finally, the modelling of the surface is produced by a variety of tools, such as radial basis functions or NURBS. Figure 8a gives a typical example of an extract from the georeferenced point cloud and the resulted modelled surface of the wall (Fig. 8b).



(a)

(b)

Figure 8: (a) Point cloud and (b) texture model of the wall surface

Clearly, a deformation analysis cannot be carried out by considering points directly, even though different scans have been georeferenced into a stable and accurate reference system. This is due to the fact that the TLS cannot acquire exactly the same point in different measurement epochs, because of the imperfect repositioning of the instrument and errors of the laser beam width [2]. Thus, the next step was the application of a semiautomatic segmentation to the object of study in order to extract vertical planes which allow the study regarding the verticality of the structure and thus to check possible deformations. However, this procedure did not give reliable results because the object has a topologically complicated geometry with the presence of several defects, damages and deteriorations. Experience as described in the literature, however, has shown that the surface parameterisation of an object is possible when surfaces are relatively smooth even for large structures and monuments (e.g. [3], [4], [5]). Perhaps, a more suitable approach for the specific monument would be the implementation of FEM-based structural analysis that can make use of the digital model produced by the TLS (e.g. [6], [7]).

In this case, a comparison between the two measuring epochs was performed on the basis of the control points. When Leica retroreflective targets are available, it is possible to define the position of their centres using the software of the laser scanner. This is possible only during the data collection stage and can be estimated at a very high accuracy, in the order of 1.5mm. A direct comparison of all points between the two epochs gave differences very small differences, in the order of 0.5-1mm which is within the uncertainty of the coordinate estimation (Fig. 9).

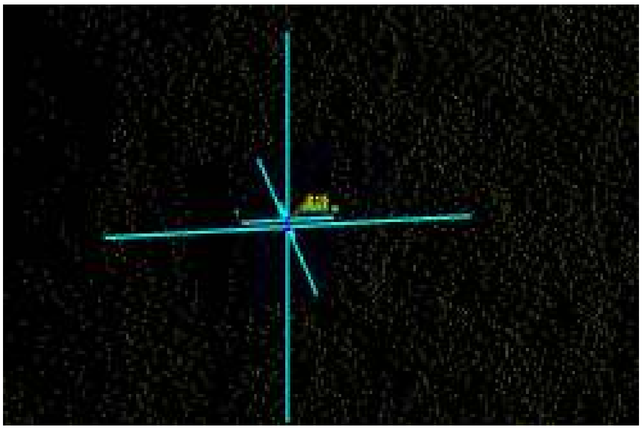


Figure 9: Difference in control point coordinate estimation

Besides the above comparison, a further comparison was made by means of a factor that shows the differences in distances between the control points provided by the TLS and the control points provided by the total station. Values close to zero suggest that the relative location of the points according to both systems is very similar. Considering that no movement was detected using the total station measurements, it can be concluded the same using the laser scanner data. Future work in this project will concentrate on fitting surfaces to non-uniformly sampled point-clouds and partial meshes that contain large irregular holes.

CONCLUDING REMARKS

This paper has presented an example of twofold employment of modern geodetic techniques for the recording as well as the structural monitoring of a cultural heritage monument. A workflow process has been tested using both conventional geodetic instrumentation of high precision and a terrestrial laser scanner to monitor the monument of Klepsydra which is the oldest water spring of the Athens Acropolis.

To this aim, the monument has been monitored for over a year by performing regular surveys. The five measuring epochs using conventional surveying gave results that showed no horizontal or vertical displacements. The two measuring epochs using the TLS gave similar results by the employment of special retroreflective targets.

The project has demonstrated that TLS is a viable technique for the structural monitoring of cultural heritage monuments that allows obtaining the geometry of the object easily regardless of its accessibility. The real possibility of acquiring dense geometric information by TLS allows the analysis through a number of different statistical and modelling approaches.

Acknowledgements

The authors acknowledge the help of Mr A. Mantis, archaeologist, and the staff of the 1st Ephorate of Prehistoric and Classical Antiquities, Hellenic Ministry of Culture.

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