

## Hephaisteion - a digital twin of the best-preserved temple of the Agora of Athens, Ancient Greece

**Robert Kayen**, Andreas Kalyvas, Mikaela Liveri, Wataru Kun, Rodrigo Corvalan, Mafe Aragon  
*University of California, Berkeley, California, USA, [kayen@berkeley.edu](mailto:kayen@berkeley.edu)*

John Papadopoulos  
*University of California, Los Angeles, USA; American School of Classical Studies at Athens, Greece.*

Tomothy Shea  
*University of North Carolina at Chapel Hill, Durham, NC, USA*

Debbie Sneed  
*California State University, Long Beach, USA*

**ABSTRACT:** The Temple of Hephaestus, located in the ancient Agora of Athens, is the best-preserved Doric-style temple of ancient Greece. Constructed between 449 and 441 B.C.E., the Temple was dedicated to the God of Metallurgy and Craftsmanship. The largely marble structure is comprised of 6 x 13 columns with an interior vestibule and rear chamber. During the early Christian period, the Temple was extensively modified. An arch was built over the cella during the Middle-Byzantine era. During the Greek War of Independence, the Temple was used as a fortress by Turkish soldiers and was heavily damaged.

The American School of Classical Studies in Athens, in collaboration with the University of California, Los Angeles, and the University of California, Berkeley, developed a hybrid digital twin model of the Hephaisteion by combining nearly 100 scan-captures of terrestrial laser scanning (TLS) data with point clouds produced by several thousand images modeled within the Structure from Motion (SfM) method using a UAV multirotor copter. Carefully placed reference reflectors and using RTK-GNSS positioning allowed for a remarkably complete and accurate registration of the entire Temple with a point position root mean square error of 0.6 cm.

This digital twin model allows us to estimate the foundation settlement of the Temple over the past 2465 years of the structure's life. Seismically displaced column sections are evident and measurable in the digital model. Rates of weathering of marble exposed to the natural weather and deposition of acid rain can be measured by analysis of the different sides of the structural columns and walls of the Temple. Much of the archaeological interest stems from the many changes to the structure over its long history. Finally, the digital twin model preserves the precise locations of each structural element of the Temple should future damage occur.

**KEYWORDS:** Temple of Hephaistos, LIDAR, SfM, point-cloud, digital-twin, water damage, earthquake damage.

### 1. BRIEF HISTORICAL ASPECTS OF THE TEMPLE OF HEPHAISTOS

The Temple of Hephaistos (Hephaisteion), situated in the ancient Agora of Athens, is among the best-preserved Doric temples of ancient Greece (Dinsmoor 1941, 1945; Dinsmoor 1976). Dedicated to Hephaistos, god of metallurgy, and Athena, patron of Athens, its exact construction date remains debated. The temenos and foundations predate the temple and were extensively excavated in the 1930s. Recent analyses (Miles and Lynch 2024) date the foundation to ~480 BCE, with superstructure completion ca. 465–460 BCE and post-426 BCE earthquake repairs.

The temple's 2,500-year history is noted by repurposing of the structure. During the Greek War of Independence (1821–1829), it served as an Ottoman fortress—damage from which remains evident in point-cloud data. In 1835, King Otto's ceremonial entrance into Athens began at the Hephaisteion, then functioning as the Church of St. George "Akamantes" (6th–10th centuries CE) (Sturm 2016; McCabe 2020). As a church, it was associated with a cemetery used primarily by foreigners (Dinsmoor, 1941). The construction date of the vaulted roof remains uncertain (Figure 1).



Figure 1. Hybrid LiDAR and SfM Point-Cloud model of the Hephaisteion and surrounding hillslope

Following independence (1830) and Athens' designation as capital in 1834, the Hephaisteion, alongside Plateia Theseiou, became a prominent cultural and archaeological site, housing the "Central Archaeological Museum" (Papadopoulos and Smithson 2002).

Constructed mainly of Pentelic marble with Parian marble accents (Thompson 1969) the temple adheres to canonical

Doric form: a peripteral layout with  $6 \times 13$  columns, pronaos, and opisthodomos. Christian modifications included an eastern arch and vaulted roof added during the Middle Byzantine era (9th/10th–13th centuries CE). As a rare, intact example of Greek temple architecture, the Hephaisteion is critical for studying Doric formalism, symbolic functions, and engineering techniques.

Doric architecture, shaped by earlier Aegean traditions, was formalized by the 6th century BCE. Defining elements include: [1] columns without bases rising from the stylobate, [2] fluted shafts with echinus and abacus capitals, [3] an architrave-frieze-entablature system with triglyphs and metopes, [4] a projecting cornice, [5] proportional refinements like entasis and corner contraction, and [6] restrained ornamentation augmented by sculptural detail.

## 1 ENGINEERING GEOMATICS

A point-cloud data campaign captured comprehensive 3D coverage of the Temple of Hephaistos from June 12–19, 2023, using Terrestrial Laser Scanning (TLS). Data were collected around the temple’s exterior, colonnade, interior Pronaos, and Opisthodomos, totaling 99 scans. As the roof was inaccessible to TLS, additional data were gathered via unmanned aerial system (UAS) imagery on July 17, 2023, and hand-held digital photography from June 8–13, 2025. A DJI Mavic II with real-time kinematic (RTK) GPS was used, with images processed via Structure-from-Motion (SfM) to integrate with the TLS point cloud.

LiDAR, a remote sensing method using laser pulses for sub-centimeter distance measurements, is ideal for archaeological surveys due to its ability to generate dense, high-resolution datasets. LiDAR produces a point cloud—georeferenced Cartesian coordinates forming the basis for 3D models. TLS data were collected with a Leica RTC 360; at high resolution, point density reached 3.1 mm at 10 m.

UAS-captured roof and elevated structural data employed SfM, which reconstructs 3D structures from overlapping 2D images by detecting shared features, estimating camera positions, and generating point clouds. SfM is particularly suited for documenting fine architectural details, excavation sites, and artifacts in archaeological contexts.

The independently registered LiDAR and SfM point clouds were merged using MapTek PointStudio. The georeferenced SfM point cloud, derived from RTK-GPS-enabled UAS data, served as the fixed reference. The LiDAR dataset was translated and rotated via least-squares optimization to achieve the best-fit alignment. Residuals—calculated along three axes between corresponding SfM and LiDAR points—determined the optimal LiDAR positioning, minimizing total error.

## 2 GEOMATIC MODEL QUALITY

The device’s internal leveling sensor adjusted data within  $\pm 18$  seconds of horizontal, achieving a 1.9 mm uncertainty at 10 m (c.o.v. = 0.00019). Scans were registered via least squares regression using Leica Cyclone, resulting in a model error of 6.0 mm (0.006 m). The final overall hybrid model maintained a  $1\sigma$  error of 6 mm.

## 3 OBSERVATIONS ON THE TEMPLE OF HEPHAISTOS

The hybrid LiDAR–SfM model assesses the temple’s structural condition and preserves architectural data. Objectives include identifying differential settlement, material

degradation, and post-construction displacement. Lampropoulos and Vomvogianni (2015) classify damage as “Special,” “Mechanical,” “Physicochemical,” and “Biological,” developing methods to evaluate movement and its causes. Issues include war impacts, Byzantine modifications, column drum displacement, marble weathering, and erosion. Examples are sarcophagus cutouts at columns six and seven (north exterior, east side), bullet impacts on the west gate’s south face, and bomb damage on the east pediment’s north section. The Temple of Hephaistos has noteworthy column offsets likely from geological and historical factors (Figure 2). Seismic activity over centuries has contributed to these misalignments (Fig. 3a and 3b; Galanopoulos, 1956; Pennethorne, 1878).

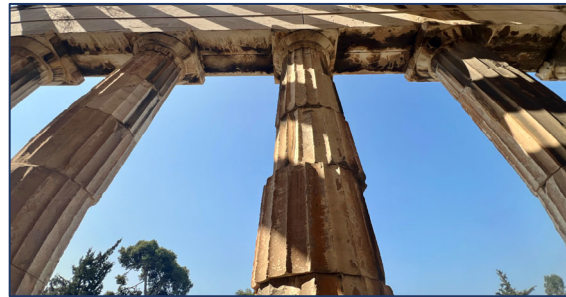


Figure 2. Example of offset and weathering damage to the interior face of columns on the south side of the Temple.

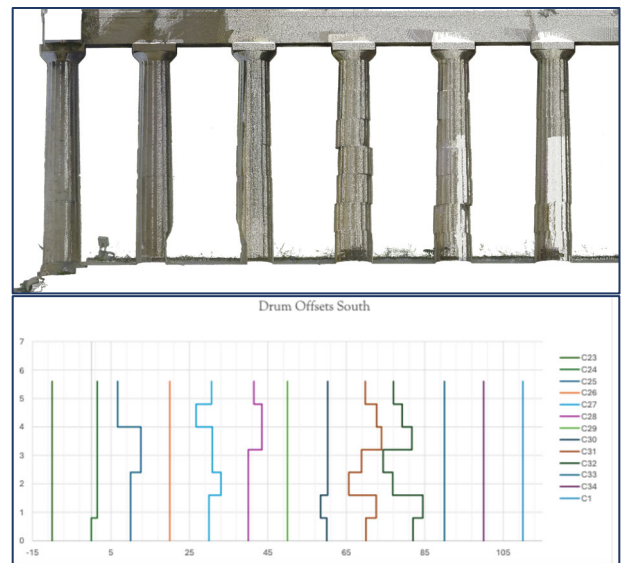


Figure 3a. Point cloud image carving space for sarcophagus and seismic-column drum offsets on the north side colonnade. 3b. exaggerated-scale measurements of the offsets looking from the inside of the colonnade.

In the mid-20th century, Athens was still considered a low-seismicity region. Offset sliding along the Temple of Hephaistos’ column drums indicates rocking during strong earthquakes (Galanopoulos 1956; Stiros 2020). Galanopoulos noted the “wave-shaped” relative offsets as signs of seismic activity near the city. Other possible earthquake-related damage includes dislocated foundation blocks and several centimeters of platform settlement. Accurate offset measurements are enabled by a precise 3D model. Offsets of every drum in the most-affected columns were recorded, and a graph showing the “trend” of displacement was produced as an exaggerated approximation of seismic movement (Figs. 3a-3b).

Weathering of the temple's stone results from exposure of walls, steps, and columns to rain, sunlight, acid deposition, and biological activity. Surface roughness is a key indicator. Based on orientation, column sides with highest and lowest temperature and rainfall exposure were identified, and roughness was measured by exporting point clouds to CloudCompare. On-site inspection found increased weathering mainly on the inner column sides, and less often on outer sides, suggesting poor stormwater drainage—not sunlight—as the main cause. The aim was to compare “inner” and “outer” roughness to identify correlations between observed weathering and computed values.

The survey of the structure in 2025 is presented in Figure 4 which shows areas visibly affected by weathering. Roughness is defined as the distance from examined points to an optimal fitting plane computed from nearest neighbors. A histogram displays the distribution of these residuals (Girardeau-Montaut, D., CloudCompare, 2025; Figure 5a-b). For instance, on Column S7, inner-side roughness is 3–4× greater than the heavily weathered outer side (Figures 5a–b). Surprisingly, results indicate increased weathering corresponds to decreased surface roughness, meaning weathering smooths the columns' surfaces.

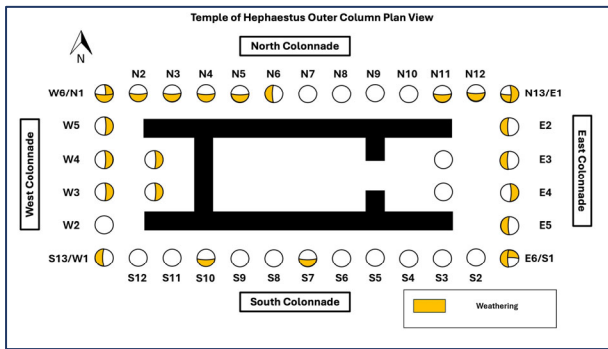


Figure 4. Parts of the columns of the Temple of Hephaistos exhibiting increased weathering

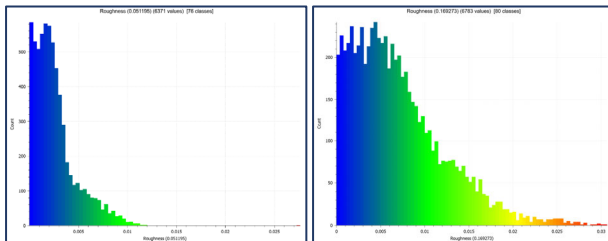


Figure 5. [a] Roughness histograms for the outer side of column S7, and [b] the inner side of Column S7.

#### 4 DAMAGE FROM THE VAULTED ROOF

Over the centuries, the Temple underwent several repurposing's, shaping its complex history. In the first millennium, the original false ceiling and wooden roof were destroyed—likely by fire—exposing the temple to the elements. This event probably occurred between the third and sixth centuries A.D. During the early Byzantine era, a segmental barrel-vaulted roof was added, its curved vault walls meeting the vertical temple walls at oblique angles. LiDAR data show the vault meets the south interior wall at 22° from vertical and the north wall at 17°, a disparity suggesting post-construction damage and displacement.

The vaulted ceiling now exhibits a 1–5 cm tension crack above the cella, most pronounced on the west end. This crack

results from the vault pushing outward on the original walls, creating tensile voids below a hidden compression pivot. The west roof is out-of-round compared to the east, indicating partial settlement. The west cella wall shows significant marble block gaps—north side displacements average 4.7 cm (1.5–11 cm) and south side 8.4 cm (6–12 cm) (Figure 6).

These displacements stem from outward wall tilting: 4.6° on the north and 8.4° on the south. The greater southern movement explains the larger vault zenith angle (21.79°) compared with the northern side (17.1°). Both are attributed to structural failure of the segmental barrel-vaulted roof.

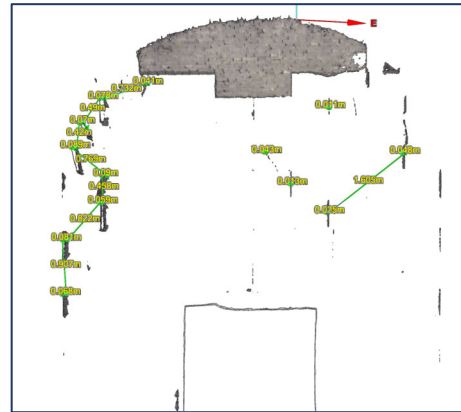


Figure 6. The pointcloud image of a 5 cm thin section within the western wall to the LIDAR scanner and the gap measurement. Open gaps in the western wall of the cella are seen as rectangular features and are the result of the roof pushing out marble blocks the cella walls.

The block displacements result from outward tilting of the temple walls—4.6° on the north side of the inner cella and 8.4° on the south. These tilts correspond to gaps in the western wall blocks, caused by outward pressure from the failing segmental barrel-vaulted roof. The greater southern tilt, double that of the north, explains the larger roof zenith angle of 21.79° versus 17.1°.

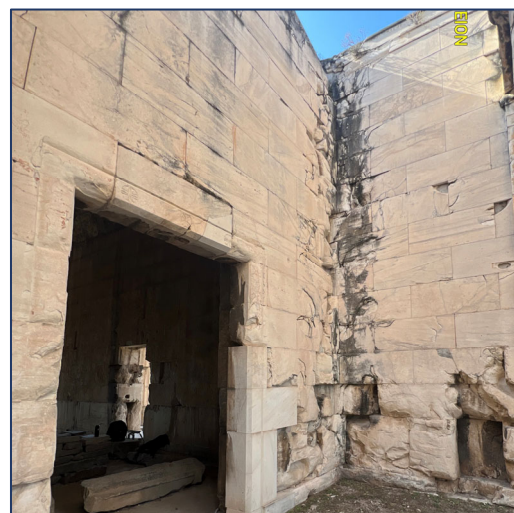


Figure 7. Photograph taken in 2025 of the water damage to the southeast corner of the west peristyle.

The mechanism of roof failure is uncertain, but static outward pressure was likely resisted by marble block interfacial friction. Earthquake-induced cyclic loads may have exceeded this frictional capacity, producing incremental permanent

displacements (Newmark, 1965; Kayen, 2017). Over roughly a millennium, these movements have damaged both roof and walls. As the zenith angle increases, outward pressure and the risk of further seismic displacement will grow, while open block gaps reduce the west wall's frictional resistance.

Significant drainage damage is also visible in the southeast corner of the western peristyle, near the southwest corner of the sloping roof (Figure 7). LiDAR-SfM data identify the source: a failed rainwater gutter at the roof eaves. The gutter, which channels water around an L-bend beyond the colonnades, is broken at the southwest edge. Point cloud analysis shows the inner gutter edge sits about 5 cm lower than the outer edge, indicating structural failure (Figure 8).

Vegetation growth within the gutter has created areas of ponding. During heavy rainfall, the water volume likely exceeds the gutter's reduced capacity, spilling into the western peristyle and accelerating block damage and erosion. As the gutter would not have existed before the roof's construction, this deterioration likely developed within the past millennium.

## 5 POTENTIALLY BENEFICIAL EFFORTS TOWARD PRESERVATION OF THE STRUCTURE

This study applies Structure-from-Motion and LiDAR techniques to create a high-precision digital twin of the Hephaisteion in Athens, Greece. Analysis reveals significant damage to the cella, peristyle, and colonnade caused by drainage failures and structural loading from the segmental barrel vault and roof. The original open-roof Athenian design offered some protection from weather and, to an extent, seismic effects. In contrast, the masonry and stone roof has enabled water infiltration, damaging exterior elements and imposing large lateral loads on the cella walls. Combined with seismic forces, these loads have pushed the walls outward, opened gaps in the west wall, created a major tension crack, and caused roof settlement into the cella.

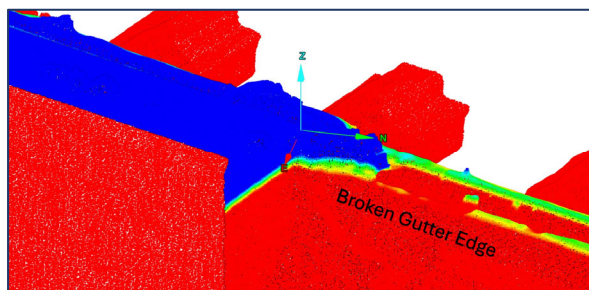


Figure 8. A spectrum color height map of the LiDAR-SfM data show a failed gutter with color ranges from blue-to-red over 8 cm. The north (interior) side of the gutter has been damaged and sits 5-87 cm lower than the opposing side.

Clearing vegetation and debris from the eaves gutter is recommended, along with repairing the southwest colonnade so the gutter's height is uniform inside and out. A more substantial solution would reconstruct the original Athenian tiled roof above the current structure, preserving Byzantine modifications while fully protecting the temple. Adequate headspace exists for such a roof, and discreet seismic restraints could be installed between the north and south cella walls to limit further lateral deformation.

By integrating LiDAR and SfM, this study produced high-resolution 3D models enabling precise measurements and visualization of column offsets, volumes, surface roughness, and overall geometry. These datasets identify key damage

patterns and demonstrate the value of combining modern sensing technologies with structural analysis to document and preserve historic landmarks.

## 6 ACKNOWLEDGEMENTS

The authors would like to thank Profs. Joe Wartman and Michael Olsen, directors of the NHERI Rapid Facility, the American School of Classical Studies at Athens, students of CE170a at UC Berkeley, and the Cotson Institute of Archaeology at UCLA.

## 7 REFERENCES

- Dinsmoor, W. B. (1941) Observations on the Hephaisteion. *Hesperia Supplements*, 5, 1-171.
- Dinsmoor, W. B. (1945) Notes on the Interior of the Hephaisteion. *Hesperia: The Journal of the American School of Classical Studies at Athens*, 14(4), 364-366.
- Dinsmoor Jr, W. B. (1976) The roof of the Hephaisteion. *American Journal of Archaeology*, 80(3), 223-246.
- Galanopoulos, A. (1956). The seismic risk at Athens. *Praktika Akadimias Athinon* 31, 464-472. (In Greek).
- Galanopoulos, A. G. (1963). On mapping of seismic activity in Greece. *Ann. Geofis*, 16(1), 37-100.
- Girardeau-Montaut, D. CloudCompare (Version 2.8.1) [GPL Software]. 2017. Availableonline: <http://www.cloudcompare.org/> (accessed on 18 June 2018)
- Kayen, R.E. (2017) Seismic Displacement of Gently Sloping Coastal and Marine Sediment Under Multidirectional Earthquake Loading, Special Issue in Engineering Geology, *Advances in Coastal Engineering Geology and Geotechnics, Engineering Geology*, Elsevier 227(2017)84-92.
- Lampropoulos, V., & Vomvogianni, C. (1999). The temple of Hephaistos in the Ancient Agora of Athens: Types of erosion and conservation propositions. *Archaeology & Arts (Archeologia & Tεχνη)*, 73, 83-90.
- McCabe, A. 2020. "Byzantine Funerary Inscriptions on the Hephaisteion (Church of Sr. George) in the Athenian Agora," in *Inscribing Texts in Byzantium: Continuities and Transformations. Papers from the 49th Spring Symposium of Byzantine Studies*, ed. M. D. Lauxtermann and I. Toth, New York, pp. 234-263
- Miles, M. M., & Lynch, K. M. (2024) The Hephaisteion in Athens: Its Date and Design. *Hesperia: The Journal of the American School of Classical Studies at Athens*, 93(2), 191-250.
- Newmark, N. M. (1965) Effects of Earthquakes on Dams and Embankments. *Geotechnique* (1965) 15 (2): 139-160. <https://doi.org/10.1680/geot.1965.15.2.139>.
- Papadopoulos, J. K., and E. L. Smithson. 2002. "The Cultural Biography of a Cycladic Geometric Amphora: Islanders in Athens and the Prehistory of Metics," *Hesperia* 71, pp. 149-199.
- Pennethorne, J. (1878) The geometry and optics of ancient architecture illustrated by examples from Thebes, Athens and Rome. By John Pennethorne, esq., assisted in the drawing and colouring of the plates and in the arrangement of the text by John Robinson, architect. Williams and Norgate.
- Stiros, S. C. (2020) Monumental articulated ancient Greek and Roman columns and temples and earthquakes: archaeological, historical, and engineering approaches. *Journal of Seismology*, 24(4), 853-881.
- Sturm, J. P. 2016. "The Afterlife of the Hephaisteion: The Interpretatio Christiana of an Ancient Athenian Monument," *Hesperia* 85, pp. 795-825.
- Thompson, W. E. (1969) The inscriptions in the Hephaisteion. *Hesperia: The Journal of the American School of Classical Studies at Athens*, 38(1), 114-118.