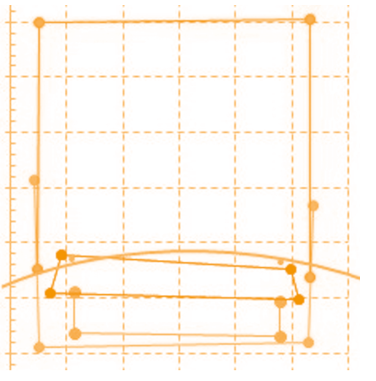
Direct sunlight in the sanctuary of Amun-Ra in the Temple of Hatshepsut at Deir el-Bahari



Abstract: This paper presents the results of astronomical calculations aimed at determining the dates when sunlight enters through skylights — openings present in the walls of the sanctuary of Amun in the Temple of Hatshepsut at Deir el-Bahari. It is also includes a report on the geodetic and astrometric measurements conducted in January and February 2015 at the temple site and in the Asasif Valley, which provided the basis for the calculations.

Keywords: Temple of Hatshepsut, Deir el-Bahari, main sanctuary of Amun-Ra, sunlight, astronomical calculations

INTRODUCTION

The Temple of Hatshepsut at Deir el-Bahari, located in the Asasif Valley, is essentially aligned with the axis of the valley itself; it is also an extension of the axis of the Karnak Temple complex on the opposite side of the Nile.

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Polish Archaeology in the Mediterranean 34.3 | Sękowski 2025: 65–77
https://doi.org/10.37343/uw.2083-537X.pam34.3.07
received 19 March 2024 | received in revised form 8 May 2024 | accepted 9 May 2024 | available online 15 November 2025

The temple complex consists of three successive terraces: the so-called lower, middle, and upper courtyards, connected by ramps (lower and upper), and crowned with colonnades (lower, middle, and upper porticoes, respectively). The upper courtyard is additionally encircled by a wall and surrounded by an internal colonnade. The natural rock wall enclosing the Asasif Valley forms the western boundary of the upper courtyard. Carved into this rock wall are three chambers, aligned sequentially along the main axis of the temple, forming the sanctuary of the god Amun-Ra. This series of chambers is accessible from the temple's upper courtyard through a short, six-column portico.

Above the entrances to the first two chambers of the sanctuary are skylights — openings that allow sunlight to reach the innermost chamber, where the statue of Amun was located. The general plan of the temple's upper courtyard and the sanctuary rooms is shown in [*Fig. 1*].

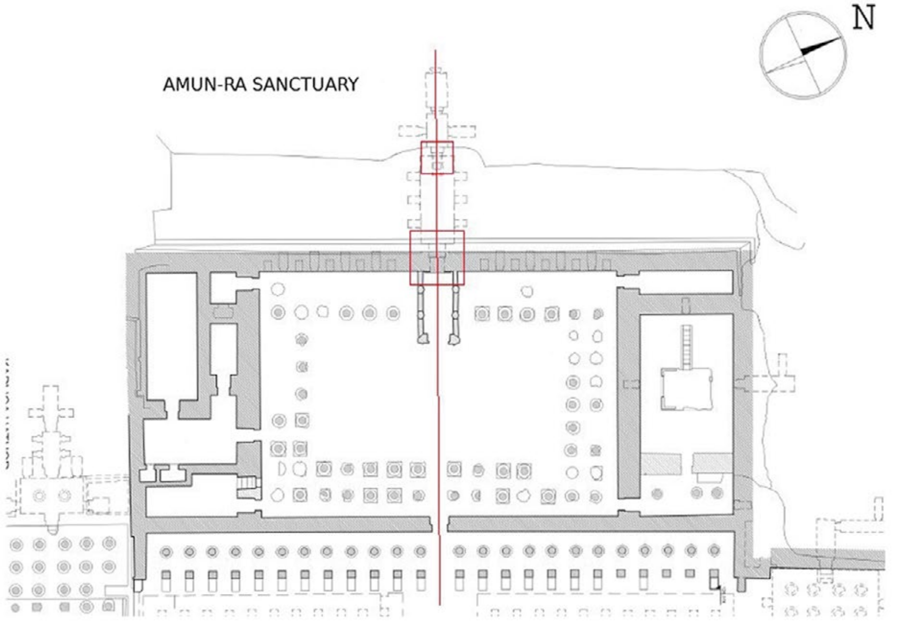

Fig. 1. General plan of the upper terrace of the temple and Amun-Ra sanctuary, indicating the openings and the main axis of the temple (PCMA UW | drawing T. Dziedzic and M. Sękowski)

DETERMINING THE ORIENTATION OF THE SKYLIGHTS' AXIS AND THE AXIS OF THE TEMPLE OF HATSHEPSUT

The basic prerequisite for determining the moments when sunlight passes through the system of openings in the sanctuary walls is to accurately establish the orientation of the axis defined by these openings. In the horizontal plane, this orientation aligns with the main axis of the temple. In order to determine the exact spatial orientation of the axis of the skylights, measurements of the local geodetic network and complementary astrometric observations were made. This approach enabled the establishment of the relationship between the position of this axis and the calculated position of the Sun. The results of these measurements also served as the basis for determining the exact size and shape of the openings themselves.

MEASUREMENT OF THE LOCAL GEODETIC NETWORK

The measurements of the local geodetic network utilized a number of existing points, previously established at various locations within the temple area and generally stabilized with metal markers (pins). This dataset was supplemented with several new permanent points, stabilized in a similar manner, as well as a number of temporary points for control and measurement quality improvement. Consequently, the coordinates of all measured points were obtained in a three-dimensional local system, which arbitrarily assumed the origin point of the system and its orientation in the horizontal plane. These coordinates, deemed sufficient for determining the geometry of the openings and the orientation of the skylight axes, formed the basis for further work. They were not transformed or linked to any other existing local or global geodetic coordinate system.

Measurements were taken using a Leica TC407 total station, with an average error of approximately 30cc (10''). A sketch of the network and a summary of the point coordinates are included in the Appendix [see below, *Tables 1, 2; Figs 9, 10*].

ASTROMETRIC OBSERVATIONS

The horizontal orientation of the local coordinate system was determined through astrometric observations, using Polaris as a reference. A series of measurements of the astronomical azimuth of the N1-N2 segment of the local geodetic network were made. The calculations used standard star time conversion tables published in sources such as the *Astronomical Yearbook* of the Institute of Geodesy and Cartography (Instytut Geodezji i Kartografii 2014), along with reduction formulas that eliminate small variations in the azimuth of Polaris. These variations, dependent on time and the observer's location, were corrected to improve accuracy. As a result of these measurements, the azimuth value $A_{(N1\text{-}N2)}$ of the N1-N2 segment was determined with an accuracy of approximately 30'':

$A_{(N1\text{-}N2)} = -43^\circ\ 19'\ 06''$

Knowing the coordinates of points N1 and N2 in the local system, and therefore the value of the angle formed by the

N1-N2 segment with the main axis of the Temple of Hatshepsut, the azimuth value of the temple's main axis A_H was calculated.

$A_H = 115° 57' 10'' \pm 30''$

Using the same measurements, the astronomical (geographic) latitude of the observation site (point N2) was also determined, yielding a value of $\phi_{N2} = 25° 43' 48''$.

Despite its much smaller value due to the internal consistency of the measurement, the error in this determination was estimated at ±20'' due to the unknown value of the deflection of the local plumb-line. By transferring the obtained value from point N2 to the upper courtyard of the temple, the value of the temple's latitude was obtained:

$\phi_H = 25° 44' 54'' \pm 20''$.

SURVEYING OF OPENINGS IN THE SANCTUARY WALLS

The measurement of the shape and size of the skylights above the main entrance to the Amun sanctuary and above the entrance from the first to the second chamber of the sanctuary was carried out simultaneously with the measuring of the coordinates of points in the local geodetic grid. The process involved determining the three-dimensional coordinates of the outlines of both skylights using a total station. Additionally, significant details of their internal shape were measured manually with a tape measure.

Both openings were measured as accurately as possible from both the outside and inside. However, their irregular shape —especially the smaller skylight above the entrance to the second chamber of the sanctuary— posed a challenge. Therefore, the measurements adopted a maximally simplified geometric description of the openings. This approach is further justified by the general uncertainty regarding the correspondence between the current state of the openings, their shape and exact location, and their historical state. The present state of the openings can be seen in the photographs [*Fig. 2*].

The results of the survey, including the simplified geometry and the three-dimensional coordinates of the points describing the openings, are presented in [*Figs 3:a–b*, *4:a–b*, and Appendix, *Table 2*].

Fig. 2. Photos of skylights in the sanctuary of the Temple of Hatshepsut: a – internal view; b – external view (PCMA UW | photo M. Sękowski)

THE PASSAGE OF SUNLIGHT THROUGH THE OPENINGS IN THE SANCTUARY WALLS

Sketches in [*Figs 3:b* and *4:b*] show the acceptable range of the sunlight angle (in the vertical plane) at which light passes through individual skylights. However, the path of sunlight is determined to a much greater degree by the geometry of the entire system of openings and obstacles —particularly their relative arrangement— than by the shapes of individual openings. The relative positions of the openings are shown in [*Figs 5, 6*]. The angular range of the Sun's altitude and azimuth, calculated from the determined geometric parameters, is $11^{\circ} < h\odot < 13.2^{\circ}$ and $113.77^{\circ} < A\odot < 117.95^{\circ}$.

Light passing through the two described openings, located above the entrances to the first and second chambers, encounters another obstacle in its path: the lintel over the entrance from the second to the third chamber of the sanctuary. This significantly further restricts the access of light to the third chamber. However, this lintel is damaged; its front

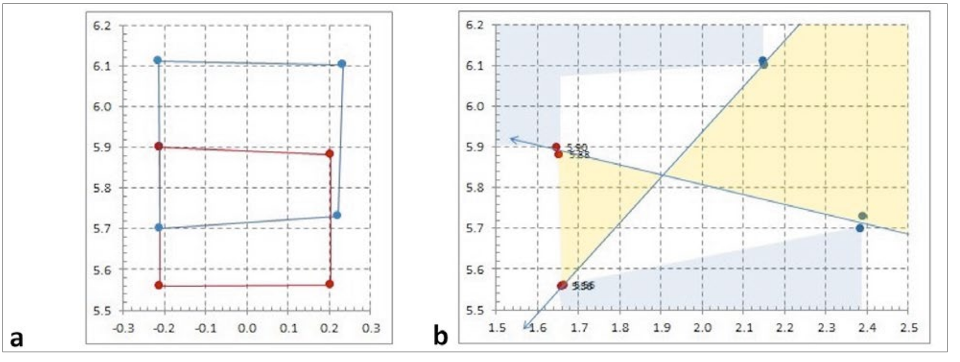

Fig. 3. Geometry of the outer skylight. Axes labeled in meters in the local coordinate system of the temple (10 cm mesh): a – view along the temple axis; b – view in the perpendicular direction (PCMA UW | drawing M. Sękowski)

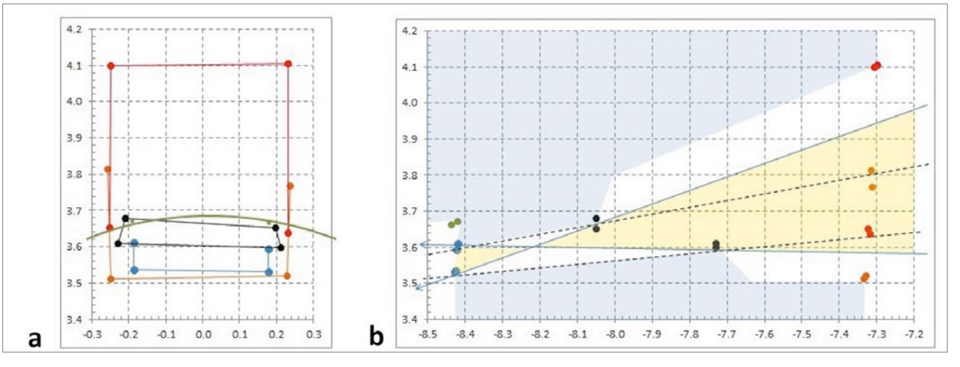

Fig. 4. Geometry of the inner skylight. Axes labeled in meters in the local coordinate system of the temple (10 cm mesh): a – view along the temple axis; b – view in the perpendicular direction (PCMA UW | drawing M. Sękowski)

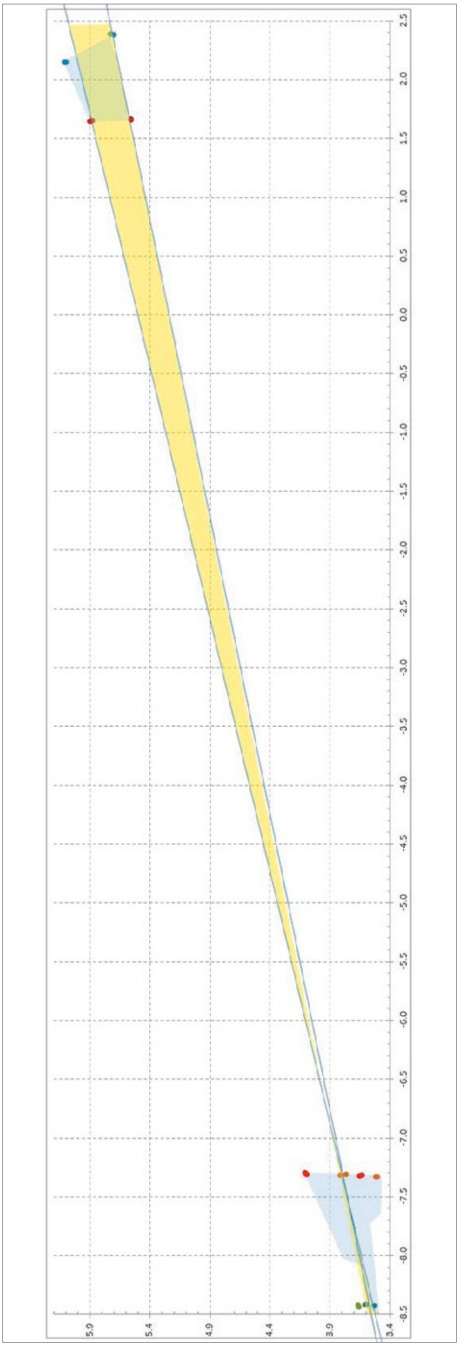

Fig. 5. Vertical cross-section of both skylights. Axes labeled in meters in the local coordinate system of the temple (sketch based on a 0.5 m mesh) (PCMA UW | processing M. Sękowski)

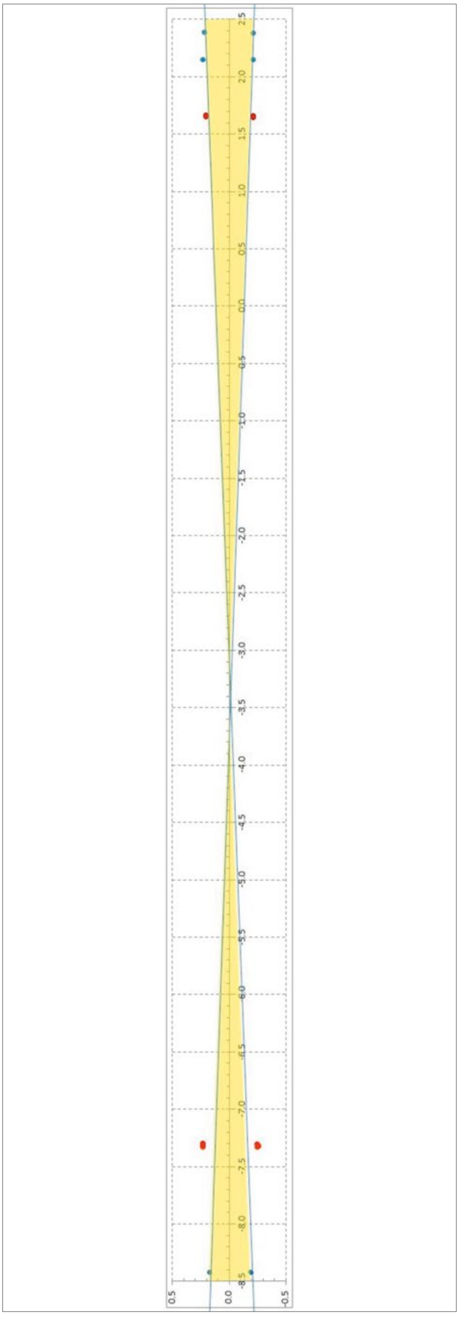

Fig. 6. Projection of the horizontal cross-section of both skylights. Axes labeled in meters in the local coordinate layout of the temple (sketch based on a 0.5 m mesh) (PCMA UW | processing M. Sękowski)

edge is irregular —chipped or scuffed— and generally lies above the line of incoming light. Only the rear edge of the lintel restricts light access to chamber III. Without investigating the cause or origin of the damage to the stone lintel beam, the angular range of the Sun's height was calculated in two scenarios. In its current state, the lintel limits the angular range of the Sun's height to $12.2^\circ < h\odot < 13.2^\circ$. In its undamaged state, it would have limited this range to $12.7^\circ < h\odot < 13.2^\circ$. The lintel does not affect the angular range of the Sun's azimuth.

POSITION OF THE SUN

The dates when sunlight entered the interior of the sanctuary through the series of skylights were determined by comparing the calculated —so-called— apparent (visible) coordinates of the Sun (expressed in the horizontal system of the observation site) with the angular range of the Sun's altitude and azimuth, as determined from measurements. The latitude of the Temple of Hatshepsut, $\phi_H = 25^\circ\ 44'\ 54''$, determined from astronomical measurements, and the longitude of the temple, $\lambda_H = 32^\circ\ 36'\ 44''$,

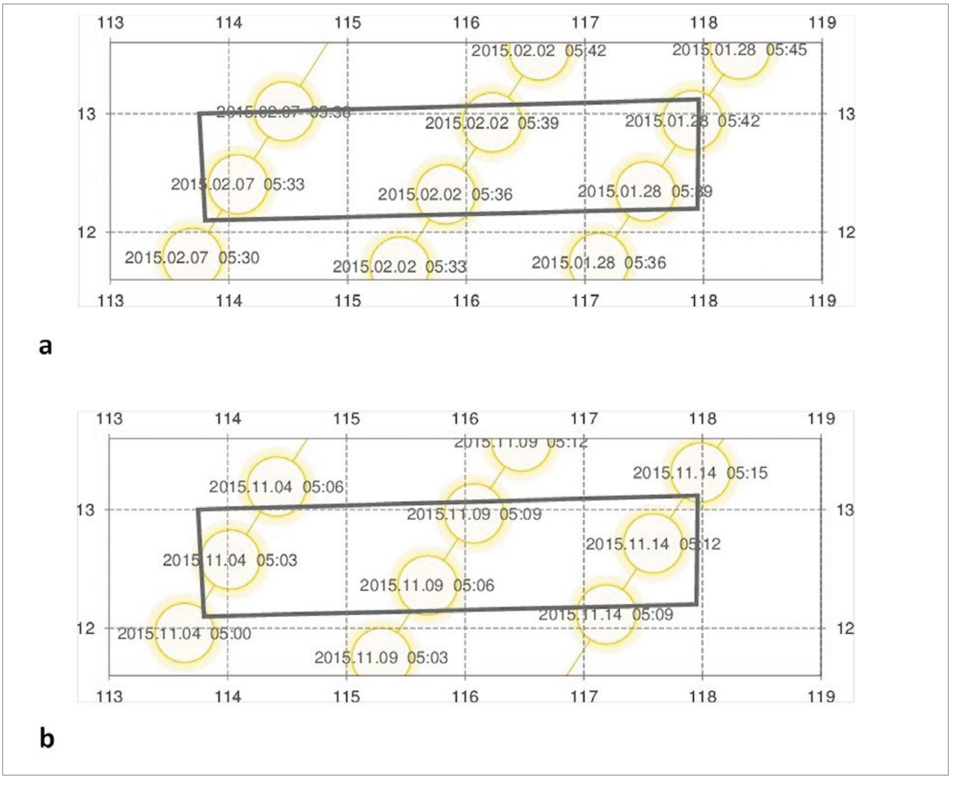

Fig. 7. Position of the Sun (altitude and azimuth) within the range that allows light to enter the third chamber of the sanctuary: a – from 28 January to 7 February 2015; b – from 4 to 14 November 2015 (PCMA UW | processing M. Sękowski)

taken from the map, were used in the calculations. The accuracy of the longitude is of much less importance for the calculation — it affects only the timing of light entry into the openings, with virtually no effect on the date of the phenomenon.

The calculations were based on a rigorous algorithm for determining the Sun's apparent position for geodetic astronomy purposes (Instytut Geodezji i Kartografii 2014), using the DE405/LE405 (Standish 1998) and, for the ancient period, the DE406/LE406 solar ephemeris data, which are a time-domain extended version of the former. The calculations accounted for the precession and nutation of the Earth's axis (based on the IAU2000 precession-nutation model (Petit and Luzum 2010)), as well as a number of factors that were not significant given the assumed low accuracy requirements of the calculations (< 30″). The effect of atmospheric refraction on the Sun's position was also taken into account.

To verify the validity of both the measurements and the calculations, the current dates for sunlight entering the sanctuary were determined. This is illustrated in [*Fig. 7*], which shows the position of the solar disk at the points where light should reach the interior of the sanctuary — seen, so to speak, from the center of the sanctuary along the axis of the skylights. The

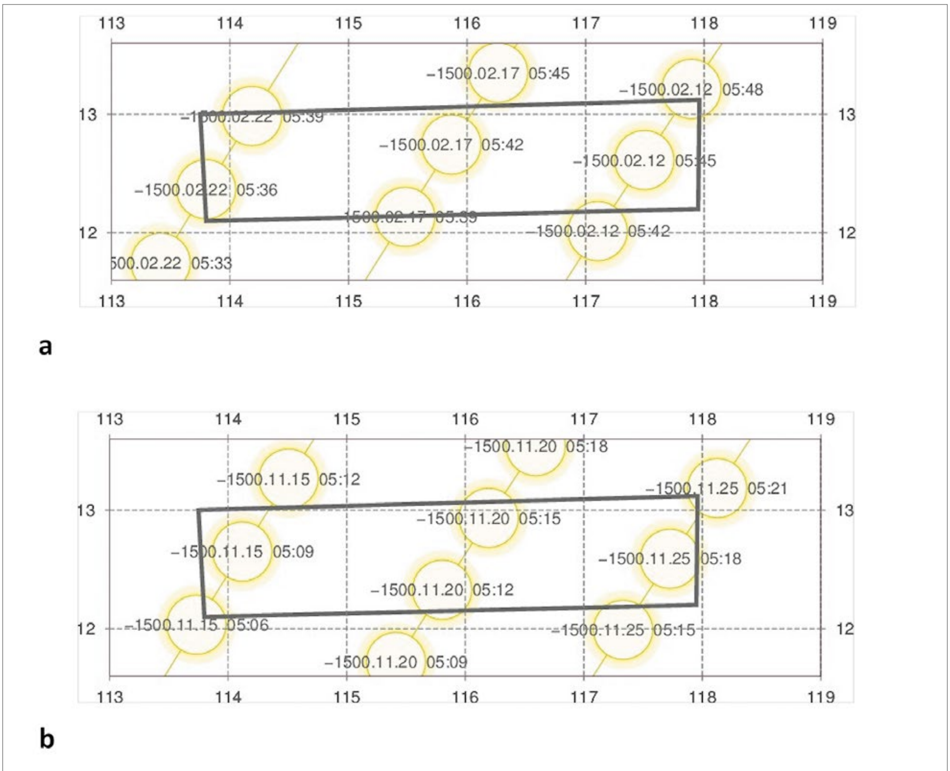

Fig. 8. Position of the Sun (altitude and azimuth) within the range that allows light to enter the third chamber of the sanctuary: a – from 12 to 22 February 1500 BC; b – from 15 to 25 November 1500 BC (PCMA UW | processing M. Sękowski)

moments when the Sun reaches these positions are also marked. The results indicate that, at present, sunlight illuminates the interior of the sanctuary for a few minutes each day between 28 January and 7 February, around 5:30 am Universal Time. These results are in agreement with the observed course of the phenomenon in nature.

Analogous calculations for the ancient period yielded the results presented in [*Fig. 8*]. The dates of the phenomena here are shifted by approximately 15 and 11 days in February and November, respectively. This shift is caused by the change in the inclination of the ecliptic relative to the celestial equator (i.e. the plane in which the Sun moves in its apparent motion across the sky relative to the Earth's equatorial plane) that occurred over a period of 3500 years.

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How to cite this article: Sękowski, M. (2025). Direct sunlight in the sanctuary of Amun-Ra in the Temple of Hatshepsut at Deir el-Bahari. *Polish Archaeology in the Mediterranean,* 34.3, 65–77. https://doi.org/10.37343/uw.2083-537X.pam34.3.07

APPENDIX: LOCAL GEODETIC NETWORK — SITUATION SKETCHES AND LIST OF COORDINATES OF NETWORK POINTS

Table 1. List of coordinates of points of the local geodetic network [***Figs 9, 10***]

Mark	x [m]	y [m]	h [m]
P1	0.00	0.00	0.00
P2	-8.80	-0.01	0.52
P3	-14.59	0.01	0.49
P4	10.88	-0.17	-0.43
P7	31.38	0.64	-0.50
P8	41.25	-0.01	-0.51
P9	29.89	30.55	5.37
P10	30.25	19.60	5.86
P11	30.51	-19.18	5.81
P12	30.49	-29.85	5.83
G1	122.15	0.09	-9.66
G2	121.56	-30.16	-9.76
G3	109.00	-59.50	-16.45
G4	112.37	-67.90	-17.07
G5	123.17	-107.30	-17.50
F	224.21	-97.54	-18.90
Z	264.86	-41.39	-19.71
N1	375.24	-228.84	-19.66

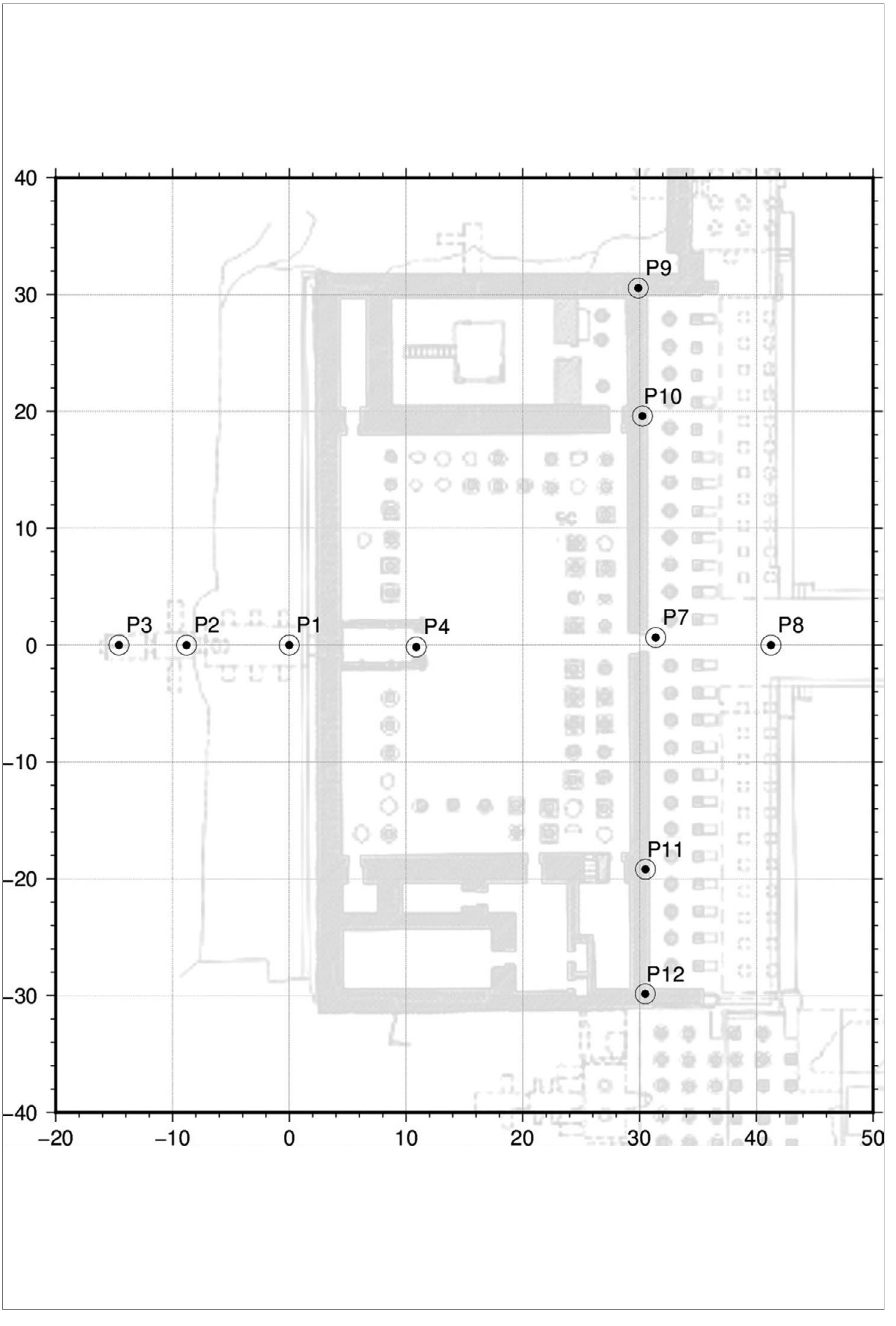

Fig. 9. Section of the network covering the upper terrace (TG) and the interior of the sanctuary (PCMA UW | drawing T. Dziedzic and M. Sękowski)

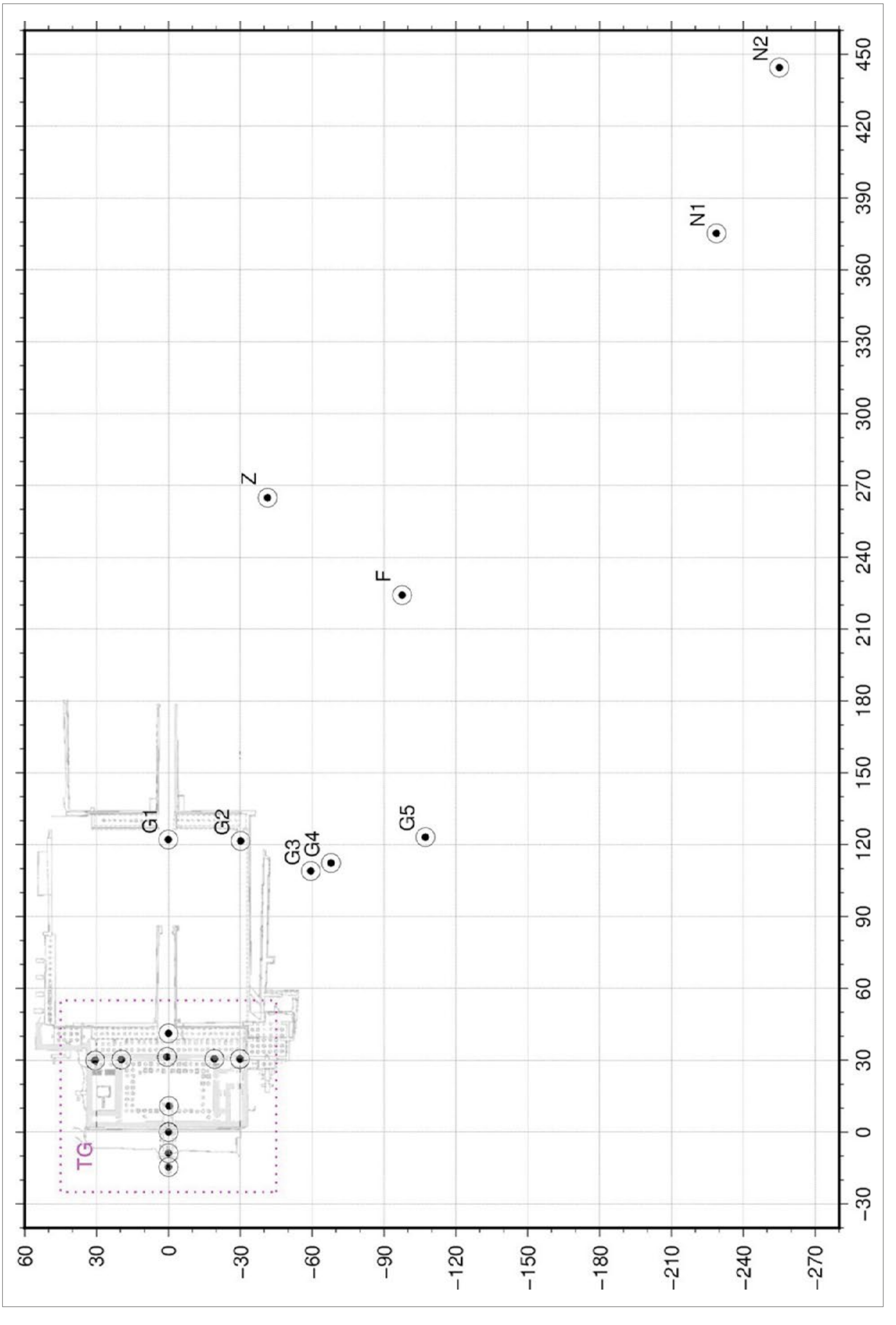

Fig. 10. General sketch of the local geodetic network (PCMA UW | drawing T. Dziedzic and M. Sękowski)

Table 2. List of coordinates of points describing the geometry of the openings: OE – external skylight, OW – internal skylight, D – lintel between the second and third chambers of the sanctuary

Mark	x [m]	y [m]	h [m]
OE1	1.65	-0.21	5.90
OE2	1.66	-0.21	5.56
OE3	1.66	0.20	5.56
OE4	1.65	0.21	5.88
OE5	2.15	0.23	6.10
OE6	2.39	0.22	5.73
OE7	2.38	-0.21	5.70
OE8	2.15	-0.21	6.11
D1	-11.93	-0.51	2.75
D2	-11.91	0.40	2.75
D3	-12.19	0.39	2.73
D4	-12.19	-0.48	2.74
OW1	-8.42	-0.19	3.61
OW2	-8.43	-0.19	3.54
OW3	-8.43	0.18	3.53
OW4	-8.42	0.18	3.59
OW5	-8.05	-0.21	3.68
OW6	-7.73	-0.23	3.61
OW7	-7.73	0.21	3.60
OW8	-8.05	0.20	3.65
OW9	-7.30	0.23	4.11
OW10	-7.31	-0.25	4.10
OW11	-7.33	0.23	3.52
OW12	-7.33	-0.25	3.51

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