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Astrogeodetic study of the orientation of ancient and Byzantine monuments: methodology and first results

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Abstract
This work presents a method for the thorough research of the orientation of monuments, based on state-of-the-art geodetic and astronomical measurements. These measurements permit the production of an astronomically-oriented, digital plan of the monument, a digital diagram of the perceptible horizon around the monument, and a digital reconstruction of the apparent path of the Sun, as it rises above the horizon at characteristic dates. The data reduction procedures are rigorous and lead to an accurate determination of the orientation of the monument. The orientation is then interpreted in terms of other, mostly cultural, information about the scope of the monument and its time of construction. In retrospect, therefore, the method provides an independent determination of the time of construction of the monument within a narrow chronological range. The effectiveness and accuracy of the method is demonstrated by its application to the late Byzantine church of the Assumption of the Virgin Mary in the Greek town of Kalabaka. The orientation of the main axis of the church is geometrically determined to an accuracy of 0.6 arcminutes. Combining all geometric data with cultural and historical information, we determine the time of construction of the church (AD 1000 ± 13 years).

Keywords: *Archaeoastronomy, orientation of monuments, chronology of monuments*

1 INTRODUCTION

Monuments belong to the cultural heritage of humanity. Scientists study them because they give information about human traces on this planet. With regard to buildings, their placement, orientation, shape, material, and the time of decoration, all give us important information about the cultural activities of a civilization (Hoskin, 2001).

In this context, religious monuments (temples) are especially valuable because their construction follows certain rules and traditions and is often connected to calendrical purposes. Religions have contributed to the development of calendars, since the positions of the Sun, the Moon, and the planets have been good time indicators (Theodossiou and Danezis, 1996). The astronomical orientation of the main axis of the temples has usually been a robust tool that has helped priests in their observations and in their efforts to achieve higher accuracy of their calendars.

Archaeoastronomy has delivered insights about the orientation of prehistoric and historical tombs, temples, and other buildings world wide. The orientation of a building towards a certain direction often reflects the way of thinking of a culture about social or religious items. Several celestial bodies were used for the orientation of buildings in many cultures, the one mostly preferred among them being the Sun. According to Malville *et al.* (1998), this rule was already followed around 6,000 BC. Hundreds of Neolithic tombs on the Iberian Peninsula, in southern France, and in the western Mediterranean dating between 7,000 and 2,000 BC clearly show a preferred orientation (see Hoskin, 2001).

As early as 1891, Sir Norman Lockyer measured the orientation of several Egyptian temples and found that some of them were oriented towards the rising Sun on the day of the celebration of the God to which they were dedicated (Papathanassiou, 1994). He found four temples oriented towards the winter solstice and two towards the summer solstice, seven to α CMa (Sirius), twelve to α Col, nine to α Cen, three to α UMa, seven to γ Dra, four to α Car, five to α Aur, and two to α Vir (see Theodossiou and Danezis, 1996). There is also no doubt that Egyptians used their astronomical knowledge for the orientation of their pyramids (Haack, 1984). The Great Pyramid at Ghiza is oriented towards the astronomical North Pole (or, equivalently, to the east) with an accuracy of better than 3 arcminutes (Spence, 2000), which enabled the determination of the year of its foundation with an accuracy of 5 years.

Papathanassiou (1994) remarks that Lockyer and Penrose investigated the orientation of ancient temples in Greece and *Magna Graecia* in 1895. She points that Penrose, in 1897, and Nissen, in 1907, determined the constellations to which many Greek temples were oriented. They also determined the dates of their foundation with low accuracy (up to eight hundred years, as proven later). The tombs of the late Minoan cemetery of Armenoi, near Rethymnon in Crete, are oriented to the arc defined by the local winter solstice, the east and the summer solstice (Papathanassiou *et al.*, 1992). Similarly, the archaic temple at Cardaki and the temple of Artemis, one kilometre to the north-west of the first one on the island of Corfou, are oriented towards the equinox (Papathanassiou, 1994). According to Dinsmoor (1939), the Parthenon of Athens is oriented towards the point where the Sun rises on the day of the celebration of the goddess Athena. It is generally accepted that ancient temples had their main entrances to the east and the statues of the deities were on the west side, looking towards the east. The axis of the temple was often defined in such a way that, on the date of the celebration of the deity, the light of the rising Sun passed through the open entrance and illuminated the statue.

Liritzis (2000) reports that rooms and sections of the palaces of the Minoan and Mycenean civilizations had their entrances preferably oriented towards the east. According to Koeberl (1983), the proper orientation of buildings was common practice in Roman Empire and early Christian times, as reported by Clement of Alexandria and Origenes.

In the Christian world, the main entrance of churches was transferred to the west and the altar to the east (*ex oriente lux*). According to the *Patrologia Graeca* (fourth century AD), churches have to be oriented to the east (Migne, 1863 and Sotiriou, 1978). Sotiriou (1978) also reports additional traditions of the Greek Orthodox Church, according to which churches have to be oriented "to the east".

The Byzantine era was one of the longest in European history lasting roughly 1,100 years. The capital of the empire, Constantinople, has often been associated with luxury and prosperity. For centuries, Byzantine architecture has demonstrated quality of construction combined with elegance, originality, and stylistic creativity. Nevertheless, the orientation of the Byzantine monuments has not been adequately investigated.

In this work, a methodology for the study of the orientation of monuments, especially Byzantine churches, is presented, along with the results of applying this method to the Byzantine church of the Assumption of the Virgin Mary, in the town of Kalabaka. The Meteora monasteries and the area of Kalabaka (Central Greece) have churches and chapels representing the cultural achievements of the last three centuries of the Byzantine State. In these centuries, the political power and influence of Byzantium was declining but, on the other hand, cultural life and scientific activities were prosperous. This is evidenced by the renaissance of the Palaiologos dynasty, which paved the way for the Renaissance in Italy a couple of centuries later.

2 METHODOLOGY

The use of modern, digital geodetic instruments for geodetic and astronomical measurements, combined with rigorous data reduction procedures, leads to the astronomical orientation of ancient or Byzantine monuments with unprecedented accuracy. This is a valuable tool for the extraction of accurate archaeoastronomical information about these monuments.

The method proposed in this work is based on the combination of four different procedures:

1) The geometric determination of the main axis or of any other special direction of the monument, which is achieved by establishing an accurate geodetic network around the monument and creating its plan.

2) The determination of the astronomical azimuth of a base of the network using observations of Polaris and transferring it, by geodetic methods, to the main axis or any other direction of the monument.

3) The geometric determination of the boundary line (silhouette) of the perceptible horizon, as seen from a specific position of the monument, through geodetic measurements.

4) The reconstruction of the apparent diurnal path of the Sun, or any other star, for characteristic dates (e.g. the celebration day of the divinity to whom the temple is dedicated, solstice, equinox etc.) related to the time of construction.

The details of the proposed method can be best understood through the following discussion of its application to the Byzantine Church of the Assumption of the Virgin Mary in the town of Kalabaka.

3 APPLICATION

3.1 The Byzantine church of the Assumption of the Virgin Mary

The church of the Assumption of the Virgin Mary is the cathedral of the town of Kalabaka. This town lies at the border of the Meteora region, by the River Peneios in central Greece. It is the gateway to the Meteora Monastic Community, since the unique paved road to Meteora passes through the town. Kalabaka appears in history in the tenth century under the name 'Stagoi' as the seat of the homonymous diocese.

According to historical sources (Sofianos, 1990, and Sotiriou, 1978), the church was founded between the eighth and the twelfth century and was dedicated to the Assumption of the Virgin Mary. It is well preserved, has two vestibules (internal and external), and in the centre a very interesting and rare pulpit of marble. On the south wall there are frescos dating from the twelfth century, while the monk Neofytos painted frescos on the church hall in 1573.

3.2 Surveying and documenting the monument

The topographic survey of the monument started with the establishment of a trigonometric network in a large area around all the churches and chapels of Meteora and Kalabaka. This network was measured by the Global Positioning System (GPS) with an accuracy of about 2 mm for the horizontal coordinates X, Y, and about 5 mm for the vertical coordinate, H. Table 1 presents the coordinates X, Y, and H of the established network, which appear in Figure 1. The coordinate H is measured in reference to mean sea level.

Table 1. Coordinates of the GPS network.

COORDINATE ADJUSTMENT SUMMARY
NETWORK = Meteora / Datum = WGS-84
Coordinate System = User-Defined Transverse Mercator (λ_0 = 24°)

Point	X (m)	Y (m)	H (m)
T0	297533.230	4398135.220	597.210
T1	296731.017	4399771.912	555.335
T2	296892.107	4399264.929	481.846
T3	296275.671	4399395.707	335.436
T4	297290.185	4397972.926	538.334
T5	296487.504	4397938.425	279.015

The establishment of such a large geodetic network is not necessary for every monument but, in this case, it was done because we wanted to place all the churches of Meteora and Kalabaka in the same official reference system.

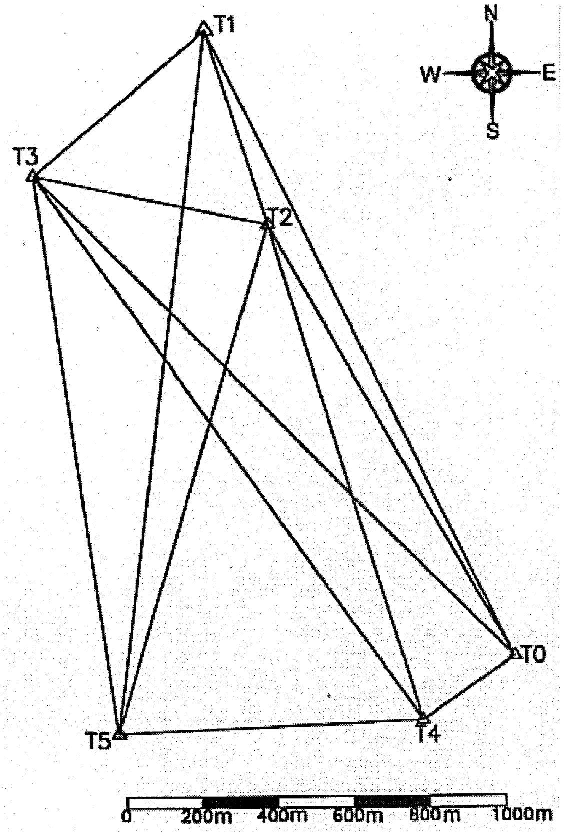


Figure 1. The GPS network.

A polygonometric network of ten points (see Figure 2) was established inside and outside the church, in order to have a view to all surfaces of the monument for the measurement of the detail points. Its elements were measured using the method of the 'three tripods', in order to eliminate the errors of centring and levelling of the instruments.

The measurements of the detail points of the church were made using an integrated Total Station that measures without a retroreflector and has a laser pointer, in order to mark each point accurately. The X and Y coordinates of each point of the monument were determined with an accuracy of ±3 mm. The orthometric heights (H) of the points were also determined with a similar accuracy. The final plan of the church is presented in Figure 3.

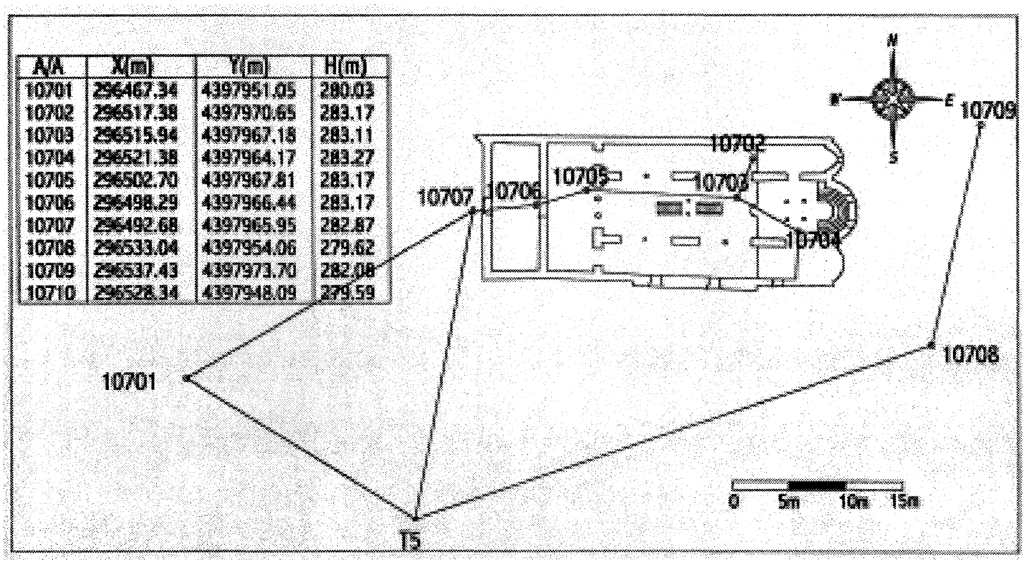
This digital plan is very useful because it permits the accurate extraction of information for all dimensions of the monument, the orientation of important directions and other construction details. The height differences between different rooms in the monument may also be easily determined.

3.3 Determination of the astronomical azimuth

In order to investigate the astronomical orientation of a monument, its plan needs to be astronomically oriented. So the astronomical azimuth of one side of the polygonometric network must be determined. This was done by observations of the Pole star (Polaris, α UMi) with a new system, consisting of the digital total station Leica TDM5000 connected to the GPS receiver Trimble 4000DL, which provides accurate UTC time.

About fifty sightings of Polaris were made in fifteen minutes, and the astronomical azimuth of one side of the polygonometric network was determined with an accuracy of ±0.5 arcsec. This accuracy is much higher than the one achieved by classical methods with poles and compass. The adjustment of the network was done holding the azimuth of this direction constant to the value of the determined astronomical azimuth. Therefore, the plan of the monument was oriented with regard to the astronomical north.

The orientation of the cathedral refers to its main axis, defined by the middle of the main entrance and middle of the altar (a distance of 26 metres). The altar is of special importance in the Orthodox Church, so its position is very well defined. The derived astronomical azimuth of the main axis of the cathedral is 90° 9′.7 ± 0′.6. This axis and its astronomical azimuth were calculated from the plan of the church, with the highest possible accuracy, and there was no need to realize it on site.



A/A	X(m)	Y(m)	H(m)
10701	296467.34	4397951.05	280.03
10702	296517.38	4397970.65	283.17
10703	296515.94	4397967.18	283.11
10704	296521.38	4397964.17	283.27
10705	296502.70	4397967.81	283.17
10706	296498.29	4397966.44	283.17
10707	296492.68	4397965.95	282.87
10708	296533.04	4397954.06	279.62
10709	296537.43	4397973.70	282.08
10710	296528.34	4397948.09	279.59

Figure 2. The polygonometric network of the Church of the Assumption of the Virgin Mary.

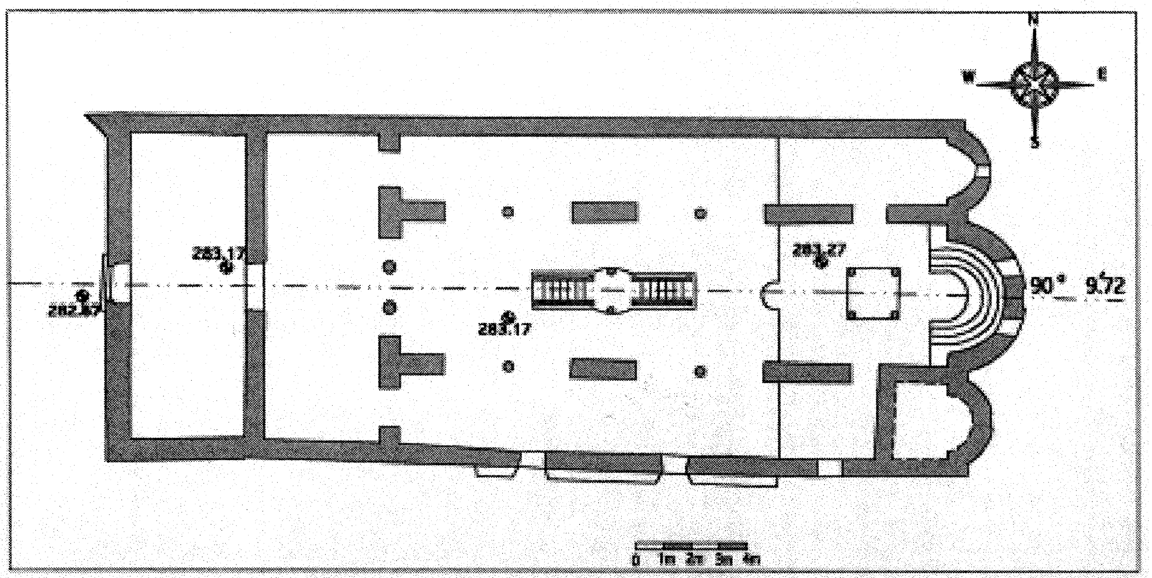


Figure 3. The plan of the Church of the Assumption of the Virgin Mary.

3.4 Determination of the perceptible horizon

A very important piece of information is the diagram of the perceptible horizon in front of the monument. The perceptible horizon is formed by the actual terrain, either natural (mountains, hills, big rocks etc.) or man-made, that is buildings that already existed at the time of construction of the monument. The diagram of the horizon is produced by measuring the azimuth and altitude of a series of points that 'silhouette' the horizon.

The measurements were done from two points of the polygonometric network. The view of the horizon as would be seen from the middle of the altar is very important, since this is the position where the priest mostly stays and performs the holy ceremony. Therefore, all measured points of the perceptible horizon (azimuths and altitudes) were adjusted to conform with the view of the horizon from the middle of the altar. This adjustment was calculated easily, since the coordinates of the points of the horizon, the network points, and the altar are all known from the geodetic network and the digital plan of the cathedral.

The final diagram of the view of the perceptible horizon to the east of the cathedral, as would be seen from the middle of the altar, is presented in Figure 4.

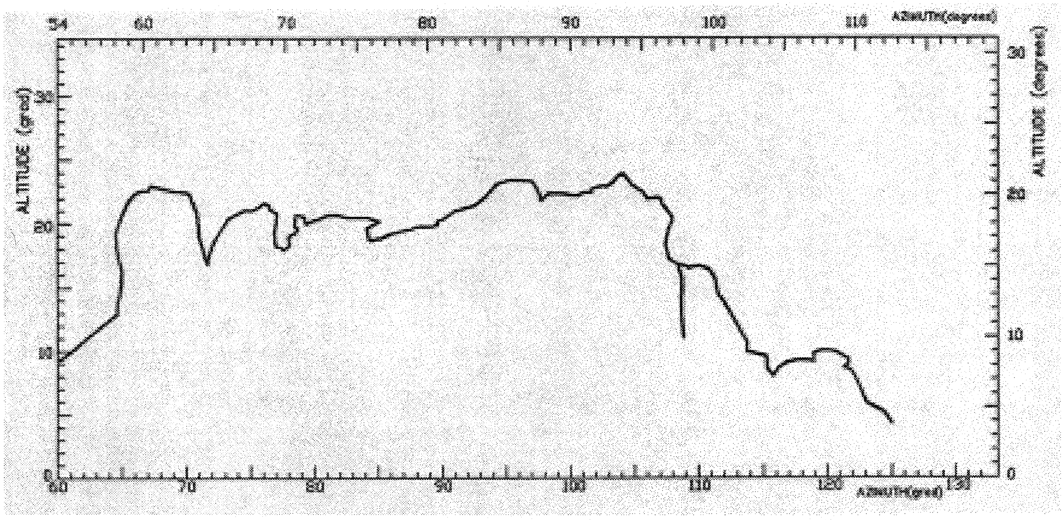


Figure 4. The diagram of the perceptible horizon of the cathedral towards the east.

The x-axis of Figure 4 shows the azimuth and the y-axis the altitude (in degrees and grads) of the horizon. The distance of the perceptible horizon from the cathedral is about nine hundred metres. The diagram of the perceptible horizon was calculated with an accuracy of about 1arcminute, due to pointing uncertainties.

As it is clearly shown in Figure 5, the huge naked rocks of Meteora dominate the eastern visible horizon.

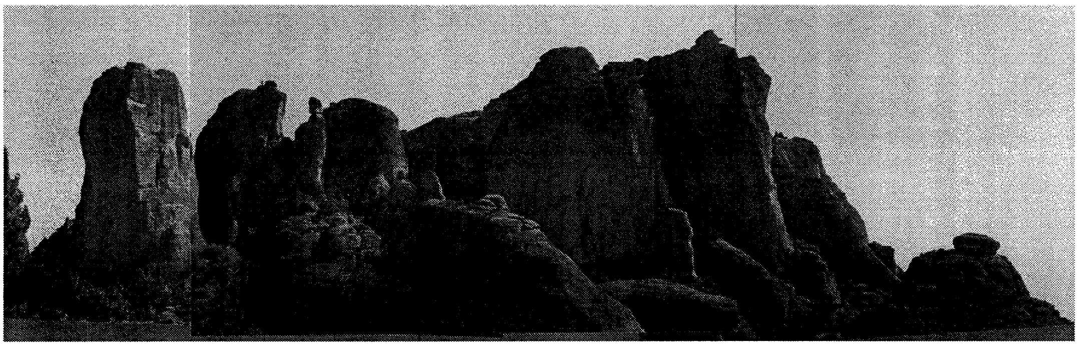


Figure 5. Photographic panorama of the eastern part of the horizon.

3.5 The path of the Sun

The apparent diurnal path of the Sun, as seen from a specific place and for a given date, was determined using available software (digital almanac & virtual planetarium SkyMap Pro 8, Marriot (2001)). Necessary input data are:

- The astronomical coordinates, φ λ, of the monument (determined with satisfactory accuracy from the GPS measurements of the geodetic network).
- The date (any date between 4,713 BC and AD 8,000) and the time interval between successive points of the position of the Sun in the sky.

A local ephemeris of the Sun is then produced, listing altitude and azimuth of the Sun (accurate to about 2 arcseconds; see Meeus, 1991) as a function of local time.

The church of the Assumption of the Virgin Mary in Kalabaka celebrates the Assumption on August 15 each year, so the calculation of the path of the Sun was performed for this date, following the Julian calendar. According to historical data, the cathedral was founded between the eighth and the twelfth century, so the path of the Sun was determined for August 15 in several years during these centuries (see Figure 6).

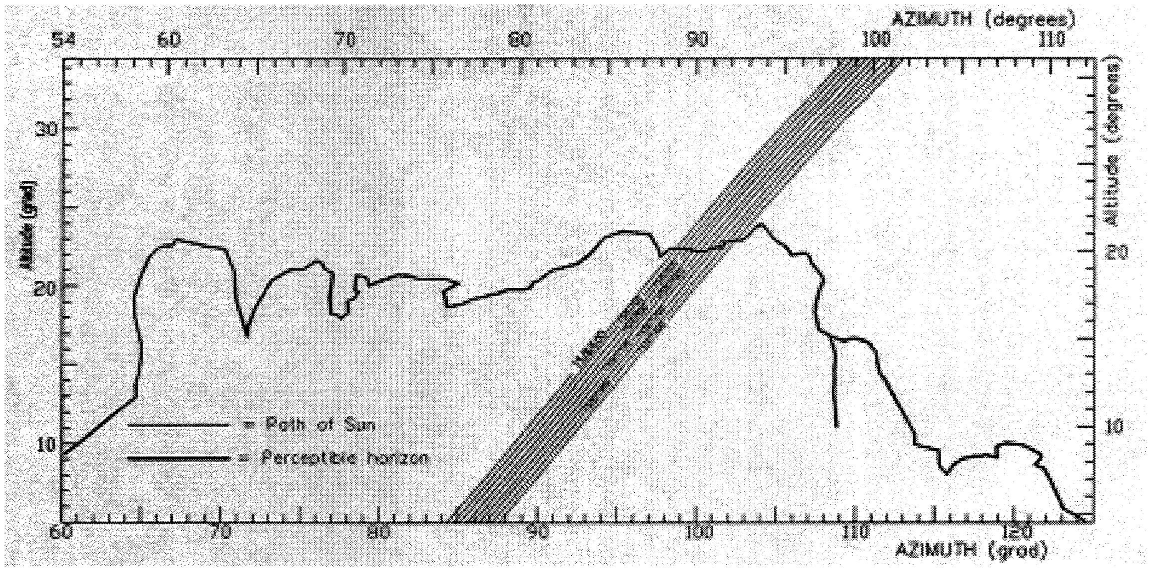


Figure 6. The apparent path of the Sun, drawn for several centuries, superimposed on the visible horizon of the cathedral of the Assumption of the Virgin Mary.

3.6 Determination of the time of foundation of the church

The orientation of a church and its time of foundation are interdependent through the apparent path of the Sun, since sunlight plays a major, symbolic role during the holy ceremony, especially on the celebration day of the church. Therefore, we compared the position of the Sun, as it was rising above the perceptible horizon, with the direction of the axis of the church for several years, always on the celebration day (August 15). This comparison is graphically shown in Figure 7, which is a combination of data from Figures 3, 4, and 6.

In this Figure one can see that the intersection of the perpendicular line representing the azimuth of the main axis of the church and of the line of the perceptible horizon almost coincides with the point of sunrise on AD 1,000 August 15. We conclude, therefore, that the year of the foundation of the church is AD 1,000 ± 13 years.

The error of this determination depends on:

- The rate of change (horizontal drift) of the apparent path of the Sun on the same day each year through the centuries. In this particular case, the drift is about 5.7 arcsec/year.
- The accuracy of the determination of the

orientation of the church. In turn, this depends on the errors of the azimuth of the axis of the church and of the diagram of the perceptible horizon. These errors are shown in the rectangular inset of Figure 7, where the dark area in the middle represents their combined effect. In this particular case, this combined error is about 73.3 arcsec.

The inclined line shows the path of the rising Sun on the date of interest. The circular inset of Figure 7 is an enlargement of the area of intersection and shows the near coincidence of the three lines for AD 1,000 August 15. The probable error in the determination of the time of construction (13 years) is derived by the ratio of the previous errors (73.3arcsec/5.7arcsec per year).

4 CONCLUSION

In the present work, we demonstrated that it is possible to determine the orientation of a monument with high accuracy using geodetic and astronomical methods. By applying the proposed method to the case of the Byzantine church of the Assumption of the Virgin Mary in Kalabaka, we also demonstrate the possibility to date a monument by the proper combination of historical, cultural, and geometric data.

In conclusion, the combination of geodetic and astronomical data, measured using modern digital total stations, allows for the determination of the orientation of a monument with high precision and reliability. Combining the above with historical data referring to the time of construction, the final interpretation of the orientation of the monument may be achieved.

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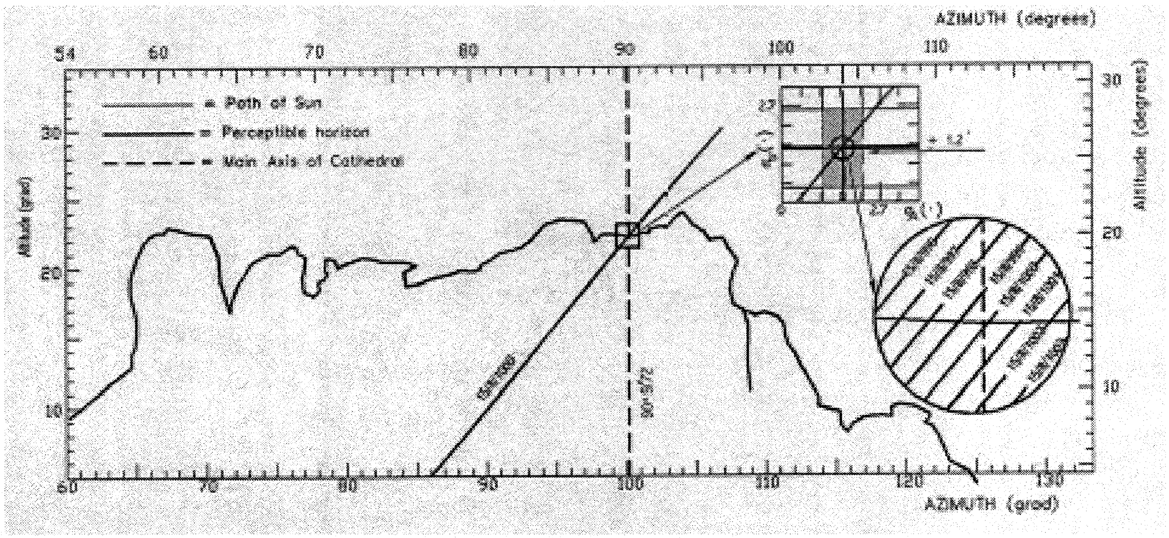

Figure 7. Determination of the time of foundation of the church.

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