A FURTHER APPLICATION OF *GOOGLE EARTH*[1] IN STUDYING THE ORIENTATION OFANCIENT GREEK MONUMENTS

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Abstract: In this paper we use *Google Earth* images to investigate the orientation of ancient Greek monuments. We examine the accuracy of the derived azimuth values, and we discuss the capabilities, advantages and restrictions of using *Google Earth* images. A comparison with the two earlier methods used for such investigations—the prismatic compass and astrogeodesy—shows that *Google Earth* is more accurate than a compass in the majority of the cases, but it is also one order of magnitude less accurate than the astrogeodetic method.

Our azimuth measurements indicate that the orientation of the Olympian Zeus temple (the Olympieion) in Athens may have been associated with the equinoxes, since according to the traditional cultural values of the Greek world the east-west line is a fundamental celestial axis of symmetry that is supposed to comply with the will of Zeus and to represent his criterion of beauty.

Keywords: History of Astronomy, archaeoastronomy, Classical archaeology, orientation of Greek temples

1 INTRODUCTION

It is widely known that Greek temples have their entrances 'in the east'. The statue of the deity stood at the west end of the *cella*, or *naos*, looking towards the light entering the temple. With some exceptions Romans followed this Greek tradition in their Empire until the fall of the old religion.

Boutsikas (2007) found that orienting religious structures, such as temples and sanctuaries, in relation to celestial objects and meteorological phenomena seems to have been a familiar concept in Greek thought. However, it was Burnouf (1847) who first argued that the determination of the astronomical orientation of a temple could be used to determine the year of its construction.

Following Burnouf's idea, during the last two centuries many researchers have determined the orientation of Greek temples (e.g., see Boutsikas, 2008; Dinsmoor, 1939, 1975; Fafoutis, 2004; Lockyer, 1894; Orlandos, 1977; Pantazis et al., 2009, 2014; and Penrose, 1894, 1897).

Some of these scholars (e.g. Boutsikas, 2008, and Pantazis, 2014), diverge from Burnouf's main point of view, and conclude that the orientation of a Greek temple was probably used to determine the beginning of certain religious festivities of the city.

Boutsikas (2007, 2008) and Hannah (2012) meticulously review studies of the astronomical orientation of Greek temples that have been made during the past two centuries, and provide comments on many of these studies. Hannah (2015) proposes that the increased refinement of Greek star calendars with a larger number of constellations might have been the result of a desire to help synchronize the divergent seasonal and lunar timetables. He also gives examples to illustrate how particular stars might have been associated with particular divinities and festivals.

Salt (2009) compared the orientation of archaic and classical Greek temples in Sicily with temples in Greece. He detected strong indications that there is a preference for solar orientations. He also found differences in alignment patterns between the Greek temples in Sicily and in Greece and suggested that these differences reflect differing tendencies in the expression of ethnic identity.

More recently García and Belmonte (2014) found that Greek temples were oriented to similar astronomical targets throughout the Mediterranean countries. They concluded that the different orientation modes, which occur among the temples in Sicily and in present-day Greece must be understood as local variations of a common pattern.

Ranieri (2014) measured the orientations of the axes and of the diagonals of 200 Greek temples, and he found 57 temples whose main axes were unequivocally cardinally oriented. Among the remaining 143 temples he found that 103 had a diagonal that was cardinally oriented, with a standard deviation of about ±2.5°. For the remaining 40 temples he found that the cardinal orientation could be attributed to the diagonals of half of the rectangle of the temple.

Finally, and in an effort to explain the northern orientation of the Epicurean and Thermios temples of Apollo in Greece, Liritzis and Vassiliou (2006) found textual evidence for the Epicurean temple of Apollo that its orientation was related to the aurorae boreales.

In the past, two methods were traditionally employed to measure the orientation of monuments: one method used a prismatic compass and the other astrogeodetic instruments. Compasses can achieve a precision of up to 1° (Boutsikas, 2008), while the astrogeodetic method has an accuracy of one arc minute (Pantazis, 2014). In their study, Castro, Liritzis and Nyquist (2015) report a compass-based accuracy of 0.5°, but this would appear to be an exceptional result. Measurements can be made with compasses and data reduced relatively quickly, whereas the astrogeodetic method is time consuming. Both methods require the physical presence of at least one researcher and their instrumentation at the site to be investigated.

2 MONUMENT ORIENTATION BY MEANS OF *GOOGLE EARTH* IMAGES

2.1 Earlier Studies

Belmonte (2009) used a *Google Earth* image in Figure 6 in his paper to show a double alignment of the temple of Hathor at Dendara. The main building was orientated close to north and possibly to the rising of Meshketyu in the late Ptolemaic period. However, the hypostyle hall of the small Isis temple located behind it was not exactly perpendicular and could have been orientated to the rising of Sothis (Sopdet), as were many other buildings at this site before it.

Klokočník, Kostelecký and Pavelka (2011) proved that *Google Earth* is a very useful tool for studying some aspects of different ancient cultures, before, during and after field measurements, thereby making these studies much easier to carry out. They used *Google Earth* images to study several ancient monuments around the globe.

Sadr and Rodier (2012) also found that *Google Earth* images along with further GIS tools justified revising maps of pre-colonial stone-walled structures in South Africa in order to study the early cultures in this landscape, following similar North American experiences.

These studies seem to later inspire Shaltout (2014) and Shaltout and Ramzi (2014) to study the orientations of ancient Egyptian temples at Luxor, using *Google Earth* satellite images. They found that the resulting azimuth values derived by the *Google Earth* and compass methods could differ by between 0.5° and 3.5°.

More recently, Castro et al. (2015) combined *Google Earth* and compass measurements to study the oracular functioning and architecture of five ancient Apollo temples. They concluded that in certain instances *Google Earth* is a useful and powerful tool.

Luo et al. (2018) provide a review of the use of *Google Earth* images for archaeological and cultural heritage applications, and they characterize *Google* Earth as a powerful tool.

Finally, Magli (2013) gives a detailed review of the very early use of *Google Earth* images for historical, archaeological and cultural heritage research.

2.2 An Azimuth Study of the Olympian Zeus Temple (the Olympieion) in Athens Using *Google Earth*

We noticed that one could repeat measurements of the orientation of a monument based on older satellite images, using the *Google Earth* 'historical imagery' option. This way, each azimuth value measured on one image can be checked for statistical consistency against the other available images, and thus the final internal accuracy of the measurements can be improved.

To test the internal consistency of the resulting azimuth of a monument by means of *Google Earth* we used all available and good-quality images of the temple of Olympian Zeus (the Olympieion) in Athens. This temple was chosen because it is large—110.35m long and 43.68m wide (Cartwright, 2015)—and its remnants are in a very good physical condition; these factors guaranteed that the internal accuracy of every single measurement would be high. Furthermore, many historical images of this temple are available on *Google Earth,* since the monument is located in the area of ancient and modern Athens that is monitored from space quite often.

Figure 1 shows a photograph of the temple of the Olympieion extracted from the *Google Earth* image of 13 April 2016. North is to the top and east is to the right. With the exception of the green line, all of the other coloured lines correspond to azimuth measurements of the temple's orientation, using the tool *line* of the *Google Earth* utility *ruler*. The yellow line gave an azimuth value of 90.01°, and the adjacent pale blue line 90.08°. The azimuth of the southern wall red line was 90.19°. We added the erroneous southern green azimuth measurement of 91.03° on purpose so as to demonstrate how difficult it is to make a stochastically erroneous measurement of even 1°. Adding to these measurements the western wall, orange coloured line, azimuth measurement of 0.06°, resulting in 90.06°, and the corresponding one of the eastern wall resulting in an azimuthof 0.00° (or a temple azimuth of 90.00°), we conclude that the final mean azimuth of the Olympieion measured internally on the *Google Earth* images of 13 April 2016 is 90.07° ± 0.03°. We then repeated this procedure for all available *Google Earth* images of this temple.

We explain here, step by step, how we got this azimuth measurement using the *Google Earth utility ruler*. We began by zooming into

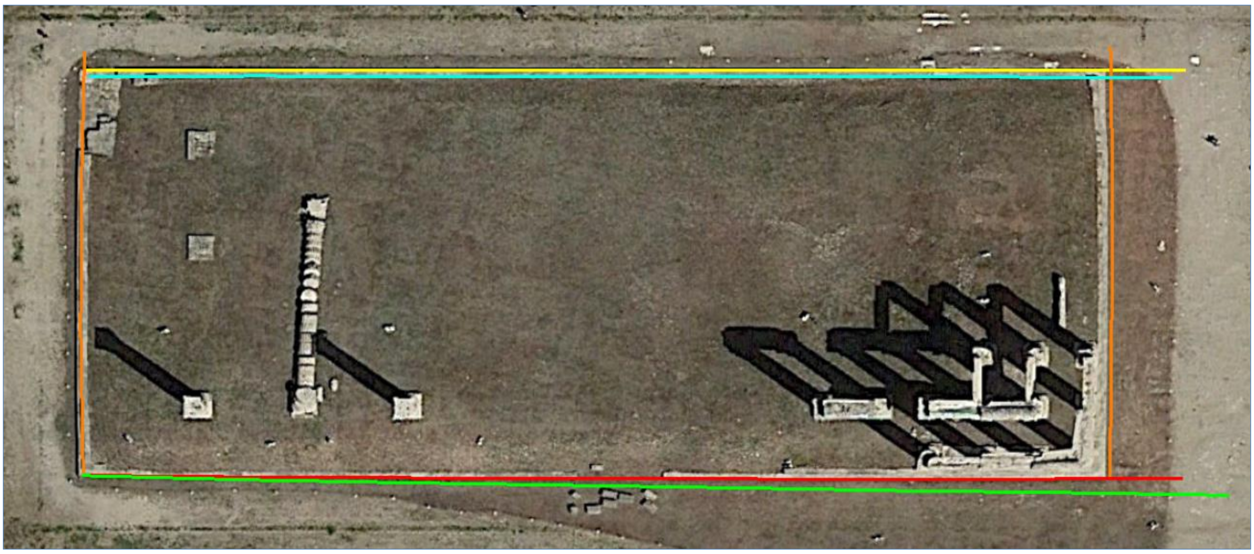

Figure 1: Ruins of the Olympian Zeus temple (the Olympieion) in Athens. The red, yellow and upper green lines indicate the directions considered as parallel or perpendicular to the axis of the monument and used in the *Google Earth* image to determine the azimuth of the Olympieion. North is to the top and west to the left. The southern green line shows an erroneous azimuth measurement of the temple, made on purpose to clearly demonstrate an azimuth deviation of just 1° from the correct value.

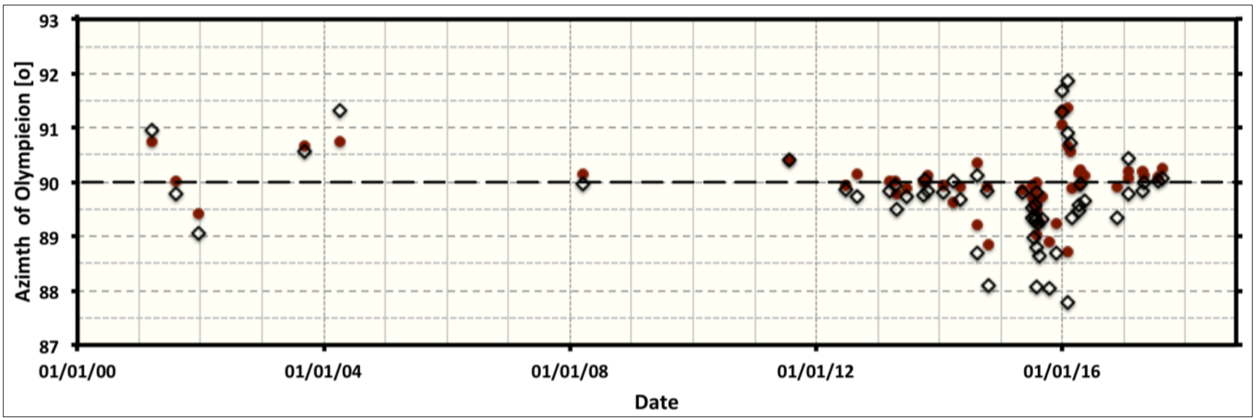

Figure 2: Azimuth measurements of the Olympian Zeus temple (the Olympieion) in Athens. The filled circles correspond to azimuths measured directly on *Google Earth* images, while open diamonds correspond to values computed after applying the corresponding O-C values.

the *Google Earth* image so that it filled our computer screen in order to be able to see most of the details of the monument contained in the image. The floor of the temple is raised above the surrounding ground in three separate levels, and this can be clearly recognized. Its sides can be used to define the azimuth of the building.

Then we activated the *Google Earth ruler* utility. By activating this utility, a ruler window opened automatically. We placed the utility marker at the north-western cornerstone point of the monument floor and we left clicked with the computer mouse to select this point. Keeping the left button of the mouse clicked, we moved the marker to the right until it fell on the north-eastern corner-stone of the monument. The ruler window showed the azimuth measurement, as well as some additional information.

We repeated the same procedure for the other three sides of the monument basement and we got three more azimuth measurements off this one *Google Earth* image. According to our experience, the azimuth measurements on each *Google Earth* image followed a normal distribution. We then calculated the mean value and standard deviation, of these measurements, as well as the standard deviation of the mean value.

We repeated the same procedure, applying it to all available *Google Earth* images. As shown in Figure 2, the azimuth estimations of different *Google Earth* images do not seem to follow a normal distribution, evidently due to internal *Google Earth* calibrations of the different images taken in different epochs often using different instruments and certainly different atmospheric conditions and orbital inclinations.

Since we do not understand the origin of the poor calibration of the orientation of some images of the same monument taken at different epochs, we did not reject any image. We then calculated the mean value of the mean azimuth

Table 1: Azimuth measurements with *Google Earth* on 56 images of the Athens Olympian Zeus temple orientation and of the axis Acropolis flagpole–Ardetos hill trigonometric control points.

Imagery Date	Az. GE	Az. O-C	Az. O	σ	Az. C	Imagery Date	Az. GE	Az. O-C	Az. O	σ	Az. C
15/03/01	113.96	-0.21	90.75 ±	0.10	90.96	21/07/15	114.37	0.20	89.58 ±	0.26	89.38
05/08/01	114.39	0.22	90.01 ±	0.02	89.79	24/07/15	114.59	0.42	89.72 ±	0.57	89.30
20/12/01	114.55	0.38	89.43 ±	0.10	89.05	27/07/15	114.35	0.18	90.00 ±	0.30	89.82
07/09/03	114.27	0.10	90.67 ±	0.09	90.57	29/07/15	114.87	0.70	89.50 ±	0.52	88.80
08/04/04	113.60	-0.57	90.75 ±	0.26	91.32	01/08/15	115.13	0.96	89.03 ±	0.58	88.07
14/03/08	114.35	0.18	90.14 ±	0.07	89.96	09/08/15	114.62	0.45	89.69 ±	0.12	89.24
22/07/11	114.16	-0.01	90.40 ±	0.06	90.41	16/08/15	114.81	0.64	89.27 ±	0.28	88.63
23/06/12	114.25	0.08	89.95 ±	0.08	89.87	03/09/15	114.59	0.42	89.73 ±	0.14	89.31
27/08/12	114.58	0.41	90.15 ±	0.10	89.74	14/10/15	115.03	0.86	88.91 ±	0.37	88.05
09/03/13	114.35	0.18	90.01 ±	0.09	89.83	24/11/15	114.70	0.53	89.23 ±	0.60	88.70
13/04/13	114.26	0.09	90.03 ±	0.06	89.94	25/12/15	113.93	-0.24	91.06 ±	0.78	91.30
25/04/13	114.45	0.28	89.78 ±	0.09	89.50	27/12/15	113.80	-0.37	91.31 ±	0.60	91.68
19/06/13	114.35	0.18	89.90 ±	0.05	89.72	29/01/16	113.66	-0.51	91.36 ±	0.40	91.87
30/09/13	114.43	0.26	90.03 ±	0.15	89.77	30/01/16	115.13	0.96	88.73 ±	0.31	87.77
09/10/13	114.13	-0.04	90.00 ±	0.08	90.04	02/02/16	113.94	-0.23	90.68 ±	0.23	90.91
23/10/13	114.46	0.29	90.13 ±	0.08	89.84	20/02/16	114.01	-0.16	90.57 ±	0.41	90.73
22/01/14	114.30	0.13	89.94 ±	0.03	89.81	23/02/16	114.70	0.53	89.88 ±	0.12	89.35
21/03/14	113.78	-0.39	89.63 ±	0.46	90.02	04/04/16	114.52	0.35	89.93 ±	0.11	89.58
04/05/14	114.39	0.22	89.91 ±	0.05	89.69	13/04/16	114.43	0.26	90.07 ±	0.03	89.81
11/08/14	114.39	0.22	90.35 ±	0.13	90.13	08/04/16	114.87	0.70	90.18 ±	0.16	89.48
14/08/14	114.69	0.52	89.21 ±	0.44	88.69	10/05/16	114.65	0.48	90.13 ±	0.20	89.65
11/10/14	114.26	0.09	89.92 ±	0.16	89.83	18/11/16	114.76	0.59	89.92 ±	0.07	89.33
18/10/14	114.92	0.75	88.84 ±	0.74	88.09	22/01/17	114.57	0.40	90.19 ±	0.10	89.79
06/05/15	114.21	0.04	89.86 ±	0.02	89.82	28/01/17	113.79	-0.38	90.06 ±	0.22	90.44
09/07/15	114.58	0.41	89.93 ±	0.52	89.52	16/04/17	114.55	0.38	90.21 ±	0.04	89.83
10/07/15	114.55	0.38	89.72 ±	0.25	89.34	27/04/17	114.29	0.12	90.12 ±	0.03	90.00
18/07/15	114.87	0.70	89.67 ±	0.32	88.97	22/07/17	114.24	0.07	90.10 ±	0.06	90.03
19/07/15	114.48	0.31	89.88 ±	0.88	89.57	18/08/17	114.35	0.18	90.26 ±	0.07	90.08
						Mean Value:	114.41	0.24	89.97	0.32	89.73
						Standard Deviation:	0.35	0.35	0.54		0.84
						Standard Deviation of the Mean:	0.05		0.07		0.11

of each image, the standard deviation of all azimuths measured on all images and the standard deviation of the mean azimuth value, as shown in Table 1.

We tried to calibrate our internal azimuth measurements by linking the *Google Earth* geographical coordinates to the Greek National Trigonometric Network of Hellenic Military Geographical Service (HMGS, 2017). The first HMGS point we used for the Olympieion was the position of the basement of the Greek flag flagpole on Acropolis Hill next to Parthenon, which serves as an HMGS trigonometric control point with coordinates 23.72797 E, 37.97183 N.

Although the HMGS trigonometric control point, alias Acropolis flagpole, is visible on most of the *Google Earth* images, this is not always the case for all control points in the Greek National Trigonometric Network. An HMGS control point is usually a cylindrical or rectangular concrete construction with approximate dimensions of 50 × 50 × 100cm^3, usually sited on the tops of hills or mountains. It is quite often the case that even the shadow of such HMGS control points is visible on *Google Earth* images. On the other hand, many of them cannot be detected on many of these images, because of many different reasons (trees, surrounding rocks,fog, clouds, etc.).

The Acropolis flagpole is regularly visited by millions of tourists every year, and is at the center of a quasi-regular octagonal yard with sides of about 3.5 meters (see Figure 3). In this photograph, one can easily see the long shadow of the flagpole towards northwest. The *Google Earth* coordinates of the flagpole appear slightly displaced on all available *Google Earth* images, and this is apparent in Figure 3.

The flagpole coordinates appear in Figure 3 to be displaced by approximately five meters in a northeasterly direction. Similar stochastically distributed displacements are observed in all *Google Earth* images without clouds or fog that include the Acropolis, and are shown in Figure 4. The mean displacement of the flagpole coordinates is 9m ± 6m, corresponding to 0.3 ± 0.2 acrseconds. Figure 4 shows that there is no trend in the data that could denote a change in the flagpole displacement with time.

For the external calibration of the azimuth measurements of the Olympieion we used the Acropolis flagpole and the trigonometric control point on Argetos Hill (23.73984 E, 37.96763 N). This axis is shown in Figure 5 by a red line. Using the HMGS data, the calculated azimuth from the Acropolis flagpole to Ardetos Hill is 114.17°, and the distance is 1140m. The corresponding azimuth measured on the *Google*

Figure 3: This is the quasi-regular octagonal yard, with about 3.5m sides, around the flagpole on the Acropolis of Athens, as it appears on the Google Earth image of 27 April 2017. The flagpole is at the center of symmetry of the octagon. Its shadow is also visible in the northwest direction. Its coordinates are 23.72797 E, 37.97183 N. One can also see many tourists on the picture. Please note that according to this Google Earth image the flagpole coordinates are displaced by approximately 5 meters, and a yellow pin indicates the point of displacement.

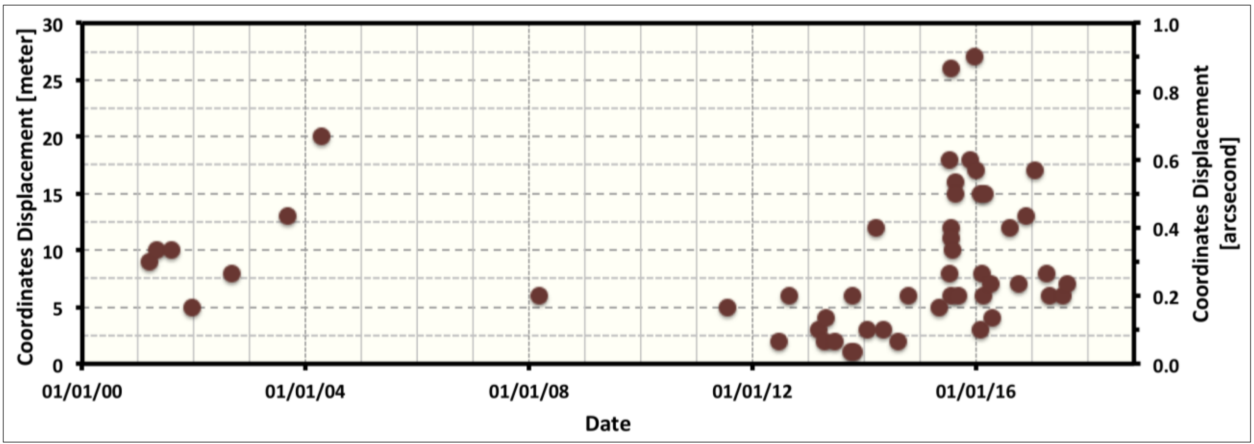

Figure 4: Displacement of the flagpole on the Acropolis in Athens, as it was measured, in meters, and computed, in arcseconds, on available *Google Earth* images.

Earth 27 April 2017 image is 114.29°.

The results of our Olympieion azimuth measurements and their calibrated values can be found in Table 1 which is split into two identical parts, namely the left and the right. Each of their lines includes the results of one of the available 56 clear *Google Earth* images. The first column contains the date of the corresponding image. The second column ('Az. GE') contains the measured azimuth of the axis defined by the two HMGS trigonometric control points, i.e. the Acropolis flagpole and Ardetos Hill. The corresponding calculated azimuth using HMGS coordinates of Ardetos Hill seen from the Acropolis flagpole is 114.17°. The difference between the observed azimuth value in column two minus the calculated azimuth (114.17°) is given in column three ('Az. O-C') for the Olympieion azimuth calibration. This is the offset correction to be applied to the azimuths measurements of the Olympieion temple, listed in column four ('Az. O'), along with the standard deviation in column five ('σ'). The difference between the values in the fourth column minus the corresponding column three contents is given in column six ('Az. C'). This value corresponds to the temple azimuth after the application of the correction, which resulted from the calibration of the orientation of the *Google Earth* images. Azimuths are given in degrees. The three bottom lines in Table 1 show mean values, standard deviations and the errors of the mean values. The mean value of the standard deviations in column five are the square root of the sum of the squares of each value, divided by

Figure 5: A photograph showing from the Acropolis flagpole to Ardetos Hill axis with Olympian Zeus temple (the Olympieion) in the middle. The axis azimuth, calculated using HMGS values and measured from Acropolis flagpole, is 114.17° and its length 1140m.

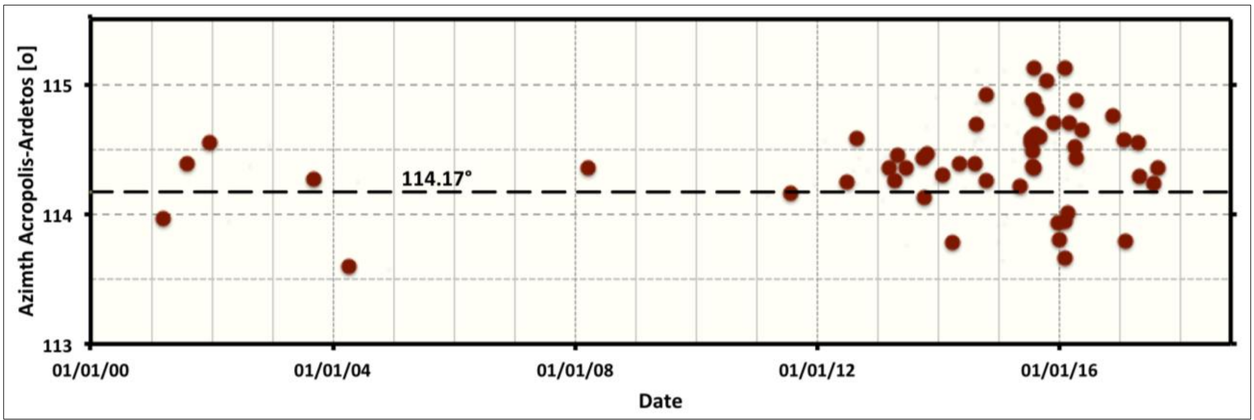

Figure 6: Azimuth measurements of the axis from the Acropolis flagpole to Ardetos Hill in Athens based *Google Earth* images. The calculated value of 114.17° (based on HMGS values) is shown by the dashed line.

56, the number of *Google Earth* images used.

Figure 6 shows the *Google Earth* azimuths of the axis defined by the two HMGS trigonometric control points Acropolis flagpole and on Ardetos Hill, listed in column 2 of Table 1. Clearly, most of the measured azimuths are larger than the calculated one of 114.17° (as shown by the dashed line), based on HMGS values, because only 11 out of the 56, O-C values are negative. Provided that the mean O-C offset value is 0.24 ± 0.35°, we conclude that the O-C values are not significantly different from zero and therefore the mean azimuth of 114.41° ± 0.35° is not significantly different from the calculated value of 114.17°.

The azimuth measurements of the Olympieion—listed in columns four and six in Table 1—are plotted in Figure 2. They correspond to azimuths directly measured on the 56 *Google Earth* images (plotted as filed circles here), and the 'calibrated' ones after the application of the corresponding O-C values from column three in Table 1 (plotted as open diamonds).

The data in Table 1 lead to the following conclusions:

(1) Provided that the mean *Google Earth* displacement of the Acropolis flagpole coordinates is 9m ± 6m and assuming that this displacement is representative for all HMGS trigonometric control points on the *Google Earth* images, the estimated standard deviation value (0.35°, in column 2) of the azimuth of the two points, the Acropolis flagpole and Ardetos Hill, at a distance of 1140m, corresponds exactly to the statistically expected azimuth error, under the condition that the errors of the positions of the two points are not correlated.

(2) The standard deviation of the Olympieion azimuths measured directly on each *Google Earth* image, and listed in column four, shows that the method presented here provides an expected orientation accuracy of 0.5° per *Google Earth* imagery.

(3) Figure 6 shows that this accuracy of each

Google Earth image orientation does not improve with time, and that there are bundles of *Google Earth* images, the azimuth estimations of which can systematically diverge by almost 1° from the final mean value and also show a maximum divergence of up to 1.5°.

(4) A comparison of the standard deviations in columns four and six proves that monument azimuth calibration using azimuth measurements of neighboring HMGS trigonometric control points does not improve the internal Olympieion azimuth measurement. Therefore, we decided to no longer use such calibrations.

(5) Our azimuth measurements show that the orientation of the Olympieion could have been influenced by the equinoxes.

2.3 Azimuth Studies of the Parthenon, Hephaisteion and the Kalambaka Virgin Mary Church Using *Google Earth*

We tried to get a first approximation of the final external accuracy of the *Google Earth* method by comparing its results to the state-of-the-art accuracy achieved by Pantazis (2014) for the Parthenon and Hephaisteion in Athens using the astrogeodetic method.

The *Google Earth* result that we obtained for the Parthenon was 77° 37′ ± 11'. Adopting Pantazis' value (77° 07′ ± 1′) as a reference we noticed that our result was the second most accurate one of the six values listed for the Parthenon in Pantazis (2014), but well behind the 77° 08′ 19″ value published by Orlandos (1977). Both Orlandos and Pantazis used the astrogeodetic method, while Boutsikas (2008) found (77° ± 1°) using a compass.

From the same table given by Pantazis (2014) we concluded that of the nine azimuth values listed for the Hephaisteion, our *Google Earth*-based measurement of 102° 53′ ± 13′ was statistically in a very good agreement with the one by Pantazis of 102° 55′ ± 1′. It was also closer to Pantazis' value than to Penrose's 1897 azimuth of 103° 06′ 02″ or Boutsikas 2008 value of 104° ± 1°, while all other values given by Pantazis were usually even less accurate.

In these two well-studied cases, our *Google Earth* azimuths deviated ≤0.5° from the recent state-of-the-art astrogeodetic values. *Google Earth* values were not only more accurate than the compass values, but they also were more accurate than all other historical measurements, even the astrogeodetic ones, listed by Pantazis.

To test the accuracy of measurements based on *Google Earth* images taken in rural and rather remote places, we measured the azimuth of the Byzantine church of the Assumption of the Virgin Mary in the Greek town of Kalambaka. The orientation of this church was measured by Pantazis et al. (2004), and its azimuth was found to be 90° 9.7′ ± 0.6′ using the astrogeodetic method. We used all six *Google Earth* images available for the church, and our measurements can be found in Table 2. The result of an F-test with 55 and 5 degrees of freedom showed that the standard deviation of 163 arcminutes for the church was much larger than the one for the Olympieion (0.54′). Therefore, the accuracy obtained by the *Google Earth* method in this case was statistically significantly lower than the corresponding value of the Olympieion case. According to the t-test, the measured azimuth of 86° 47′ was significantly smaller than the Pantazis et al. value of 90° 9.7′. This very low accuracy for the *Google Earth* method for the azimuth of the Virgin Mary church in the remote locality of Kalambaka shows the weakness of the method and it motivated us to compare azimuth values obtained with a compass and using the *Google Earth* method for other Greek temples in order to evaluate the accuracy of the two methods.

Table 2: Azimuth measurements of the orientation of the Kalambaka Virgin Mary church from six *Google Earth* images.

Image Date	Azimuth °	Azimuth ′	σ ′
04 April 2009	89	59	10
24 October 2013	85	25	72
12 October 2014	89	15	25
07 May 2015	87	38	60
07 November 2015	84	19	24
09 July 2016	83	42	54
Mean Value	86	47	
Standard Deviation	02	43	
Error of the Mean	01	07	

3 COMPARING THE ACCURACY OF THE COMPASS AND THE *GOOGLE EARTH* METHODS

We used *Google Earth* images to measure the azimuths and orientations of 43 monuments listed by Boutsikas (2008) in order to evaluate the *Google Earth* method and to check whether the low accuracy of 3° obtained for the church in the remote town of Kabambaka would occur frequently or was an exception. The results of our measurements are given in Table 3 along with the compass values by Boutsikas (in italics) for comparison. In fact, these 43 new ancient Greek temples orientations were our first results obtained using the *Google Earth* method.

Table 3 has five columns relating to the identification of the monument, its year of construction, its azimuth, the corresponding azimuth altitude of the local horizon, and the declination. Every monument takes up three rows in the Table 3, as it is described below.

The first row of the first column contains the temple identifier, which includes the name of the deity to which the temple was dedicated and the name of the place in which it was built. The second row contains the geographical co-ordinates of the temple. The geographic coordinates were taken from *Google Earth* and listed in Table 3 to quickly establish the location of the monument.

The two rows of the second column contain the year, or the century in which the temple was built for the first time: sometimes there is a second temple constructed on the remnants of the first building. The time of the construction of the newer temple is provided in the second row. The input in the second column has relatively low accuracy and should be used with care. We listed this information mainly to study a possible correlation between the year the temple was founded and its orientation; however such a correlation was not detected.

The first row of the third column shows the azimuth of the temple axis in degrees and usually in arc minutes using *Google Earth* images; the second row contains the standard deviation in arc minutes or degrees.

The fourth column shows the altitude of the local horizon point corresponding to the direction of the azimuth of the temple, in degrees. Greek temples were often built in prominent places like acropolises, on the tops of hills (e.g. the Poseidon temple at Sounion), the central square of a city (or a sanctuary), or on large flat spaces outside of, but close to, the city wall (e.g. earlier versions of the temple of Olympian Zeus in Athens). For this reason the altitude of the local horizon was usually small, up to a few degrees. Exceptions to this rule, such as for the temple of Apollo at Delphi are rare. For this special case there is a detailed study by Liritzis and Castro (2013). The height of the local horizon (altitude) of every temple has been easily computed using the *Google Earth* tool *elevation profile* on the line connecting the temple axis from the temple to the local horizon. In most cases of Greek temples, the local horizon is at a distance of several kilometers from the monument, so that the error contribution of this distance is negligible for the final error calculation of the height of the local horizon. On the other hand, even if the elevation of the temple and of the point defining the local horizon were estimated with a maximum uncertainty of 20 meters, the calculation of the height of the local horizon error would usually be <1°. But, according to Mather and Koch (2011), uncertainties for *Google Earth* are usually 5–15 meters. The method that we used to calculate the altitude of the local horizon is detailed by Castro et al. (2015: see Figures 3 and 9). Comparing, again, our local horizon altitude estimates with these published by Castro et al. (2015) we found that they generally agreed to the expected level of 1°.

Taking into account the azimuth, the altitude of the local horizon and the geographic co-ordinates of a temple, we then calculated the corresponding declination of stars rising or setting at the specific point on the visible horizon which corresponded to the temple's azimuth. Atmospheric refraction was taken into account using Bennett's (2007) formula. Declinations are given in degrees in the fifth column.

The third row contains the corresponding measurements by Boutsikas (2008) and are given (in italics) for comparison between the results obtained by compass and those derived using the *Google Earth* method, while the indication '*Boutsikas*' is given in first column.

Temples in Table 3 are ordered alphabetically according to the name of the deity mentioned in the first column. A horizontal line separates the temples from one another. A narrow empty row separates the temples dedicated to different deities to improve the readability of the Table.

Two temples in our list have not been associated with a deity yet. They are therefore appended after the temples of Zeus and separated from them by a wide empty row.

When we examine Table 3 we see that there are six cases of temples in which the two methods produce incompatible azimuths. These are discussed below.

The first double-case refers to the old and the new temples of Hera at Argos, for which Boutsikas' azimuths are 118° and 119°, while our *Google Earth* values are 106° 39′ ± 29′ and 105° 53′ ± 29′ respectively. To check the orientation of the *Google Earth* images for this region we used the two HMGS trigonometric control points (22.75138 E, 37.70820 N) and (22.78983 E, 37.68361 N), since there are two temples of Hera between them and almost on the line connecting them. The calculated azimuth of the second point seen from the first is 128.81° at a distance of 4.4km. The corresponding mean azimuth on the 17 *Google Earth* images is 128.9° ± 0.2°, proving a very accurate orientation of the *Google Earth* in this region and thus confirming the correctness of the *Google Earth* results for the orientations of the two temples of Hera in Table 2, while the corresponding compass results are >10° off.

The second case is the temple of Asclepius at Messene, for which Boutsikas' azimuth is 115° and our *Google Earth* one is 108° 20′. Here we used the two HMGS trigonometric control points (21.92658 E, 37.18559 N), at the Ithomata sanctuary of Zeus and 21.90192 E, 37.15826 N, with a calculated azimuth of 215.86° at a distance of 3.7km. The corresponding *Google Earth* azimuth was 215.6°± 0.6°, confirming the correctness of the *Google Earth* Asclepius temple orientation and the deviation of the compass by about 7°.

The third case is the temple of Apollo at Corinth for which Boutsikas' azimuth is 77° and our *Google Earth* value is 68° 50′. Using the two HMGS trigonometric control points (22.87546 E, 37.89185 N), at the temple of Aphrodite on the top of the Acrocorinthos (22.88975 E, 37.93336 N) we calculate their azimuth 15.27° and the distance of 4.8km. Our corresponding azimuth, using the available *Google Earth* images, is 15.2°± 0.3°, confirming once again the robustness of the *Google Earth* method. In this case the compass azimuth is about 8° off.

For the fourth case, the temple of Poseidon at Isthmia with Boutsikas' azimuth of 97° and *Google Earth* 87° 28′) we used the two HMGS points (23.01711 E, 37.90019 N) and (22.97861 E 37.92928 N) resulting in an azimuth of 133.63° at the distance of 4.7km. The *Google Earth* method gave 133.7°± 0.2° reaffirming our Poseidon temple azimuth and finding the compass measurement nine degrees off.

The fifth case is the temple of Zeus in Nemea. The HMGS points used were (22.71977 E 37.80307 N) and (22.68260 E, 37.82949 N) with a calculated azimuth of 131.83° and a distance of 4.4km. The azimuth measured using the *Google Earth* method was 132.1°± 0.5°. The corresponding azimuth of the temple of Zeus was 70°± 49′, while Boutsikas lists 75°. We think therefore that the compass measurement is of rather of low accuracy at >4° off.

The last case is the temple of Artemis (Apollo) at Sicyon, for which Boutsikas' azimuth of 95° is almost 5° larger than the *Google Earth* one of 90° 04′± 0.19′. Using the two easily locatable HMGS points (22.68097 E, 38.00020 N) and (22.73053 E 37.97895 N) with an azimuth of 118.43° and a distance of 5.0km, we measured with *Google Earth* a corresponding azimuth of 118.5°± 0.1°, confirming yet again the *Google Earth* result.

In these six cases (out of 43, or about 15% of all cases studied), we see that the compass can produce inaccurate azimuths, that sometimes deviate by more than 4° from the correct values and even by >10° in rare cases.

On the other hand, although the *Google Earth* method is generally much more accurate than the compass method, it has, nevertheless, its weaknesses as well: in 17 cases (40%) the final internal accuracy of the measurements was ≤1°; in 9 cases (20%) it was ≤2°; in two cases it was just 3°; and in one case it was 5°. These usually occurred in remote places such as Kalambaka, or when the ancient temple remnants were inconspicuous on the *Google Earth* images, or the temples were very small, or a combination of these factors. This is shown in the case of the temples in Dodona, Calydon, Gortys, where the accuracy of the *Google Earth* method was very low (see Table 2). In the remaining 60% of the *Google Earth* results with final internal accuracies of >1°, the median accuracy was 0.6°.

Table 3: A comparison of monument orientations measured by Boutsikas with a compass and our results using *Google Earth*.

Monument	Year (BCE)	Azimuth (degrees)	Altitude (degrees)	Declination (degrees)
Temple of Aphaea on Aegina	1· 600	69° 12′	1°	17°
(37° 45′ 15.54″ N 23° 31′ 59.61″ E)	2·· 500	±12′		
1. Boutsikas		*67°*	*1°*	*18.5°*
Temple of Aphrodite on Rhodes	3·	92° 13′	0°	-2°
(36° 26′ 45.28″ N 28° 13′ 38.50″ E)		±46′		
2. Boutsikas		*93°*	*0°*	*-3°*
Temple of Aphrodite at Dodona	4·	112°	8°	-11°
(39° 32′ 48.66″ N 20° 47′ 21.90″ E)		±2°		
3. Boutsikas		*116°*	*8°*	*-14°*
Temple of Apollo at Corinth	1· 625	68° 50′	3°	18°
(37° 54′ 21.62″ N 22° 52′ 45.09″ E)	2·· 540	±33′		
4. Boutsikas		*77°*	*3°*	*12°*
Temple of Apollo at Thermum	4·(?)	190° 33′	5°	-46°
(38° 33′ 35.60″ N 21° 40′ 05.60″ E)		±25′		
5. Boutsikas		*191°*	*5°*	*-45°*
Temple of Apollo on Naxos (Portara)	530	138° 04′	0°	-37°
(37° 06′ 36.60″ N 25° 22′ 20.93″ E)		±29′		
6. Boutsikas		*140°*	*0°*	*-38°*
Temple of Apollo at Kameiros	?	355° 55′	1°	53°
(36° 20′ 14.55″ N 27° 55′ 16.30″ E)		±27′		
7. Boutsikas		*357°*	*0.5°*	*54°*
Temple of Artemis at Calydon	?	119°	3°	-20°
(38° 22′ 19.47″ N 21° 31′ 47.35″ E)		±2°		
8. Boutsikas		*122°*	*3°*	*-22°*

Temple of Artemis Limnatis at Messene (37° 10' 43.50'' N 21° 55' 48.50'' E) *9. Boutsikas*	3°	117°39' ±15' 115°	11° *11°*	-14° *-12°*
Temple of Artemis (Apollo) at Sicyon (37° 59' 02.10'' N 22° 42' 49.30'' E) *10. Boutsikas*	6°	90°04' ±19' *95°*	2° *2°*	1° *-3°*
Temple of Artemis Orthia at Sparta (37° 04' 58.3'' N 22° 26' 06.5'' E) *11. Boutsikas*	570	99° 04' ±17' *100°*	1° *4°*	-19° *-6°*
Temple of Asclepius at Messene (37° 10' 32.14'' N 21° 55' 13.75'' E) *12. Boutsikas*	200	108° 20' ±19' *115°*	6.4° *11°*	-11° *-12°*
Temple of Asclepius at Asclepeion of Kos (36° 52' 30.85'' N 27° 15' 24.25'' E) *13. Boutsikas*	300(?)	25°8' ±27' *25°*	1° *1°*	47° *47°*
Ionian Temple at Asclepeion of Kos (36° 52' 32.80'' N 27° 15' 24.35'' E) *14. Boutsikas*	300(?)	114° ±1° *114°*	3.8° *2°*	-17° *-18°*
Temple of Asclepius at Gortys (37° 32' 23.29'' N 22° 02' 42.74'' E) *15. Boutsikas*	?	108° ±2°30' *108°*	11.2° *20°*	-7° *-1°*
Parthenon at Athens (37° 58' 17.35'' N 23° 43' 35.75'' E) *16. Boutsikas*	448	77° 37' ±11' *77°*	2° *2°*	11° *11°*
Erechtheum (Temple of Athena and Poseidon), Athens (37° 58' 19.53'' N 23° 43' 35.40'' E) *17. Boutsikas*	421	355° 54' ±34' *353°*	3° *3°*	5° *54°*
Temple of Athena at Sounion (37° 39' 10.55'' N 24° 01' 37.35'' E) *18. Boutsikas*	460-450	97° 53' ±40' *98°*	1° *1°*	-6° *-6°*
Temple of Themis at Dodona (39° 32' 49.50'' N 20° 47' 22.45'' E) *19. Boutsikas*	?	125° ±3° *129°*	7° *7°*	-21° *24°*
Temple of Athena Lindia at Lindos (36° 05' 27.72'' N 28° 05' 17.80'' E) *20. Boutsikas*	300	35°07' ±1° 14' *34°*	0° *0°*	41° *41°*
Older Temple of Athena Pronaia at Marmaria, Delphi (38° 28' 49'' N 22° 30' 30.1'' E) *21. Boutsikas*	ca. 500	173° ±2° 10' *177°*	6° *7°*	-45° *-45°*
Newer Temple of Athena Pronaia at Marmaria, Delphi (38° 28' 49'' N 22° 30' 27.6'' E) *22. Boutsikas*	370	189° 9' ±58' *190°*	3° *8°*	-47° *-43°*
Temple of Demeter on Naxos (37° 01' 45'' N 25° 25' 52.7'' E) *23. Boutsikas*	530	212°45' ±58' *213°*	0° *0°*	-42° *-42°*
Temple of Demeter at Eleusis (Telesterion) (38° 02' 27.47'' N 23° 32' 18.52'' E) *24. Boutsikas*	430	115°33' ±19' *115°*	2° *2°*	-19° *-18°*
Temple of Dione 1 in Dodona (39° 32' 50.93'' N 20° 47' 23.02'' E) *25. Boutsikas*	3°	108° ±2° 110°	8° *8°*	-9° *-10°*
Temple of Dione 2 in Dodona (39° 32' 50.52'' N 20° 47' 23.00'' E) *26. Boutsikas*	3°	174° ±2° *176°*	11° *12°*	-37° *-38°*
New Temple of Dionysus at Athens (South slope) (37° 58' 11.45'' N 23° 43' 39.95'' E) *27. Boutsikas*	340	75° 30' ±1° 10' *75°*	4° *4°*	14° *14°*
Temple of Dionysus on Naxos (37°04' 39.70'' N 25° 22' 50.''75 E) *28. Boutsikas*	14°	201°31' ±44' *203°*	4° *4°*	-44° *-44°*
Temple of Hephaestus at Athens (37° 58′ 32″ N 23° 43′ 18″ E) (Pantazis, 1014)) *29. Boutsikas*	446	102°53' ±13' *104°*	5° *5°*	-7° *-8°*

Temple of Hera (?) at Mantinea (37° 37’ 04.92’’ N 22° 23’ 33.90’’ E) *30. Boutsikas*	4°	92°27’ ±25’ *93°*	8° *8°*	3° *3°*
New Temple of Hera at Argos (37° 41’ 31.17’’ N 22° 46’ 29.96’’ E) *31. Boutsikas*	540-400	105°53’ ±29’ *119°*	3° *3°*	-11° *-20°*
Old Temple of Hera at Argos (37° 41’ 31.17’’ N 22° 46’ 29.96’’ E) *32. Boutsikas*	6°	106° 39’ ±29’ *118°*	3° *3°*	-11° *-19°*
Temple of Hera on Samos (37° 40’ 18.69’’ N 26° 53’ 07.70’’ E) *33. Boutsikas*	530	78°02’ ±12’ *79°*	0° *0.5°*	9° *9°*
Temple of Hera at Olympia (37° 38’ 19.87’’ N 21° 37’ 47.52’’ E) *34. Boutsikas*	600	86°54’ ±30’ *87°*	2° *2°*	3° *4°*
Temple of Heracles in Dodona (39° 32’ 50.47’’ N 20° 47’ 24.70’’ E) *35. Boutsikas*	3°	153° ±5° *158°*	4° *3°*	-40° *-43°*
Temple of Poseidon at Sounion (37° 39’ 00.78’’ N 24° 01’ 28.82’’ E) *36. Boutsikas*	444	104°36’ ±36’ *104°*	1° *1°*	-11° *-12°*
Temple of Poseidon at Isthmia (37° 54’ 56.68’’ N 22° 59’ 34.73’’ E) *37. Boutsikas*	700-600	87°28’ ±19’ *97°*	1° *1°*	2° *-5°*
Temple of Themis at Dodona (39° 32’ 49.50’’ N 20° 47’ 22.45’’ E) *38. Boutsikas*	?	125° ±3° *129°*	7° *7°*	-21° *24°*
Temple of Zeus at Olympia (37° 38’ 16.56’’ N 21° 37’ 48.86’’ E) *39. Boutsikas*	472- 456	82°12’ ±15’ *83°*	3° *3°*	8° *7°*
Temple of Zeus in Dodona (*Hiera Oikia*) (39° 32’ 50.17’’ N 20° 47’ 23.02’’ E) *40. Boutsikas*	3°	123°45’ ±47’ *125°*	8° *7°*	-20° *-21°*
Temple of Zeus in Nemea (37° 48’ 34.28’’ N 22° 42’ 37.53’’ E) *41. Boutsikas*	330	70° ±49’ *75°*	7° *7°*	20° *16°*
Heroon of Calydon (38° 22’21.’’35 N 21o 31’ 59.’’93 E) *42. Boutsikas*	100	180° 22’ ±1° 53’ *180°*	0.9° *0°*	-51° *52°*
Podareion at Mantinea (37° 37’ 05.76’’ N 22° 23’ 34.12’’ E) *43. Boutsikas*	?	87° 34’ ±1° 28’ *86°*	8° *8°*	7° *8°*

We checked whether sometimes the Boutsikas and *Google Earth* azimuths were statistically the same (equal mean values). In 22 cases (50%) the azimuths were the same at the 0.05 level of significance and in 30 cases (70%) at the 0.01. For the 26 most accurate cases of the *Google Earth* method, when the final internal azimuth accuracy was better than 1° the corresponding percentages were 58% (15 cases) and 77% (20) respectively. These values were computed assuming that the Boutsikas compass mean values resulted from 25 independent measurements per monument and that the final internal accuracy achieved was always 1°. If this last value is optimistic, then the above percentages obviously get larger and then more temples have statistically the same azimuths. In conclusion, at least half of the measurements by means of the two methods were statistically the same (at the 0.05 level) and up to 70% of them were very probably statistically the same (at the 0.01 level).

Apart of temple orientations, but slightly related to them, using *Google Earth* images we measured the altitudes of 28 of 258 best-known Greek mountains higher than 1000 meters. We found that the two altitudes for the same mountain were linearly correlated by the equation

$$y = 1.0127x + 2.539 \quad (1)$$

with a correlation coefficient of $r = 0.9993$, where x is the altitude measured using *Google Earth* and y the correct one, with an average accuracy of 15.3m. In the same way we also used *Google Earth* to measure the level of the Mediterranean Sea along the coast around the ancient Greek world and we found that it often differed from zero (the correct value), with a standard deviation of 3 m and an absolute value for the maximum deviation of 12 m.

4 DISCUSSION AND CONCLUSION

Upon evaluating the accuracy of the Greek temple azimuth measurements obtained using the *Google Earth* method we conclude:

(1) The internal accuracy based on one *Google Earth* image depends on the quality of the image itself, e.g. its pixel resolution, the geometrical dimensions of the monument, the quality of the monument remnants, the elevation of the Sun at the time the photograph was taken, and the transparency of the Earth's atmosphere at that time.

(2) Azimuth estimations of different *Google Earth* images seem not to follow the normal distribution, due to internal *Google Earth* calibrations of the different images taken in different epochs, using different instruments and certainly under different atmospheric conditions and orbital inclinations. There are bundles of *Google Earth* images, the azimuth estimations of which can systematically diverge almost 1° from the final mean value and which show a maximum divergence of up to 1.5°. Thus, the accuracy of each Google Earth image orientation does not seem to improve with time. We did not reject any image, and we calculated the mean value of the mean azimuth of each image, the standard deviation of all azimuths measured on all images and the standard deviation of the mean azimuth value, as shown in Table 1.

(3) In the case of the Olympieion in Athens we found that the final internal azimuth accuracy of the *Google Earth* images was usually much better than 1°.

(4) In the cases of the Parthenon and the Hephaisteion, we found that the *Google Earth* method can be even more accurate than 0.5°, and sometimes surpass the accuracy of the older historical measurements, even those made with astrogeodetic instruments.

(5) For about 60% of the newly oriented temples by the *Google Earth* method, the final internal azimuth accuracy obtained was better than 1°. In these cases, approximately 60% of the *Google Earth* and compass azimuths were statistically the same at the 0.05 level of significance and 75% of them at the 0.01 level. This proves that orientations obtained by the compass and the *Google Earth* methods are statistically the same in the majority of cases for the Greek temples that we investigated.

(6) Nevertheless there were some remote places, such as the Kalambaka Virgin Mary church, where the orientations of *Google Earth* imageries were of rather poor consistency. In such cases, the *Google Earth* azimuths were usually less accurate than the compass values, and could be as low as 3°. In these instances, we think that 4° would be very close to the lowest limit of the final azimuth accuracy of the *Google Earth* method.

(7) On the other hand, one should probably expect that 10%, or even more, of the compass results will have a much lower accuracy than 4°.

Liritzis et al (2015) found that errors in *Google Earth* compass tool computations with regard to *in situ* readings for azimuth and angular altitude were ±1–2°, which approximately agrees with our conclusions.

We believe that users of *Google Earth* images should usually expect measurement accuracies of better than 1°, which is the adopted accuracy limit of the prismatic compass. The *Google Earth* azimuths were seldom less accurate than 4°, as was the case for more than 10% of the compass results. The *Google Earth* method is applied easily and quickly, is widely available, and has no cost. It can therefore easily replace the compass and be used as a valuable tool in preliminary orientation studies and for all other cases where the highest possible accuracy is not necessary. When high accuracy is required the use of the astrogeodetic method remains mandatory.

The accuracy of the local horizon altitude in front of a Greek temple computed using the *Google Earth* method was usually 1°. However, in some situations (e.g. when there was precipitous terrain, as at Delphi) where the horizon included nearby steep terrain, the *Google Earth* method alone could not give a reliable result. Fortunately, Vlachos et al. (2018) were able to give this for the Delphi temple.

The final results of Greek temple orientations (declinations) obtained with the exclusive use of *Google Earth* images should in general be more accurate as these obtained using a compass.

Our study of the temple of Olympian Zeus (the Olympieion) in Athens shows that the temple was probably intentionally oriented with respect to the equinoxes, which is not the case for any of the other four Zeus temples listed in Table 2. The construction of the Olympieion's colossal platform was apparently begun around 520 BCE by Hippias and Hipparchus, the sons of Peisistratos, and the temple was designed by the architects Antistates, Callaeschrus, Antimachides and Pornius (Aristotle, around 340 BCE). Its axis might have been related to the equinoxes and defines the unique line of the horizontal plane that was shared by the equatorial and the ecliptic ones. Selecting this direction, Athenians very probably intended to show their highest appreciation of and respect for the king of the Olympian Gods who ruled over the Earth and the heavens.

One could interpret this special orientation of the Olympieion by considering the fundaments of the Greek culture, for which geometry was one of its major pillars. The geometrical element of symmetry gives to the Greek works their characteristic sense of harmonious and beautiful proportions and balance. The east-west direction divides the path of yearly solar rising and setting points on the horizon into two symmetrical sectors. Therefore, this line has been a major celestial axis of symmetry, complying with the most important Greek ideals concerning beauty and cultural values.

The Greek passion for symmetry was also confirmed by Pantazis (2014) who found that the two largest temples in ancient Athens, the Parthenon and the Hephaisteion, were oriented in and east-west direction with an astronomical orientation of their main axis to 77° 07′ ± 1′ to the north-east and 102° 55′ ± 1′ to the south-east respectively.

On the other hand, in ancient Greek religion Zeus was the god who ruled as the king of gods. For the Athenians in the era of Peisistratus the east-west axis of fundamental celestial symmetry was the main element of harmony and beauty honoring Zeus. Therefore the Athenians respectfully oriented the axis of his new temple, the Olympieion, to these cardinal directions.

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