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Investigation on the Accuracy of Existing Qibla Directions of the Mosques from Different Periods: A Case Study in Çorum City, Turkey

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Abstract: The main goal of this study is to introduce two different approaches (i.e. based on spherical trigonometric formula and using sun qibla time) that can be used to determine the qibla directions of the existing mosques were oriented with sufficient accuracy according to Islamic criteria. In order to do this, eight mosques which were constructed in different periods, 14th, 16th, 17th and 21st centuries in Çorum City, Turkey, were handled. The existing qibla directions of each mosque were calculated with spherical trigonometric formula and compared with the precisely calculated real qibla directions. The existing qibla directions of the same mosques were once more compared with the real qibla directions which were determined by using the qibla time calculated based on the location and the time of the measurement. The results show that the qibla directions of the recently built mosques were oriented to Kâ'ba with higher accuracy while the earlier with more deviations. However, the results show that all the deviations were at acceptable levels in terms of Islamic criteria.

Keywords: GNSS; mosque orientation; qibla determination; sun qibla time

1 INTRODUCTION

The sacred direction, i.e. qibla, has great importance for Muslim people in their daily lives. Especially during prayer, it is a requirement for every Muslim to face towards the Kâ'ba in Mecca City of Saudi Arabia (Fig. 1).

Figure 1 Qibla direction for Çorum City, Turkey on Google Earth

Facing towards the qibla, i.e. Istikbal-i Qibla, is one of the six conditions or requisites of the prayer for being valid. In other words, if a person does not turn his/her face to the qibla direction within an acceptable declination, his/her prayer is invalid according to scholarly consensus. Thus, the direction of the qibla should be established as accurately as possible. The qibla direction is not only important for prayer, but also for performing various ritual acts like reciting the Qur'an, announcing the call to prayer (azan) and the ritual slaughtering of animals for sacrifice. Furthermore, Muslim graves and tombs are laid out so that the body would lie on its right side and face the qibla [1]. The angle of the qibla direction is not fixed and depends on the location in the world and thus, it should be calculated for each mosque very precisely with a proper method.

There are several mosques all over the world that have been oriented in a direction which varies from the real directions even several degrees, whether due to different interpretations, incorrect data, or inaccurate calculations [2]. Several academicians and researchers have made numerous studies to verify how accurately the mosques (and masjids) have been constructed and to orient the new ones precisely. For instance, Almakky and Snyder [2] described a method to provide an equation with which a person can determine the accurate azimuth of qibla direction at any location. Kimerling [3] gave information about cartographic methods for determining the qibla direction. Ishak and Ali [4] presented the mathematical calculation in qibla determination with modern approach. Pantazis and Lambrou [5] investigated the orientation of the mosques according to the Islamic rules using geodetic surveying method and common geodetic equation. Asiri [6] investigated more than seven thousand places in Saudi Arabia and their qibla directions were determined with basic spherical trigonometric formula. Schwartz [7] explained a new spherical trigonometric approach to determine the qibla direction precisely. Yilmaz [8] investigated the correctness of the mosque orientation in Turkey before seventeenth century using geometric or trigonometric formulas. In these studies, mainly trigonometric computation methods have been handled. The main purpose of this study is to introduce different methods that can be used to verify how accurately the existing qibla directions of mosque reaching to 90,000 in Turkey and more than a dozen times in all around the world are oriented or not according to Islamic criteria. Within this context, the azimuths of the existing and real qibla directions of eight mosques located in Çorum City that were constructed between 14th and 21st centuries were determined by using spherical trigonometric formulas based on GNSS/conventional geodetic measurement methods. Additionally, the most precise and easiest applicable method, the Sun Qibla Time method was handled with the formulas required for the calculations. In this approach, the existing qibla directions of the same mosques were compared with the real qibla directions determined by the Sun Qibla Time method. The existing and real qibla directions were compared and the differences were interpreted according to the Islamic criteria. The obtained results were also compared to each other in terms of accuracy, cost, ease of application and some proposals were made to a person to do such studies.

2 QIBLA DETERMINATION METHODS

The sacred direction, i.e. qibla, has a great importance for Muslim community in their daily lives while praying and performing various ritual acts. Thus, determination of qibla direction is very important for approximately 1.7 million Muslims all over the world. Over the centuries, qibla determination and orienting of mosques towards the Kâ'ba have been a subject of many scientific studies and investigated seriously by numerous Muslim scientists, including al-Khwarizmi (780-850), al-Battani (858-929), Abu al-Wafa al-Buzjani (940-998), Ibn al-Haitham (965-1040), al-Biruni (973-1048), and al-Tusi (1201-1274) [9].

During the first two centuries of Islam, when mosques were being built in different geographic location, Muslims did not have sufficient scientific background to find the direction of qibla. Starting from the 8th century, Muslim astronomers were interested in determining qibla direction as a mathematical geography problem. This included the knowledge of geodetic coordinates and the calculation of direction from one point to another with geometry or trigonometry, such as analemma or spherical trigonometry. Solid trigonometry and projection methods were formulated to obtain accurate solution in the early 9th century, then with spherical trigonometry in the 10th century [10]. A trigonometric formula for determining exact qibla from any location in the world was found by a Syrian astronomer Shams al-Din al-Khalili (1320-1380) and soon after qibla compasses were developed [11]. During those times, the direction of the road that pilgrims use for Mecca was taken as qibla direction because they barely knew which way they would go from where they were. Two approaches were taken into consideration. The first one is based on the orientation of the Prophet Hz. Mohammed (SAS) was oriented to south during his prayer when he was in Medina City (north of Mecca) in Saudi Arabia. Thus, orientation towards south for qibla was accepted by some authorities. This explains the fact that many early mosques from Andalusia to Central Asia face towards south. Second approach is standing precisely towards Kâ'ba according to Quran [1]. It can be said that, the qibla determination methods have changed from traditional approach to more precise modern approach depending on the scientific and technological improvements.

There are numerous studies in this field and the qibla direction is determined with different equipment and computational methods including both the approximate and exact methods by using different approvals and approaches [1-10, 12, 13]. Through the centuries, a number of simple, practical and reliable techniques have been used by the Muslim people to orientate the mosques towards the Kâ'ba. Some of them are given below [8, 9, and 10]:

- spherical trigonometric computations,
- using the sun qibla time,
- using qibla maps,
- table containing the qibla angle as a function of longitude difference from Mecca and latitude,
- practical methods involving astronomical instruments such as astrolabes and various types of quadrants,
- solar observations directly at certain times.

It should be noted that, for the determination of the qibla direction, there are two possible alternative directions which are the great circle and the rhumb line. Thus, before calculating the qibla direction, the path between the given place and the Kâ'ba should be established either as a great circle (or geodesic path) or a rhumb line (loksodrom or spherical helix). Nonetheless, the great circle gives the correct direction rather than the rhumb line for qibla determination and the qibla can be defined as the direction to the Kâ'ba along the great circle [9]. In this study the qibla direction is also established as a great circle.

On the other hand, a question has arisen; what is the boundary (hadd) in facing the Qibla when praying? According to Muslim scholars, a person could turn 45 degrees to the left or right from the Kâ'ba direction [14].

For the determination of the qibla direction of the mosques, besides the several methods including the ones mentioned above, the most common method is calculation of the azimuth of the real qibla direction through trigonometric formulas and stake out the mosques with conventional geodetic methods. Furthermore, sun qibla time method has still been used to determine the qibla direction of a mosque as the most accurate and easy method. A brief explanation of these two approaches will be given as they were used in this study.

2.1 Qibla Determination using Spherical Trigonometric Formula

For construction of the mosques facing towards the Kâ'ba, azimuth of the great circle, i.e. qibla angle, (a great circle if the Earth is accepted as a sphere, a geodesic path if ellipsoid) from the mosque to the Kâ'ba should be calculated. This calculation can be achieved with the Second (Inverse) Geodetic Problem solution (given two known points, determining the azimuth and length of the line that connects them) on the sphere or ellipsoid by using geodetic coordinates of the Kâ'ba and the mosque. Although the calculations are carried out on the ellipsoid more precisely, the solution on the sphere is significantly simpler. Furthermore, this approach gives enough accuracy when considering the expected qibla determination precise.

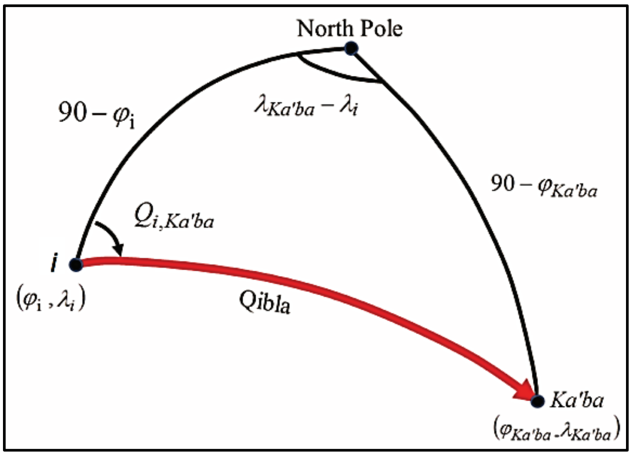

Figure 2 Qibla angle on a spherical triangle

The necessary formula can be obtained by solving the spherical triangle whose vertices are the North Pole, the point (*i*) where the qibla direction can be determined, and the Kâ'ba depicted in Fig. 2.

Although a number of alternative formulas are given in different handbooks and textbooks on spherical trigonometry, with the '*world shape is a sphere*' assumption, the basic trigonometric formula that is derived from *four-part (or cotangent) theorem* to calculate the qibla direction is given as [6 and 9]:

$$\cos(90-\varphi_i)\cos(\lambda_{\text{Ka'ba}}-\lambda_i) = \\ = \sin(90-\varphi_i)\cot(90-\lambda_{\text{Ka'ba}})-\sin(\lambda_{\text{Ka'ba}}-\lambda_i)\cot Q_{i,\,\text{Ka'ba}}, \quad (1)$$

$$\cot Q_{i,\,\text{Ka'ba}} = \frac{\cos\varphi_i \cdot \tan\varphi_{\text{Ka'ba}} - \sin\varphi_i \cdot \cos(\lambda_{\text{Ka'ba}}-\lambda_i)}{\sin(\lambda_{\text{Ka'ba}}-\lambda_i)} \quad (2)$$

$$\tan Q_{i,\text{Ka'ba}} = \frac{\sin(\lambda_{\text{Ka'ba}}-\lambda_i)}{\cos\varphi_i \cdot \tan\varphi_{\text{Ka'ba}} - \sin\varphi_i \cdot \cos(\lambda_{\text{Ka'ba}}-\lambda_i)} \quad (3)$$

$$Q_{i,\text{Ka'ba}} = \arctan\left\{\frac{\sin(\lambda_{\text{Ka'ba}}-\lambda_i)}{\cos\varphi_i \cdot \tan\varphi_{\text{Ka'ba}} - \sin\varphi_i \cdot \cos(\lambda_{\text{Ka'ba}}-\lambda_i)}\right\} \quad (4)$$

where, $Q_{i,\text{Ka'ba}}$ is the azimuth of a great circle arc at a given location from the north direction to the direction towards the Kâ'ba, i.e. qibla angle, (measured clockwise from the north); φ_i, λ_i latitude and longitude of a given location (i) respectively; and $\varphi_{\text{Ka'ba}}$, $\lambda_{\text{Ka'ba}}$, latitude and longitude of the Kâ'ba in Mecca respectively.

2.2 Qibla Determination using Sun Qibla Time

There is a specific time of the day called the qibla time that can be used for the qibla determination accurately and easily. Qibla time is the time when given location, Kâ'ba and the Sun are on the same direction (Fig. 3).

In order to determine the qibla time, the azimuth of Kâ'ba is calculated by solving the spherical triangle using the Eq. (4). The azimuth shows the qibla direction which is invariable for the given location. When the azimuth of the sun at the given location becomes equal to the pre-calculated azimuth of Kâ'ba, Hour Angle of the Sun (t) is calculated for that moment by solving the astronomic triangle with the declination of Sun for that day. Then the Local Apparent Solar Time (τ) is calculated as [15-18]:

$$\tau = t - 12^h \quad (5)$$

The time which is used in daily life is Local Mean (Solar) Time (LMT). The difference between the Local Apparent Solar Time (τ) and the Local Mean (Solar) Time ($\overline{\tau}$) which is called Equation of Time (E) is expressed as [15-18]:

$$E = \tau - \overline{\tau} \quad (6)$$

The Local Mean (Solar) Time (LMT) of observation point is found as [15-18]:

$$\overline{\tau} = \tau - E \quad (7)$$

From this, Universal Time (UT) is found as [15-18]:

$$UT = \overline{\tau} \pm \lambda \quad (8)$$

where λ is the longitude of a given location (− for eastern longitude, + for western longitude). By adding the Zonal Correction or Zonal Description, λ_{Zone}, (the current time difference or offset from UTC) to this value, Zone Time (ZT) is found as [15-18]:

$$ZT = UT \pm \lambda_{\text{Zone}} \quad (9)$$

This calculated time, i.e. ZT, is Qibla Time for the given location. More information about the astronomical calculations can be found in [15-18].

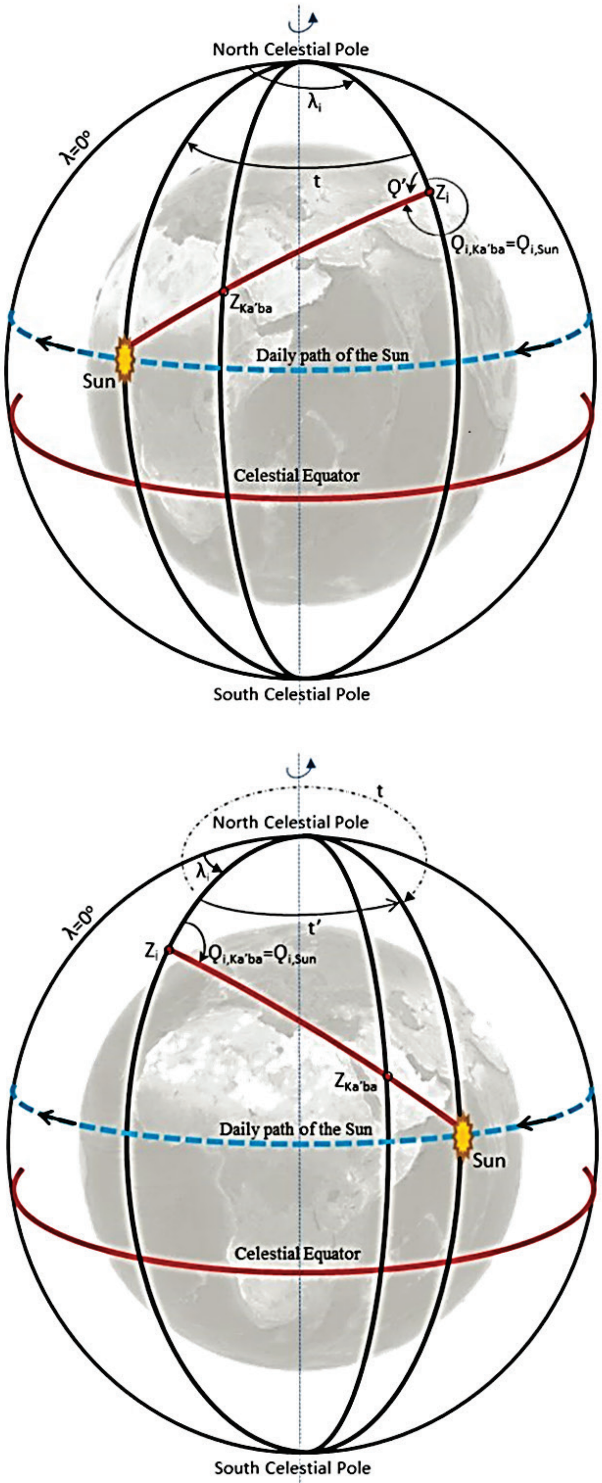

Figure 3 Astronomical triangle at the qibla time (*up:* the given location is on the east side of the Kâ'ba; *down:* the given location is on the west side of the Kâ'ba)

After calculation of the qibla time, a stick or rod is erected vertically at a place taking direct sunlight in order to determine the qibla direction. The shadow of this object shows the opposite side of the qibla direction at the moment of the exact qibla time (Fig. 4).

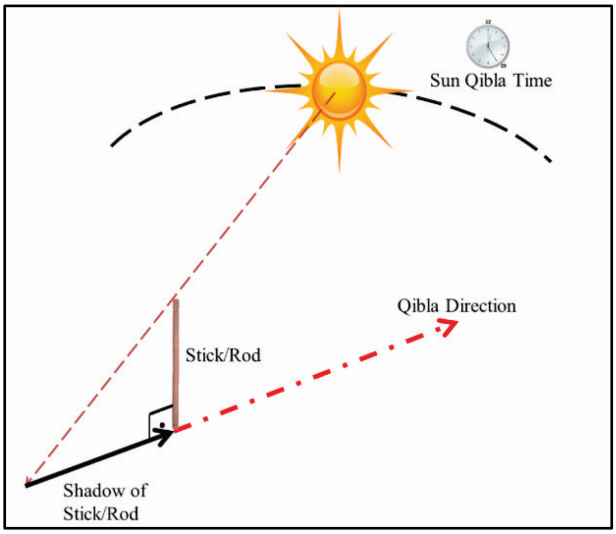

Figure 4 Qibla determination with the sun qibla time method

Although an expert could calculate the qibla time with complex astronomical formulas, it is also calculated by official religious authority and published in the daily calendar. It should be expressed that, this time (moment) varies according to the season and is also different for each place on Earth.

3 CASE STUDY

In this study, accuracy of the existing qibla direction of selected mosques placed in Çorum City, Turkey, which were constructed in different periods between the 14th and 21st centuries, were investigated. For this purpose, two different approaches were applied. The measurement procedures of these approaches are given in the following sections.

3.1 Determination of the Accuracy of Existing Qibla Directions of the Mosques by using GNSS & Conventional Measurements

The geodetic coordinates of the mosque corners were determined with conventional geodetic methods because of the impossibility of direct GNSS measurements on the mosque corners and the unavailability of the measurements from the domes/roof of the mosques due to logistic reasons. For this purpose, two geodetic points were established in the courtyard (or around) of the mosque and their coordinates were determined accurately with GNSS measurements. Spectra Precision Epoch50 and SP80 multi-frequency GNSS receivers were employed at least 30 minutes to collect the data in static mode (Fig. 5).

The provided accuracy (RMS) for these receivers is given in Tab. 1.

In order to determine the known coordinates of the established geodetic points, two of the Turkish RTK Continuously Operating Reference Stations Network (TUSAGA-Aktif) stations, i.e. CORU (40°34'13.48" N, 34°58'55.93" E) and SUNG (40°09'14.32" N, 34°22'08.08" E) were used as reference stations. Brief information about this network is given in the Section 3.2. The static data collected at the reference stations were downloaded from the Internet site of the system.

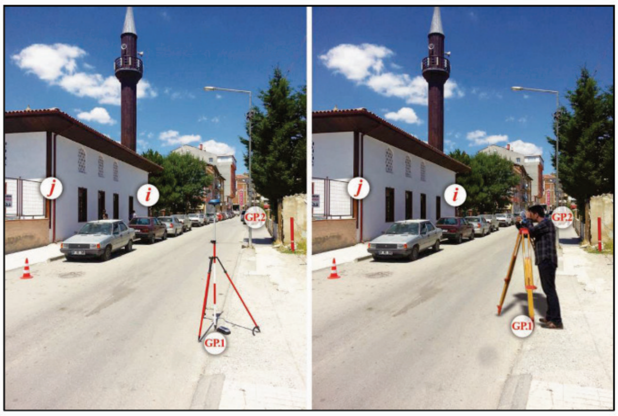

Figure 5 GNSS (left) and conventional (right) measurements

Table 1 Accuracy of Epoch 50 and SP80 GNSS receivers [19]

Method	Accuracy	
	Horizontal	Vertical
Static & Fast Static	3 mm + 0.5 ppm	5 mm + 0.5 ppm
High-Precision Static	3 mm + 0.1 ppm	3.5 mm + 0.4 ppm

The adjusted ellipsoidal geodetic coordinates of the established points were calculated ±5 mm or better level of positional accuracy by processing of the baselines from these reference stations in ITRF96 using the Leica Geo Office commercial GNSS processing package.

After this, the electronic total station, Spectra Precision FOCUS 8, was set up on the geodetic point and two corner points of the mosques that coincide with the qibla direction of the mosque (i.e. point *i* and *j* in Fig. 5) were coordinated with conventional method, i.e. polar observation. It should be noted that the constituted line from point *i* to *j* establishes the qibla direction. Horizontal angles were observed two times in both the face positions to the survey targets located at mosque's corner and the horizontal distances were measured with the electronic total station (Fig. 5). The stated measurement accuracy for the FOCUS 8 total station is given as [20]:

- for distance measurement ±(2+2 ppm × D) mm (with prism, in precise mode),
- for angle measurement 2" (horizontal), 5" (vertical).

The plane coordinates of the mosque's corner points in Gauss Kruger Projection were calculated with conventional geodetic formula expressed by:

$$X_i = X_{GP_1} + S_{GP_1,i} \cos t_{GP_1,i} \tag{10}$$

$$Y_i = Y_{GP_1} + S_{GP_1,i} \cos t_{GP_1,i} \tag{11}$$

where, X_{GP_1} and Y_{GP_1} are the plane coordinates of the known point GP_1; $S_{GP_1,i}$ is the horizantal distance between Point GP_1 and Point i. $t_{GP_1,i}$ is the bearing (angle measured from the north in a clockwise direction) of side of the $GP_1 - i$ and calculated with the following common formula:

$$t_{GP_1,i} = t_{GP_1,GP_2} + \beta_i \pm k \cdot 200 \tag{12}$$

where, t_{GP_1,GP_2} is the bearing of the $GP_1 - GP_2$ line; β_i is the observed horizantal angle between survey line of $GP_1 - GP_2$ and $GP_1 - i$. The t_{GP_1,GP_2} is calculated by:

$$t_{GP_1,\,GP_2} = \arctan\frac{Y_{GP_2} - Y_{GP_1}}{X_{GP_2} - X_{GP_1}} \tag{13}$$

where, X_{GP_1}, Y_{GP_1} and X_{GP_2}, Y_{GP_2} are the plane coordinates of the known points, GP_1 and GP_2, respectively.

In order to calculate the accuracy of the calculated coordinates, the *Error Propagation Law* is applied to Eq. (10)-(13) with respect to the independent variables (X_{GP_1}, Y_{GP_1}, S_{GP_1}, $t_{GP_1,\,GP_2}$, β_i). To derive the error, the following partial derivatives from Eq. (10)-(13) are required:

$$d_{X_i} = \frac{\delta X_i}{\delta X_{GP_1}} dX_{GP_1} + \frac{\delta X_i}{\delta S_{GP_1,\,i}} dS_{GP_{1,\,i}} + \frac{\delta X_i}{\delta t_{GP_1,\,i}} dt_{GP_{1,\,i}} \tag{14}$$

$$d_{Y_i} = \frac{\delta Y_i}{\delta Y_{GP_1}} dY_{GP_1} + \frac{\delta Y_i}{\delta S_{GP_1,\,i}} dS_{GP_{1,\,i}} + \frac{\delta Y_i}{\delta t_{GP_1,\,i}} dt_{GP_{1,\,i}} \tag{15}$$

$$m_{X_i}^2 = m_{X_{GP_1}}^2 + \cos^2 t_{GP_1,\,i}\, m_{S_{GP_{1,\,i}}}^2 + S_{GP_{1,\,i}}^2 \sin^2 t_{GP_1,\,i} \frac{m_{t_{GP_{1,\,i}}}^2}{\rho^2} \tag{16}$$

$$m_{Y_i}^2 = m_{Y_{GP_1}}^2 + \sin^2 t_{GP_1,\,i}\, m_{S_{GP_{1,\,i}}}^2 + S_{GP_{1,\,i}}^2 \cos^2 t_{GP_1,\,i} \frac{m_{t_{GP_{1,\,i}}}^2}{\rho^2} \tag{17}$$

$$dt_{GP_1,\,i} = dt_{GP_1,\,GP_2} + d\beta \tag{18}$$

$$dt_{t_{GP_1,\,GP_2}} = \frac{\delta t_{GP_1,\,GP_2}}{\delta Y_{GP_2}} dY_{GP_2} + \frac{\delta t_{GP_1,\,GP_2}}{\delta Y_{GP_1}} dY_{GP_1} + \frac{\delta t_{GP_1,\,GP_2}}{\delta X_{GP_2}} dX_{GP_2} + \frac{\delta t_{GP_1,\,GP_2}}{\delta X_{GP_1}} dX_{GP_1} \tag{19}$$

$$m_{t_{GP_1,\,GP_2}}^2 = \rho^{cc}\left[\frac{\cos^2 t_{GP_1,\,GP_2}}{S^2}\left(m_{Y_{GP_2}}^2 + m_{Y_{GP_1}}^2\right) + \frac{\sin^2 t_{GP_1,\,GP_2}}{S^2}\left(m_{X_{GP_2}}^2 + m_{X_{GP_1}}^2\right)\right] \tag{20}$$

$$m_{t_{GP_1,\,i}}^2 = m_{t_{GP_1,\,GP_2}}^2 + m_\beta^2 \tag{21}$$

The positional accuracy of the i and j points of the mosque corners is expressed by:

$$m_{\text{Pos.}}^2 = m_{X_{GP_1}}^2 + m_{Y_{GP_1}}^2 + m_{S_{GP_1,\,i}}^2 + S_{GP_1,\,i}^2\, m_{t_{GP_1,\,i}}^2 \tag{22}$$

It is assumed that there is no correlation between the independent variables. According to calculation based on Eq. (22), the coordinates were determined with accuracy (standard error) of ±5 mm in average.

All these coordinates were converted to geodetic coordinates by using common equation, and then the existing azimuth of each mosque's qibla direction was calculated with the trigonometric formula given in Eq. (4). In order to assess the accuracy of the existing qibla direction, the azimuth of the real qibla direction of each mosque was calculated using the same trigonometric formula (Fig. 6).

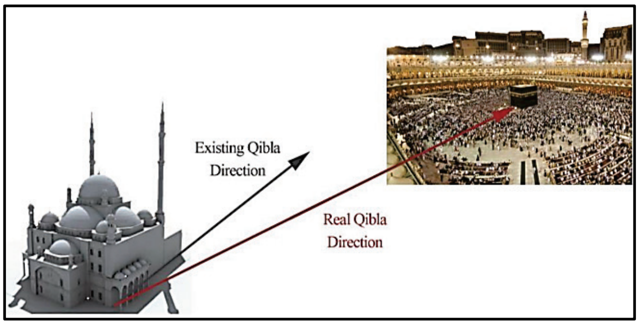

Figure 6 Schematic depiction of existing and real qibla direction

The geodetic coordinates for the Kâ'ba can be found in several sources and may differ more or less from each other. It appeared more suitable to receive the coordinates of the Kâ'ba from one of the most common applications, Google Earth. It gives the ellipsoidal geodetic coordinates of the Kâ'ba as $\varphi_{\text{Ka'ba}}$ = 21°25'21" N; $\lambda_{\text{Ka'ba}}$ = 39°49'34" E (on WGS84 ellipsoid). For practical uses, the reference ellipsoid of the ITRF (GRS 80) is accepted as identical to the WGS84.

According to the calculation, it was found that recently built mosques 1, 2, 3 and 4 had a south-eastern orientation which varies between 166°09'54" and 169°08'11". Existing qibla direction of earlier dated mosques 5, 6 and 7 was calculated as varying between 183°31'13" and 184°02'09". For mosque 8, the azimuth of existing qibla direction was calculated as 172°40'11".

Mosque orientations obtained from the situ measurements (i.e. existing azimuth of the qibla direction of each mosque) were compared to their real value and angular differences (deviations) are given in Tab. 2.

Table 2 Differences between the existing and real qibla directions' azimuth from GNSS & conventional measurements

Mosque Number	Building Year/ Period	Differences	Lay inside the permitted declination boundary
1	1988	2°43'10"	YES
2	2009	2°12'37"	YES
3	2013	0°00'39"	YES
4	1997	0°58'31"	YES
5	C14th.	17°41'31"	YES
6	1660	17°10'03"	YES
7	1650	17°35'51"	YES
8	1579	6°19'40"	YES

According to the results given in Tab. 2, the differences varied between $0°00'39''$ and $17°41'31''$. In general, as expected, larger differences were found in older mosques but all qibla directions of the studied mosques were laid inside the permitted declination boundary.

3.2 Determination of the Accuracy of Existing Qibla Directions of the Mosques by using Network-RTK GNSS Measurements

Although the method discussed above gives results with very high accuracy, it might be exhausting, time consuming and expensive due to the necessity of both GNSS and conventional measurements. Taking this fact into account, a more practical method was applied with direct GNSS measurements for the determination of the qibla direction. Within this context the other two points (*ii* and *jj*) were established on the direction of the mosque's wall representing the qibla direction (Fig. 7).

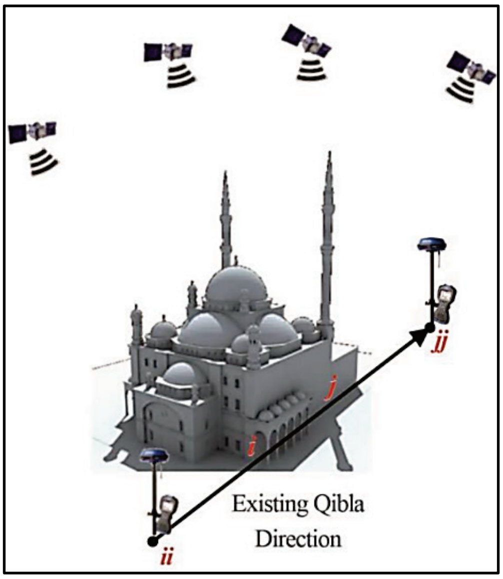

Figure 7 Schematic depiction of field measurement with network-RTK GNSS measurements

Table 3 Differences between the existing and real qibla directions' azimuth from network-RTK GNSS measurements

Mosque Number	Building Year/ Period	Differences	Lay inside the permitted declination boundary
1	1988	2°47'42"	YES
2	2009	2°11'08"	YES
3	2013	0°00'32"	YES
4	1997	0°53'41"	YES
5	C14th.	N/A*	*
6	1660	16°51'07"	YES
7	1650	17°06'02"	YES
8	1579	6°22'16"	YES

*Measurement could not be conducted because of the unavailability of the suitable place for Network-RTK GNSS measurement.

The established geodetic points (point *ii* and *jj*) were coordinated with the Network-RTK GNSS method utilizing the TUSAGA Aktif Network (or Turkish RTK CORS Network/CORS-TR). The TUSAGA Aktif Network was put into service for civilian use in 2009. This network has 146 stations through Turkey including the Turkish Republic of Northern Cyprus with an average spacing of 70-100 km. In this system, VRS, FKP and MAC, and Differential GPS (DGPS) techniques are implemented. TUSAGA Aktif has been extensively used in Turkey for all kinds of positioning applications, geodetic and cadastral surveys and GIS applications producing economical and rapid solutions within a few cm-level of accuracy, i.e. under 3 cm horizontal and 5 cm vertical accuracy, even in a couple of seconds, fast, easy and cost-effectively, at any time and all year round in real-time [21 and 22]. More detailed information about Turkish RTK CORS Network, CORS-TR, can be found in the literature [21 and 23]. Fix solutions were obtained within a few minutes and the coordinates were determined in the field in real-time within a few cm-level of accuracy. Then, the azimuth of the existing qibla direction at the handled mosque was calculated by using the spherical trigonometric formula given in Eq. (4). Meanwhile, azimuths of the real qibla directions $Q_{i,\text{Ka'ba}}$ were also calculated with the same formula by using the coordinates of Kâ'ba given in previous chapter.

The existing azimuth of the qibla direction of each mosque is compared to their real value and the differences are shown in Tab. 3 for each mosque.

When the results presented in Tab. 3 are evaluated, the differences for the mosques dated between the 16th and 17th centuries were found more than recent ones. The overall results show that all of the existing qibla directions were laid inside the permitted declination boundary.

3.3 Determination of the Accuracy of Existing Qibla Directions of the Mosques by using Sun Qibla Time

In this part of the study, the real qibla directions of each mosque was determined by using the sun qibla time method and they were compared with the existing qibla directions. For this purpose, a range rod, 2.5 m long, was set vertically with a tripod to one of the suitable points, *ii* or *jj* which were established in the qibla direction of each mosque. The necessary qibla time was calculated by using Eq. (5, 6, 7, 8, and 9) and at that moment, the end of shadow of the rod was precisely marked (Fig. 8). In this way the real qibla direction was established.

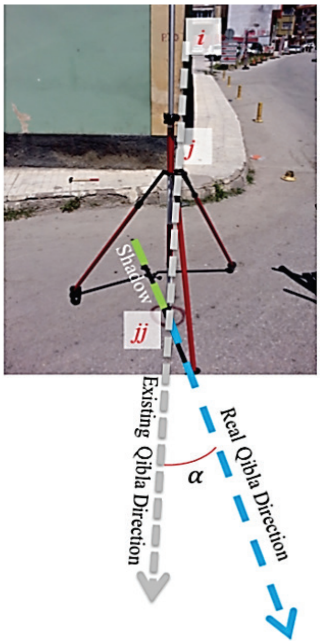

Figure 8 Determination of qibla direction by using sun qibla time

Table 4 Differences between the existing and real qibla directions' azimuth from sun qibla time

Mosque Number	Building Year/ Period	α Angle	Lay inside the permitted declination boundary
1	1988	2°36'44"	YES
2	2009	2°29'09"	YES
3	2013	0°06'56"	YES
4	1997	0°31'53"	YES
5	C14th.	18°00'39"	YES
6	1660	16°48'55"	YES
7	1650	16°25'15"	YES
8	1579	6°58'19"	YES

Then the difference between the shadow direction obtained from the sun qibla time and the existing qibla direction, α angle, was measured precisely with an electronic total station instrument, Spectra Precision FOCUS 8, and the results are given in Tab. 4.

The differences found were very similar to the ones from previous measurements. Although there were larger differences for the mosques of the 14th, 16th and 17th centuries, all of the existing qibla directions of the handled mosques were laid inside the permitted declination boundary. Comparative results of the three methods are summarized in Tab. 5.

Table 5 Summary of the differences between the existing and real qibla directions' azimuth

Mosque Number	Building Year/ Period	Differences between Real and Existing Qibla Angles		
		from GNSS & Conventional Meas.	from Network RTK GNSS Meas.	from Sun Qibla Time
1	1988	2°43'10"	2°47'42"	2°36'44"
2	2009	2°12'37"	2°11'08"	2°29'09"
3	2013	0°00'39"	0°00'32"	0°06'56"
4	1997	0°58'31"	0°53'41"	0°31'53"
5	C14th.	17°41'31"	N/A	18°00'39"
6	1660	17°10'03"	16°51'07"	16°48'55"
7	1650	17°35'51"	17°06'02"	16°25'15"
8	1579	6°19'40"	6°22'16"	6°58'19"

As can be seen from Tab. 5, the differences from each of the three methods were obtained very close to each other. In general, the qibla directions of the mosques determined in this study alongside the real qibla direction were within acceptable boundaries for each mosque as depicted in Fig. 9.

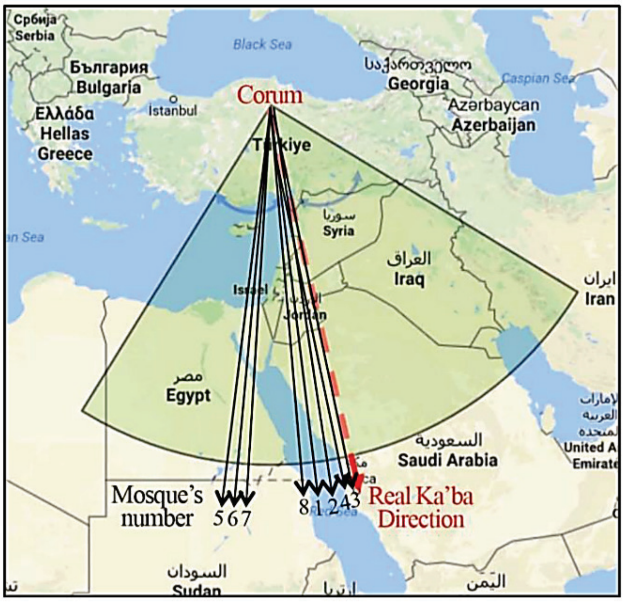

Figure 9 Existing mosque orientations, Kâ'ba direction and accepted boundaries on Google Earth

When the results given in Tab. 5 and Fig. 9 are examined, it is clearly seen that the existing qibla directions of all mosques lay inside the permitted (45 degree) declination boundary (hadd). The results reveal that the differences from the real qibla direction were found negligible according to Islamic criteria. The differences for the older period mosques (i.e. built in 14th, 16th and 17th centuries) were found relatively large when compared with the recent one that varies between 6° and 18° interval from the real value. For more recent period mosques, i.e. constructed within last 3 decades, the differences found were smaller and varied between a few arc seconds and about 3 ° interval. Also, when the results of the Spherical Trigonometric Formula and the Sun Qibla Time Methods were compared, they were found very close to each other within about less than one degree.

It is seen that the old mosques, in which very large differences were obtained compared to recently built ones, were oriented more towards the south than the Kâ'ba (directions 5, 6 and 7 in Fig. 9). The following reasons can be suggested to explain these differences although they are in the limits according to the Islamic criteria:

- imprecise calculations or improper method,
- study of inexperienced people,
- orienting to a wrong/different direction.

The first reason does not apply when considering the fact that highly accurate solution algorithms had been existing since the 8th century as it was stated in Chapter 2. Moreover, it would not make much sense to imply that all the mosques which were built with meaningful time differences were oriented with the same error. The same approach weakens the thesis that work was conducted by inexperienced people. It is expressed in Chapter 3.1 that the qibla angles of the mosques 5, 6 and 7 vary between 183°31'13" and 184°02'09". From this it is clearly seen that these mosques were oriented as if to south direction like in earlier times and probably by using a compass. Indeed, as it was mentioned in Chapter 2, several early mosques from Andalusia to Central Asia were also oriented to the south rather than Kâ'ba like ours. Thus, the differences for these mosques cannot be attributed to calculation or application mistakes. However, it should be noted that all of these are interpretations since there is no evidence -until this work- on how these mosques were oriented. In order to reach a more definite result, it is necessary to work on other similar dated mosques not only in Çorum province but also in the nearby geography. This will be added to our future study plan.

4 CONCLUSIONS

In this study, after giving general information of qibla determination methods, two different approaches based on Spherical Trigonometric Formula using GNSS and/or conventional surveying measurements and the Sun Qibla Time were discussed. Although there are several ways to determine the qibla, these two methods can be used to determine the qibla very accurately. The first one, i.e. using GNSS and/or conventional surveying measurements, requires certain calculations and an experienced technical personnel having knowledge of surveying techniques at a satisfactory level as well as a geodetic equipment. This approach requires almost one day of work for every mosque due to the need for field work and office work. Additionally, a field work which is quite expensive in terms of equipment is necessary and it requires application of many geodetic processes (data evaluation, adjustment, datum/coordinate transformation, epoch shift, etc.) in order to obtain accurate results. When considering that only an expert geodesist is expected to do this, this approach presents a challenging, time consuming and costly solution. The NetworkRTK GNSS, although it is easier than the previous one, has some disadvantages. The most prominent ones require a GNSS specialist, necessity of a NetworkRTK-equiped receiver which is more expensive than a classical one, being based on a communication infrastructure such as GSM or internet which all countries might not have. The other approach, Sun Qibla Time Method, gives quite accurate results as long as the qibla time is determined correctly and applied precisely. This method is very practical and easy to apply which requires only suitable measurement conditions and an accurate clock.

As a result, it should be stated that the responsible technical person of this kind of study paid special attention to orient the mosque during the building stage. The position of the current location and correct qibla angle should be calculated and staked out to field very carefully and seriously with an expert person who has sufficient knowledge and experience in using the latest technology.

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