www.gi.sanu.ac.rs, www.doiserbia.nb.rs,
J. Geogr. Inst. Cvijic. 68(3) (307-320)

Original scientific paper

UDC: 911.3:528.288(497.13)
DOI: https://doi.org/10.2298/IJGI180718001T

A THEORETICAL EXPLORATION OF A SUNDIAL OF THE FRANCISCAN FRIARY IN DUBROVNIK (CROATIA)

Milutin Tadić[1], *Zorica Prnjat*[1]*
[1] University of Belgrade, Faculty of Geography, Belgrade, Serbia; email: tadic@gef.bg.ac.rs; zorica.prnjat@fil.bg.ac.rs

Received: July 18, 2018; Reviewed: July 27, 2018; Accepted: August 20, 2018

Abstract: The Franciscan friary in Dubrovnik (Croatia) has two old wall sundials mounted in the small and large monastery cloisters. Both indicate equinoctial hours according to the apparent solar time. It is known for one who made it and the year it was made in — Paško Baletin in 1770, and for the other, there are no data. The second sundial has two scales; on the upper scale, the direction of the shadow indicates hours counted from midnight (*Ore francese*), whereas on the lower scale, the hours counted from the previous sunset are indicated by the tip of the shadow i.e. its "sunlet" (*Ore italiche*) as it has been believed so far. In order to check this, we calculated both scales, made drafts and compared them with the existing sundial scales: hour lines on the upper scale coincide, while on the lower scale all calculated hour lines deviate from the existing lines towards the west. However, when the calculations for the lower scale are done in accordance to the hours counted from the end of the civil twilight (*Ore italiche da campanile*) there is complete compatibility. This was confirmed by on-site observation of the sundial. It remains to search through Dubrovnik archives to discover when the two-scale sundial was made. The last-mentioned variant could have been brought to Dubrovnik in the second half of the 18th century, and since then there was a need to construct a two-scale sundial.

Keywords: gnomonics; sundial; Ore italiche; Ore italiche da campanile; mathematical geography

Introduction

On the territory of the former Yugoslavia, there are several rather interesting, old, wall mounted sundials (Tadić, 1999), especially in the Central Dalmatia (Tadić, 2010) and in the area of the former Dubrovnik Franciscan province (Tadić, 2011). In the friaries of the city of Dubrovnik, there were at least four old sundials, of which only two are in function today in the Franciscan friary (Tadić, 2004), both made in sgraffito technique and both recently restored (in 2012 and 2015). One is placed on the south-facing wall of a small cloister, while the other, a larger one, is placed on an almost parallel northern wall above the large cloister. In addition to the inscription — *Solis iter signans metitur tempora ab illo disce fugam rapidi temporis et pretium*, the sundial in the small cloister has the initials "P. B." on the basis of which it is presumed that the sundial was

* Correspondence to: zorica.prnjat@fil.bg.ac.rs

made by Paško Baletin in the second half of the 18th century. He constructed a mechanical clock in 1770 for the same friary (Sunčani sat u malom klaustru, Anon., June 28, 2012).

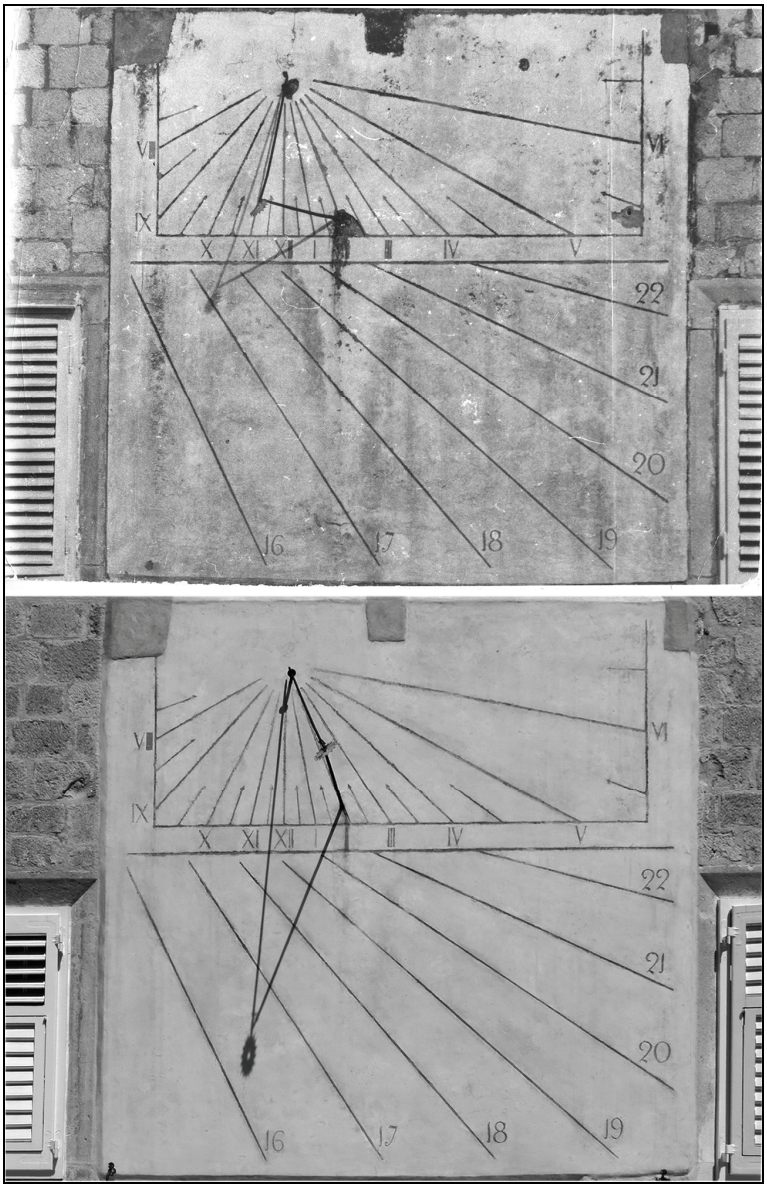

Figure 1a/b: The sundial in a large cloister photographed in 1985 (above) and after the restoration in 2015, photographed in 2018 (below)

The sundial in the large cloister is almost a perfect square (277 x 272.5 cm). Unlike the previously mentioned smaller one it does not have any decorative details or inscriptions. It is not known when it was made and who it was made by. It is remarkable for its two scales (Figure 1a/b), both for the equinoctial system. The upper scale presents a contemporary (French Hours) and the lower the Italian Hours variant. In contrast to the hour lines of the lower scale, the hour lines of the upper scale diverge from the common pole. On the upper scale, the direction of the shadow indicates hours counted from midnight, whereas on the lower scale, the hours apparently counted from the previous sunset are indicated by the tip of the shadow. Apparent solar time, two scales, two variants of the same time system, two ways of reading can confuse an observer not sufficiently familiar with gnomonics, who tries to check the accuracy of the sundial by using a watch/clock. This is the reason for the incorrect explanations what the shadow on the lower scale indicates and how accurate it is.

Because of difference between the time indicated by the tip of the shadow and the expected/calculated time, a question arose whether the lower scale had been constructed for hours counted from the previous sunset (*Ore italiche*) or perhaps for hours counted from the end of the previous evening civil twilight (*Ore italiche da campanile*) (Tadić, 2002; 2004). Since it was found through immediate on-site observation that the shadow on the lower scale is always "behind" for about half an hour, it is reasonable to assume that the lower scale was constructed for the *Ore italiche da campanile* variant.

Methods and Results

To test the validity of hypothesis it was first necessary to construct both hour scales, for the contemporary variant and for both variants of the Italian Hours system, compare them with the existing ones, and then check on the sundial whether the shadow indicates the time as it is theoretically predicted. The first fact needed for the calculation for the upper scale is the latitude of the city (φ = 42°47'); the longitude (λ = 19°18.5') is not needed because the scale refers to the apparent solar time. The second fact is the azimuth of the wall (A = 102.3°). To make calculation for the lower scale, apart from the two previously mentioned facts, it is necessary to know the length of the polos. On the sundial in Dubrovnik, the polos is a copper rod 95 cm long, whose stability is secured by a stand that is not fixed in the subnodus (Figure 1a/b and Figure 3).

The test procedure took eight steps:

1) First, based on the geographic coordinates of the city (φ_0 = 42°47', λ_0 = 19°18.5'), all elements of the solar geometry required for the

analysis were calculated: apparent solar time, sunrise and sunset, daylight length, civil twilight (beginning and end), moments when the Sun crosses the vertical of the sundial (A = 102.3°). For the purpose of this test, the evening civil twilight is especially important: the moment when the Sun is 6° below the horizon (h = – 6°) is determined as the key moment while taking into account the prolongation of the day due to astronomical refraction, in Dubrovnik the civil twilight lasts from 28 to 35 minutes, the average is 30.7 minutes. (On the basis of these data, Figure 6 was constructed).

2) Sun path polar chart for Dubrovnik with the exact-hour sun positions and the projection of the sundial's vertical (the wall on which it is mounted) was constructed. The graph allows to determine the theoretical "working hours" of the sundial: the wall deviates only 12.3° from the plane of the prime vertical allowing the Sun to illuminate it during the course of the year from 8.5 to 11 hours per day, and throughout most of the winter half of the year during the whole daylight period (Figure 2, Figure 6).
3) According to the known formulas (Zenkert, 1984, p. 56), the elements necessary for the correct orientation of the polos were calculated (Figure 3). These are the angle that the polos forms with the plane of the wall (a = 45.95°) and the angle that the projection of the polos, subpolos, forms with the vertical (b = 13.03°). The rectangular coordinates of the nodus are x = 14.89 cm, y = -64.35 cm, z = 68.28 cm, and the polar coordinates of its projection, subpolos: α = 13,03°, d = 66.05 cm. The position of the copper polos on the sundial in Dubrovnik is consistent with the calculation, that is, it forms with the vertical and the subpolos the angles equal to the calculated ones.

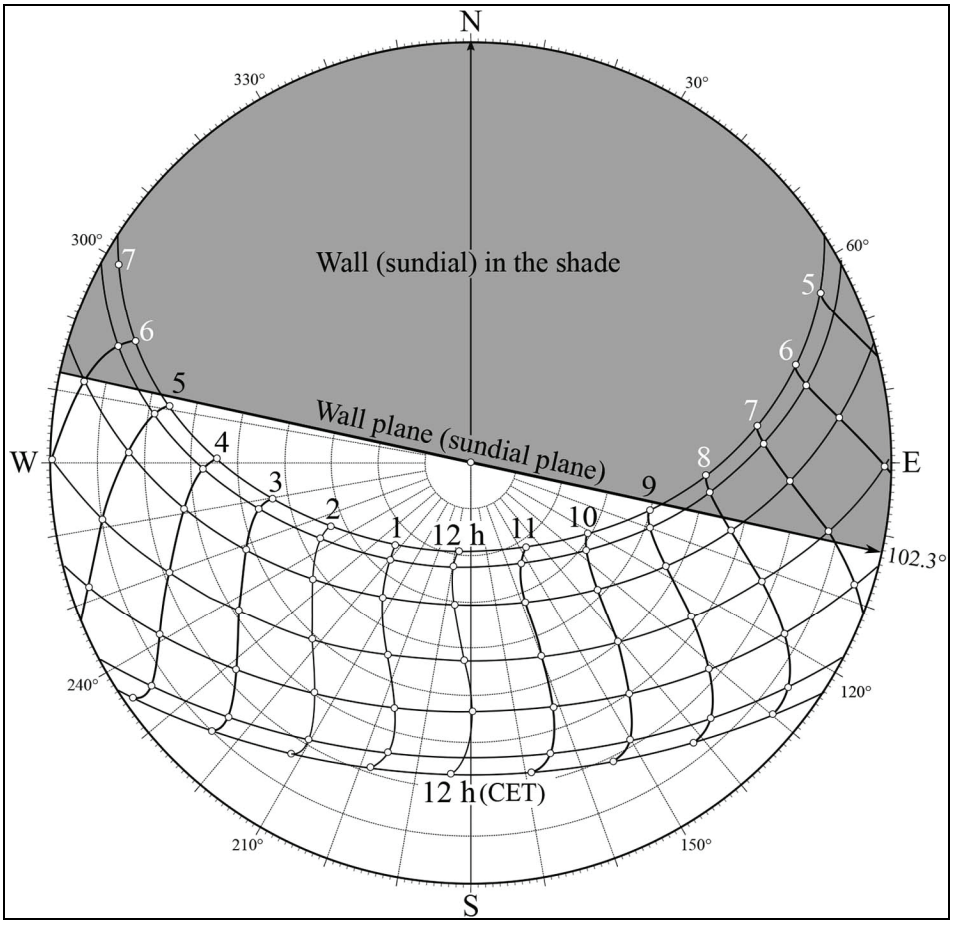

Figure 2: Cross-section of the sundial plane with apparent daily sun paths presented at the plane of Dubrovnik horizon ($\varphi_0 = 42°47'$, $\lambda_0 = 19°18.5'$) in the azimuthal equidistant projection

4) Then, according to the known formula (Zenkert, 1984, p. 54), the angles of the hour lines were calculated by inserting hour angles of the sun at a distance $\Delta t = 15°$ (Table 1) starting from the apparent noon. The calculated hour lines completely coincided with hour lines on the upper scale (Figure 3).
5) Based on the known angles of the hour lines and the length of the polos, according to the known formula (Zenkert, 1984, p. 105), the lengths of the shadows of each full hour were calculated during the solstice and equinox days (Table 1). These lengths were applied along the appropriate hour lines, and then, by joining the outermost points, the projections of the celestial equator and the tropic of

Capricorn (dashed lines in Figure 4) were constructed. The draft clearly shows that a gnomonist who designed the sundial in Dubrovnik drew hour lines of the lower scale from the winter solstice hyperbola, just as it should be.

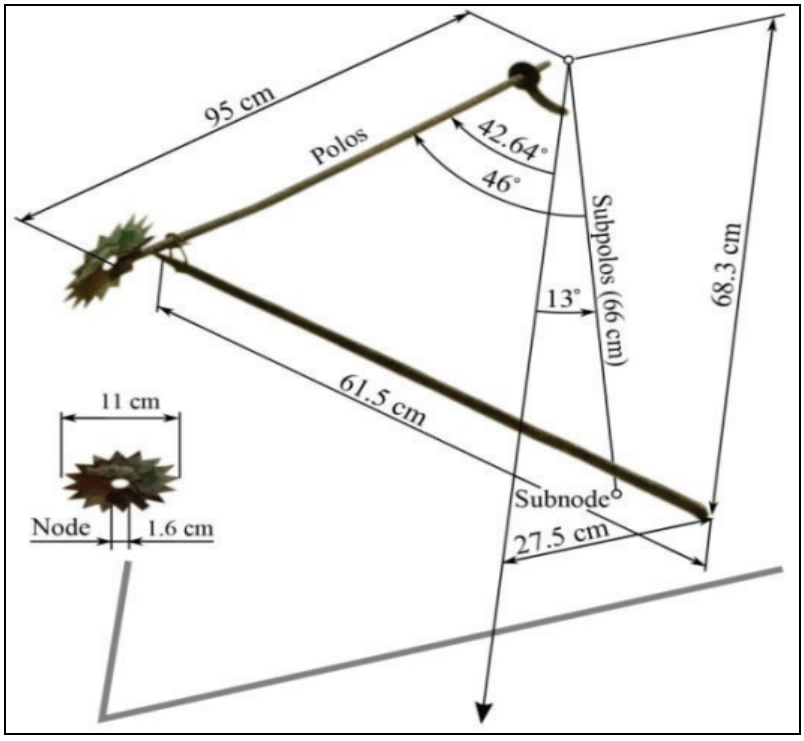

Figure 3: Dimensions and position of the polos

6) In the next step, hour angles of the Sun were calculated at the moment of its sunset for the winter solstice and equinoxes (t = 66.46°, t = 90°) and then by adding orderly 15° in the formula, the polar coordinates of the ends of the shadows were calculated, that is, angles and lengths of the shadows in the range of the hour scale (Table 1). The tip points of these shadows end on the hyperbola line of the winter solstice and on the equinoccial line: by connecting the intersection points, hour lines for the Italian Hours were obtained (Figure 4). Unlike the calculation for the upper scale, the calculated hour lines (in Figure 4, the dashed oblique lines) are completely incompatible with the existing hour lines (Figure 4).

Table 1: The angles of the hour lines and lengths of shadows during the solstice and equinox days

Hour (Apparent solar time)	Angles of the hour lines (°)	Length of the shadow (cm)		
		22. VI	21.III, 23. IX	22. XII
VII	-80.9			
VIII	-60.3			152.1
IX	-41.5		235.2	118.7
X	-25.4	525.0	174.4	104.6
XI	-11.9	322.8	150.6	98.2
XII	0.0	265.0	140.2	95.3
I	11.0	248.0	136.7	94.4
II	21.8	255.3	138.3	94.8
III	33.3	293.4	145.6	96.8
IV	46.1	412.2	163.0	101.6
V	61.1		204.5	
VI	08.9			

7) After the apparent discrepancy between the calculated hour lines for hours counted from the sunset and the existing hour lines was established, the calculation procedure was repeated by calculating hour angles of the sun at the end of the evening civil twilight (t = 75.84°, t = 98.17° it = 123.67°) for the solstice and equinox days, that is, hour angles of the sun at the moments when the sun is 6° below the horizon on these days (Table 2). By joining the points on the winter solstice hyperbola and on the equinoccial line, hour lines for the *Ore italiche da campanile* variant were obtained. These lines fully correspond to the existing hour lines of the lower scale of the sundial.

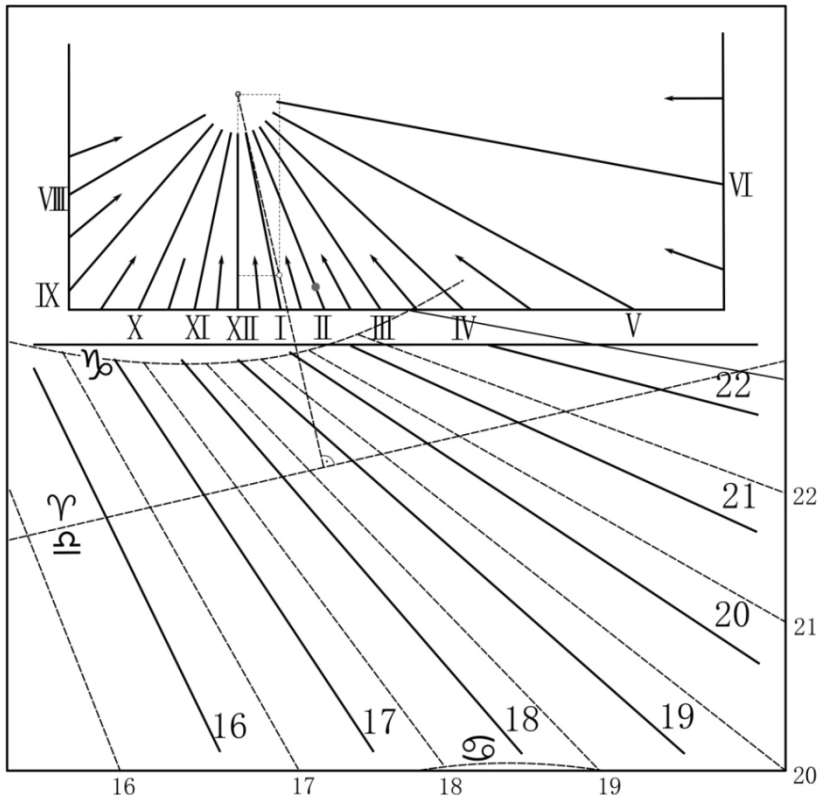

Figure 4: The draft of hour line grid of the Dubrovnik sundial: on the lower scale, all calculated hour lines (dashed oblique lines) are visually behind the existing lines

8) In the end, the accuracy of the sundial was checked on the site: a) for the selected dates, the values of the sun declination (δ) and the time equation (e) were taken from the tables and basing further calculations on them the sunset and the end of the civil twilight were calculated; b) the CET moments when the sunlet (Prnjat & Tadić, 2018) coincides precisely with one of the hour lines on the lower scale were calculated and then converted into the corresponding apparent solar time; c) the moments of the apparent solar time were calculated, that is, the moments when the selected hours according to the Italian Hours variant and hours according to the *Ore italiche da campanile* variant correspond to the contemporary equinocial system; d) by comparing these moments with what the shadow indicated, the accuracy of the sundial was verified (Table 3, Figure 5a/b and Figure 6).

Table 2: Polar coordinates of the end of the shadows during the winter solstice and equinox days

Hour	Ore italiche (Italian Hours)					Ore italiche da campanile (Bell Tower Italian Hours)				Hour
	22. XII		21. III, 23. IX			22. XII		21. III, 23. IX		
	α (°)	d (cm)	α (°)	d (cm)		α (°)	d (cm)	α (°)	d (cm)	
16	-51.9	133.9	-25.4	174.4		-40.5	117.5	-17.8	159.1	16
17	-34.2	111.2	-11.9	150.6		-24.6	104.1	-5.2	143.9	17
18	-19.3	101.2	0.0	140.2		-11.2	98.0	6.0	137.7	18
19	-6.6	96.7	11.0	136.7		0.6	95.3	16.9	136.9	19
20	4.8	94.7	21.8	138.3		11.6	94.4	27.9	141.4	20
21	15.6	94.4	33.3	145.6		22.4	94.9	40.0	153.3	21
22	26.6	95.4	46.1	163.0		33.9	97.0	53.9	180.8	21
23	38.6	98.4	61.1	204.5		46.9	102.0	70.4	253.7	23

Note: α – polar angle, d – length of a shadow

When the size and age of the sundial and the fact that it has been restored are taken into account, the observed inaccuracies are expected and practically negligible.

Table 3: Results of the Dubrovnik sundial accuracy test

Elements		Observation date	
		January 29, 2018.	April 22, 2018.
Sun declination (δ) Time equation (e) Sunset (AST) End of civil twilight (PSV) Length of civil twilight		-17,88° -13 min 06 s 16 h 51 min 17 h 26min 35 min	12,26° 1 min 26 s 18 h 46 min 19 h 21 min 35 min
Observation time	CET	12h 29 min	10 h 58 min
	AST	12 h 28 min	11 h 12 min
The shadow direction indicates		12 h 34 min (ahead 6 min)	11 h 20 min (ahead 8 min)
End of the shadow indicates		19 h	16 h
Time calculated according to the *Ore italiche* (Italian Hours) variant		11 h 51 min (behind 37 min)	10 h 46 min (behind 32 min)
Time calculated according to the *Ore italiche da campanile* (Bell Tower Italian Hours) variant		12 h 26 min (behind 2 min)	11 h 21 min (behind 1 min)

Note: CET – Central European Time, AST – Apparent Solar Time

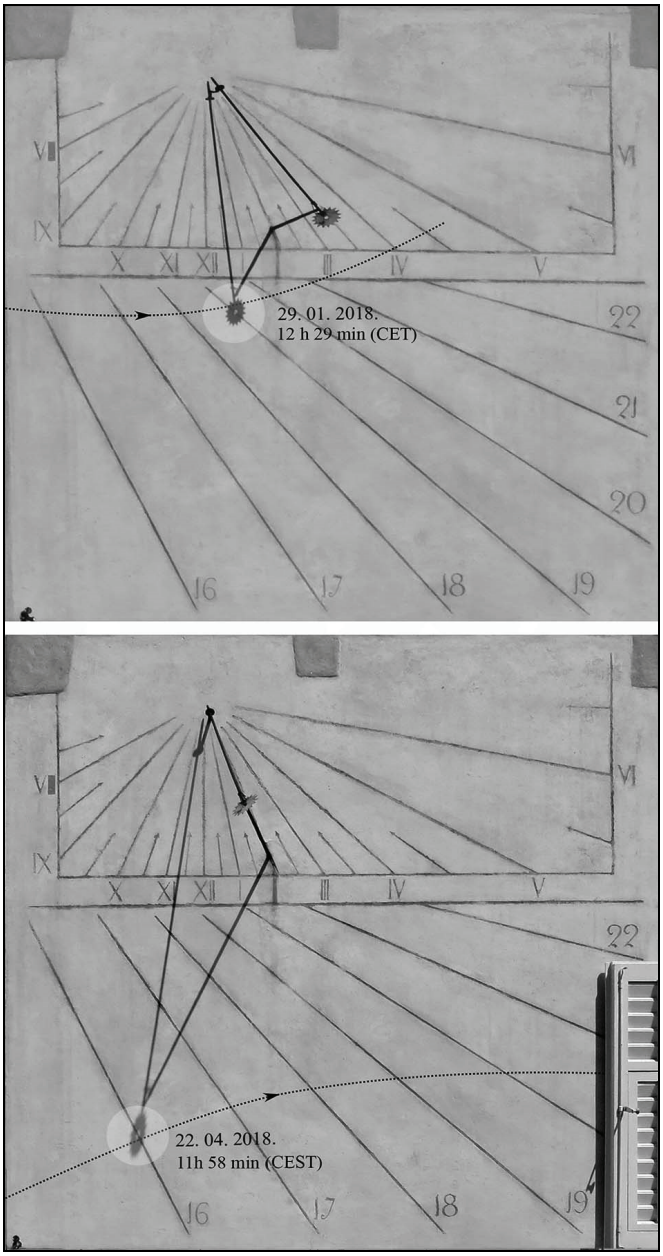

Figure 5a/b: Accuracy test of the Dubrovnik sundial: photographs contain theoretical exploration of the shadow path and the hyperbolas along which the sunlet of the shadow should move on the selected dates

Discussion

Why was the end of the evening civil twilight and not the sunset used as the zero moment for counting hours — why *Ore italiche da campanile* instead of *Ore italiche*? Because day light does not end with the sunset; it ends when the sun's disc lowers 6° below the horizon, that is, until the end of the evening civil twilight. At that moment, the gates of fortified cities used to be closed and everybody who worked outside the city hurried back. The end of the evening civil twilight was announced by church bells, so the meaning of *Ore italiche da campanile* is "bell time/hours".

On the lower scale of the sundial in Dubrovnik, the hours range from 16.00 to 22.00 according to the *Ore italiche da campanile* variant. It is the "working time" of the sundial, but not the period during which the wall it is mounted on is sunlit (Figure 6, Figure 2). The wall is sunlit from sunrise to sunset from October 16 to February 25 ($\delta = -9°$), theoretically from 13.00. From February 25 to April 13, and from August 30 to February 16, the wall is sunlit until sunset, and is shaded only in the morning. From April 13 to August 30, the wall is shaded both in the morning and in the evening. On the day of the summer solstice, for example, the wall and the sundial itself are sunlit from 9:47 to 18:14 CET, a total of 8h 27min and they are shaded for 6h 52min (4h 38min in the morning and 2h 14min in the evening), that is, they are shaded for about 45% of the daylight hours. On that day, the sunlet of the shadow appears on the sundial for only about one hour (Figure 4).

The questions when the sundial in Dubrovnik was made and who made it remain unresolved. The sundial was certainly made after the devastating earthquake of 1667, when the Franciscan friary was completely burned. According to a letter from one nobleman, it was not known "where the church and the friary had been" (Samardžić, 1983, p. 241). It is important to note that the manuscript of the *Quastiones physico-mathematicae* from the first half of the 18th century is kept in the library of the Franciscan friary. The ninth chapter of the manuscript *Gnomonica practica* is devoted to construction of sundials. The manuscript was written by a Dubrovnik poet and translator Ignjat Đurđević (1675–1735), but it is not known whether he is the author or "they were some kind of notes that he copied and used, so his signature at the beginning only indicates that they belonged to him" (Dadić, 1982, p. 235).

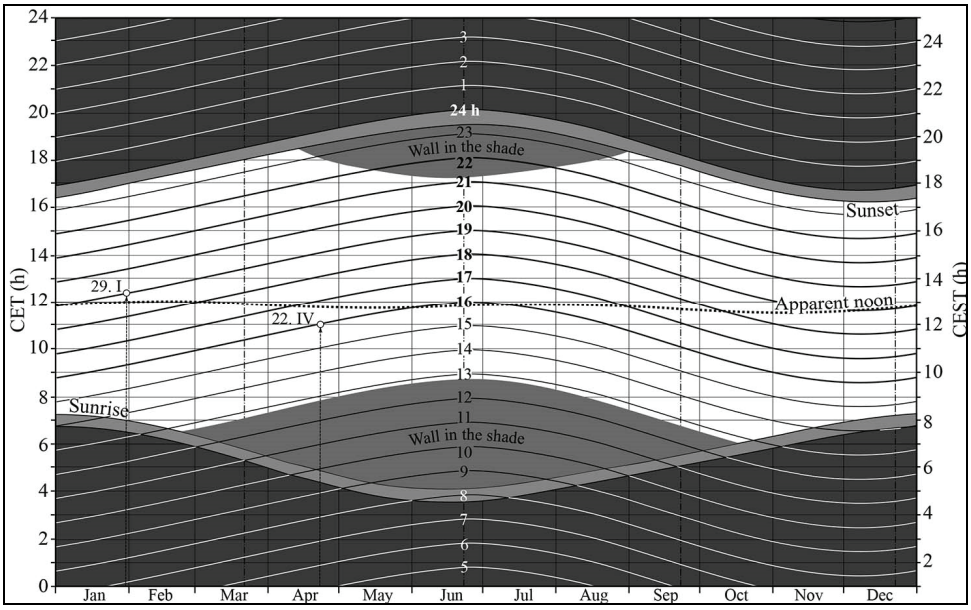

Figure 6: The ratio of hours counted from midnight and hours counted from the end of the civil twilight during the year in Dubrovnik. Circles mark the dates and hours when the accuracy test of the sundial was performed

The data on who constructed the two-scale sundial and the year of its construction remain to be found in the archives of the Franciscan friary and the archives of the Dominican and the Jesuit friaries in Dubrovnik, which also had sundials. The search could be focused to a more precise period if it is previously found in the Dubrovnik State Archive when all three variants of the equinoctial time system were brought to and used in Dubrovnik, that is, when the need to recalculate the time shown by the variant *Ore italiche da campanille* into the time indicated by the *Ore Francese* variant emerged in Dubrovnik.

Arnaldi (2007, p. 5) suggested it is erroneously believed that the counting of hours from the end of the evening civil twilight (*Ore italiche da campanile*) disappeared in the mid-18th century. Counting of hours from midnight (*Ore francese*) with 12 double hours was gradually introduced during the 18th century into Italian regions and cities: Liguria (1722), Florence (1749), Parma (1755), Milan, Mantova and Bergamo (1786), Bologna (with the entry of the French troops, 1796), Brescia (1797), etc. (Paltrinieri, 2002, p. 5). In Rome, the introduction of a new system came much later, in 1846, when the first public mechanical clock that showed time according to the *Ore francese* variant was set up at the Quirinale Palace. Public clocks in Rome continued to indicate time

according to the old variants even in the 20th century, until 1944 (Arnaldi, 2007, p. 9).

After the initials of a gnomonist who constructed the sundial in the small cloister of the Franciscan friary were discovered, the sundial was dated to the second half of the 18th century. This leads to conclusion that the modern time system came quickly from Italy to Dubrovnik. It was the formal time system during the French rule in Dubrovnik (1806–1815) and in other cities and regions occupied by the French army. The need to construct a sundial with two scales indicates the existence of two parallel time systems, as was the case in many Italian cities (Paltrinieri, 2002, p. 10).

Conclusion

Both scales of the two-scale sundial of the Franciscan friary in Dubrovnik indicate apparent solar time. Theoretical exploration and on-site observation prove that on the upper scale the direction of the shadow accurately shows the equinocial hours counted from midnight (*Ore Francese*), and on the lower scale the equinocial hours counted from the end of the evening civil twilight (*Ore italiche da campanile*) rather than from the sunset (*Ore italiche*).

The previously presented and documented theoretical exploration will make it possible for the two-scale sundial of the Franciscan friary in Dubrovnik to be preserved and, if necessary, reconstructed; the draft that shows precise position of the polos is particularly important because the polos will no longer need to be adjusted through observation. It remains to discover who constructed it and when: for now, we certainly know that the two-scale sundial of the Franciscan friary in Dubrovnik was constructed by a master gnomonist.

Acknowledgements
We deeply appreciate cordiality and assistance given to us by the Guardian of the Franciscan friary Fra Veselko Grubešić and Mr. Ante Glavor when we did on-site observations of the sundial.

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