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Review / Pregledni znanstveni članak

Precise Measurement and Analysis of the Olympic-size Swimming Pool Lanes Distance

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ABSTRACT. This paper analyzes the precise distance measurements of a long course Olympic-size swimming pool lanes in the swimming pool complex Svetice in Zagreb. Geodetic survey of 10 longitudinal pool lanes distance was performed with a hand-held laser distance meter. It is concluded that the distances of all swimming pool lanes are within dimensional tolerances provided by International Swimming Federation. By processing the data, statistical parameters of pool distances are determined. Standard measurement uncertainty of Type A, standard measurement uncertainty of Type B, combined standard measurement uncertainty and expanded measurement uncertainty are shown as measurement quality parameters. Comparative analysis between the accuracy of time measurement in swimming competitions and the distance measurement of the swimming pool is shown. It is concluded that the maximum allowable deviation from the prescribed dimensions of the pool lanes does not affect the results achieved by swimmers in competitions.

Keywords: Olympic-size swimming pool, precise distances measurement, hand-held laser distance meter, measurement uncertainty.

1. Introduction

Given the principle and physical basis on which the distances measurement is based, there are three basic methods of measurements: mechanical, optical and electronical (Benčić 1990). In this paper, the distances of 10 longitudinal lanes of the 50 m long Olympic-size swimming pool in the swimming pool complex

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Svetice in Zagreb were measured (Fig. 1) and the statistical parameters of the measurement results were analyzed.

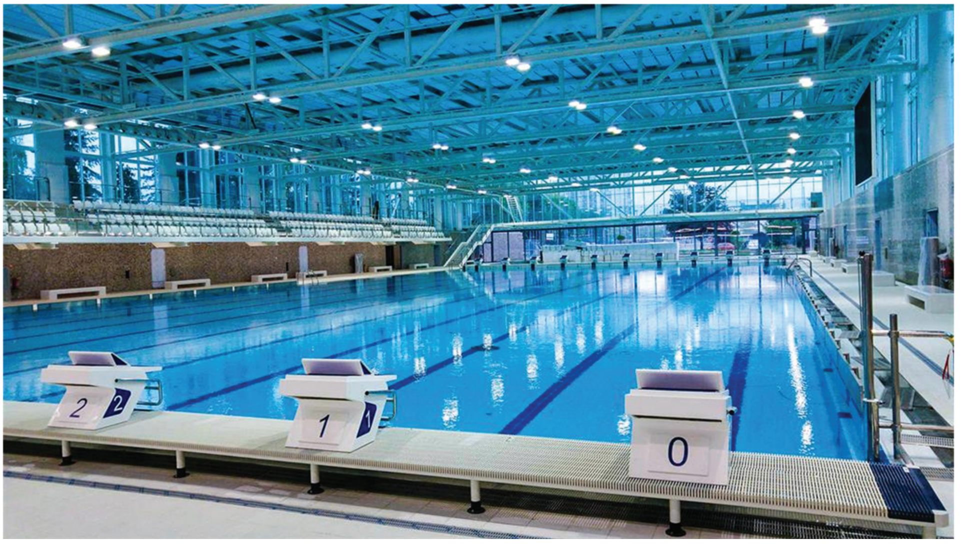


Fig. 1. *Long course Olympic-size swimming pool in the swimming pool complex Svetice in Zagreb (URL 1).*

At the request of the Natator Swimming Club, the Laboratory for Measurements and Measuring Technique of the Faculty of Geodesy, University of Zagreb performed a precise lane distances measurements of the long course Olympic-size swimming pool in the swimming pool complex Svetice in Zagreb (Fig. 2). Natator Swimming Club was founded in 2003 by Croatian Paralympian Ana Sršen, whose main goal was to create a club of equal opportunities for all people who want to swim. The goal of this club was to enter the calendar of competitions of the World Paralympic Organization, in order for the achieved results in that Olympic-size swimming pool in Zagreb to enter the World and European rankings. The condition for entering the competition calendar is that the Olympic-size swimming pool, i.e., the distance of the pool lanes must be calibrated and have a certificate of dimensions authorized by State Office for Metrology (URL 2). The authors of this paper could not find any published work in the field of distance calibration of Olympic-size swimming pools.

It is known from history that people have used various swimming techniques as a way of crossing water obstacles. As a sport, swimming has been in the program of the Olympic Games since the first modern games in 1896 in Athens, and in the program of the Paralympic Games since 1960, held in Rome. International Swimming Federation (fr. *Fédération Internationale de Natation* – FINA) is the international federation recognized by the International Olympic Committee for administering international competitions in water sports (URL 3). The aim of the Federation was to establish unified rules for swimming, diving and water polo, applicable at Olympic Games and other international competitions. For these purposes, FINA has published the Facilities Rules (FINA 2017).

One of the items in the Facilities Rules is the length of the swimming pool lanes and the admissible tolerances from the prescribed dimensions (Table 1).

Table 1. *Swimming pool dimensions (FINA 2017).*

Swimming pool length [m]	Minimum and maximum length [m]
25.000	25.020 – 25.030
50.000	50.020 – 50.030

According to the FINA Facility Rules, a 50 m long swimming pool is considered a standard Olympic-size pool. When touch panels of Automatic Officiating Equipment are used on the start or additionally on the turning end, the thickness of which are 10 mm, the pool must be of such length that ensures the required distance of 50.000 m between the two panels. Deviations from the nominal length are allowed, so that the minimum length of the Olympic-size pool is 50.020 m and the maximum 50.030 m. The number of lanes in the swimming pool depends on the type of competition, so for the needs of the Olympic Games it is necessary to provide eight lanes (1 – 8) and for the needs of the World Championships 10 lanes (0 – 9).

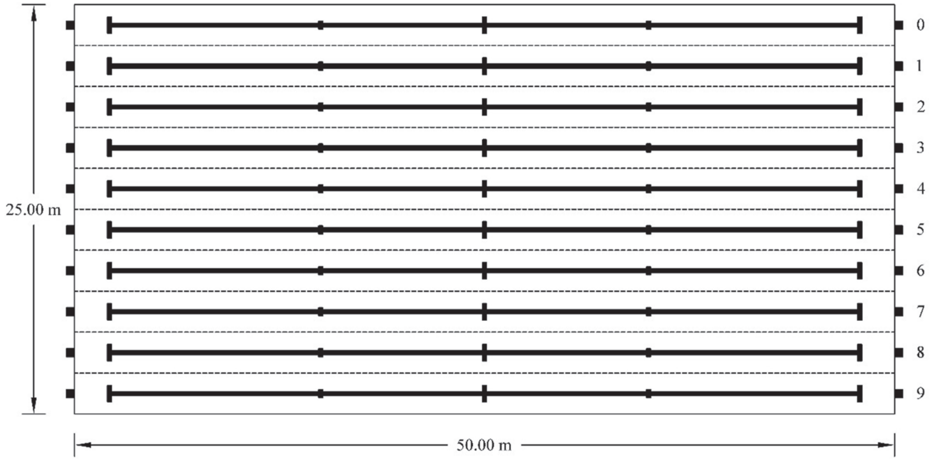
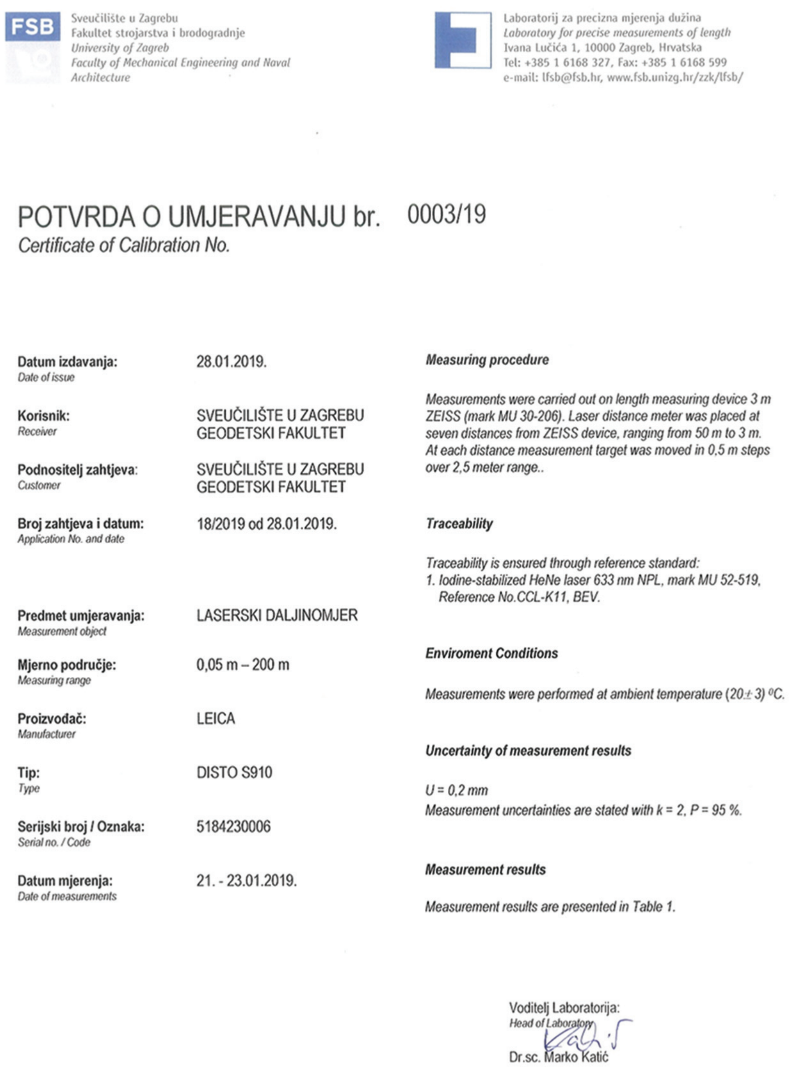


Fig. 2. *Dimensions of long course Olympic-size swimming pool in the swimming pool complex Svetice in Zagreb.*

2. Measurement Data

Geodetic distance measurements of the long course Olympic-size swimming pool lanes in the swimming pool complex Svetice were performed in two series of measurements with the hand-held laser distance meter Leica DISTO S910 (URL 4). Preliminary measurements form the first series of measurements performed on February 8, 2019. The data of the second series of measurements, which were performed on April 1, 2019, are fully presented and analyzed in this paper. Also, atmospheric parameters, $t = 25.8$ °C, $p = 992.4$ hPa, $h = 37.5\%$, were measured with a Lufft XA1000 meteorological measuring device (URL 5) with a precise temperature and hygrometer probe Lufft 8130.TFF (URL 6). The hand-held laser distance meter was calibrated in the Laboratory for Precise Measurements of Length at the Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb. As a result of calibration of the hand-held laser distance meter, the expanded measurement uncertainty value of 0.2 mm was obtained with a coverage factor $k = 2$ and a 95.4% probability (Fig. 3).



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POTVRDA O UMJERAVANJU br. 0003/19
Certificate of Calibration No.

Datum izdavanja: *Date of issue* — 28.01.2019.

Korisnik: *Receiver* — SVEUČILIŠTE U ZAGREBU GEODETSKI FAKULTET

Podnositelj zahtjeva: *Customer* — SVEUČILIŠTE U ZAGREBU GEODETSKI FAKULTET

Broj zahtjeva i datum: *Application No. and date* — 18/2019 od 28.01.2019.

Predmet umjeravanja: *Measurement object* — LASERSKI DALJINOMJER

Mjerno područje: *Measuring range* — 0,05 m – 200 m

Proizvođač: *Manufacturer* — LEICA

Tip: *Type* — DISTO S910

Serijski broj / Oznaka: *Serial no. / Code* — 5184230006

Datum mjerenja: *Date of measurements* — 21. - 23.01.2019.

Measuring procedure

Measurements were carried out on length measuring device 3 m ZEISS (mark MU 30-206). Laser distance meter was placed at seven distances from ZEISS device, ranging from 50 m to 3 m. At each distance measurement target was moved in 0,5 m steps over 2,5 meter range..

Traceability

Traceability is ensured through reference standard:
1. Iodine-stabilized HeNe laser 633 nm NPL, mark MU 52-519, Reference No.CCL-K11, BEV.

Enviroment Conditions

Measurements were performed at ambient temperature (20 ± 3) °C.

Uncertainty of measurement results

U = 0,2 mm
Measurement uncertainties are stated with k = 2, P = 95 %.

Measurement results

Measurement results are presented in Table 1.

Voditelj Laboratorija:
Head of Laboratory
Dr.sc. Marko Katić

Fig. 3. *Certificate of Calibration of hand-held laser distance meter Leica DISTO S910.*

For calibration purposes the measurements were performed in a partially emptied pool with water, at a time without the presence of swimmers. Each swimming pool lane (0 – 9) was measured three times. The measurements were performed without touch panels of Automatic Officiating Equipment. Table 2 shows the data of measurements performed on April 1, 2019.

The measured distance values were corrected for the additive correction and for the standard deviation of 0.4 mm, which was determined by calibrating the hand-held laser distance meter at a distance of 50 m. Based on the corrected values of the swimming pool lanes, the mean value and the corresponding standard deviation for each lane was determined by the arithmetic mean. Deviations of the mean lane distance value from the minimum length value 50.020 m of the Olympic-size swimming pool, which is prescribed by the FINA Facility Rules, were also calculated.

Table 2. *Distance measurements of long course Olympic-size swimming pool lanes.*

Lane number	Measured value [m]	Corrected value [m]	Mean value [m]	Standard deviation [mm]	Deviation of mean value from 50.020 m [mm]
0	50.0385	50.0285	50.02853	0.06	8.53
	50.0386	50.0286			
	50.0385	50.0285			
1	50.0348	50.0248	50.02443	0.32	4.43
	50.0342	50.0242			
	50.0343	50.0243			
2	50.0286	50.0282	50.02823	0.25	8.23
	50.0289	50.0285			
	50.0284	50.0280			
3	50.0265	50.0261	50.02577	0.31	5.77
	50.0261	50.0257			
	50.0259	50.0255			
4	50.0247	50.0243	50.02410	0.35	4.10
	50.0247	50.0243			
	50.0241	50.0237			
5	50.0295	50.0291	50.02913	0.25	9.13
	50.0298	50.0294			
	50.0293	50.0289			
6	50.0289	50.0285	50.02883	0.31	8.83
	50.0295	50.0291			
	50.0293	50.0289			
7	50.0340	50.0240	50.02417	0.15	4.17
	50.0343	50.0243			
	50.0342	50.0242			
8	50.0312	50.0260	50.02587	0.42	5.87
	50.0306	50.0254			
	50.0314	50.0262			
9	50.0396	50.0296	50.02953	0.12	9.53
	50.0394	50.0294			
	50.0396	50.0296			

3. Result Analysis

The mean distance value of each swimming pool lane and the corresponding standard deviation were determined. The mean distance of all 10 swimming pool lanes is 50.0269 m with standard deviation of 0.25 mm (Table 3). From the measurement data, the statistical indicators of the measured distances were calculated, which are shown in Fig. 4 in the form of a box plot diagram. Fig. 5 shows the standard deviations of the mean distance values of the swimming pool lanes and the linear regression equation.

Table 3. *The mean distance value of long course Olympic-size swimming pool and its standard deviation.*

Parameter	Value
The mean distance value	50.0269 m
Standard deviation	0.25 mm

When measuring the distance of the long course Olympic-size swimming pool, a relative measurement accuracy of 1 : 200 108 was achieved. According to Benčić and Solarić (2008), the distances measurement is classified into the categories according to their relative accuracy (Table 4). The achieved relative measurement accuracy of 1 : 200 108 belongs to the category of precise distances measurement.

Table 4. *Distances measurement categories according to relative accuracy (Benčić and Solarić 2008).*

Distances measurement category	Relative accuracy
Highly accurate	$< 10^{-6}$
Precise	$10^{-6} – 10^{-5}$
Medium accurate	$10^{-5} – 10^{-4}$
Ordinary	$> 10^{-4}$

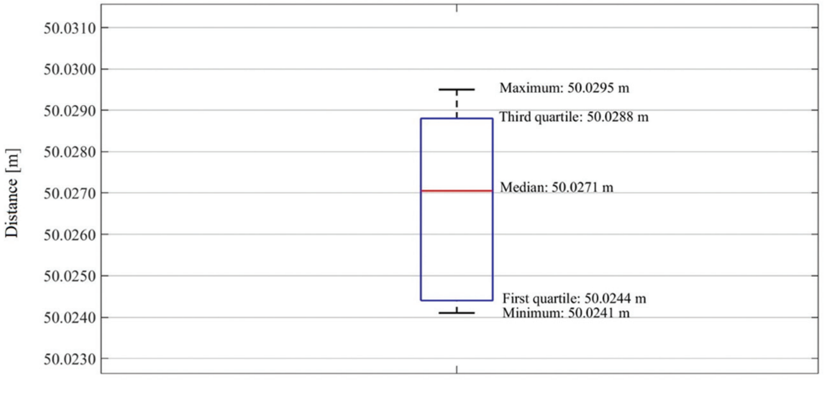

Fig. 4. *Statistical indicators of the measured long course Olympic-size swimming pool lane distances.*

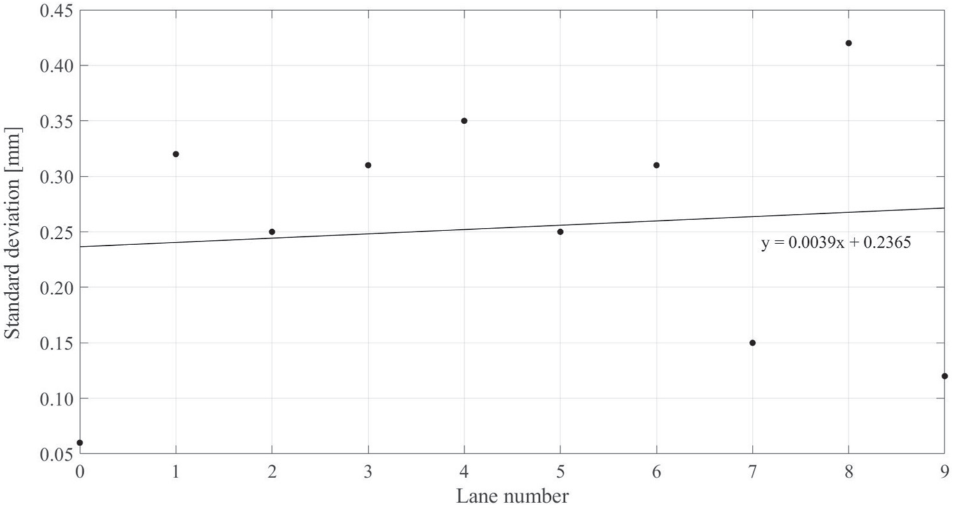

Fig. 5. *Standard deviations of long course Olympic-size swimming pool lanes mean distance values and the linear regression equation.*

3.1. Estimation of measurement uncertainty

The presentation of measurement results must be clear and unambiguous in order for their quality to be objectively assess. Thus, the quality of measurement results is most often determined by estimating the measurement uncertainty.

The measurement uncertainty of the results consists of several components which, according to the way in which their numerical value is estimated, can be classified into two classes: uncertainty of Type A and uncertainty of Type B. The standard measurement uncertainty of Type A is determined based on the statistical distribution of the measurement series. The standard measurement uncertainty of Type B is determined from the assumed probability distributions based on experience as well as from other data. Both standard measurement uncertainties are quantitatively expressed by variances, i.e., standard deviations (ISO/IEC 2008, Benčić and Solarić 2008).

Standard measurement uncertainty of Type A, u_A, is a component of measurement uncertainty whose estimation is determined by statistical analysis of values determined by repeated measurements under prescribed conditions. It is calculated according to the expression (Benčić and Solarić 2008):

$$u_A = \frac{s}{\sqrt{n}} \tag{1}$$

where:

s – standard deviation of repeated measurements,
n – number of repeated measurements.

Standard measurement uncertainty of Type A depends on the number of measured values n and theoretically the measurement uncertainty should decrease with the increased number of measurements. The number of measurements should be large enough to ensure that the mean value of the results from n size measurements gives a reliable estimation of the random variable expectations. To express the measurement uncertainty, it is recommended to apply the Student's t-distribution factor in the case of a small number of repeated measurements ($n < 10$) (Benčić and Solarić 2008).

The estimate of the standard measurement uncertainty of Type B is calculated by scientific judgment based on all available data on the possible variability of the input data. Such input data can include previous measurement data, experience with substances and instruments or general knowledge of behavior and properties of essential substances and instruments, manufacturer specifications, data given in calibration certificates and other certificates, and uncertainties assigned to reference data taken from the manual (ISO/IEC 2008). The standard measurement uncertainty of Type B, u_B, in this paper is defined as:

$$u_B = \text{device calibration data.}$$

As a final expression of the measurement result uncertainty, combined standard measurement uncertainty, u_c, is used, and it is calculated according to the expression (Benčić and Solarić 2008):

$$u_c = \sqrt{u_A^2 + u_B^2} \tag{2}$$

where:

u_A – standard measurement uncertainty of Type A,
u_B – standard measurement uncertainty of Type B.

However, it is often required to express a measurement uncertainty that determines the interval around a measurement result for which it can be expected to include a large portion of value distribution that can be associated with the measured quantity within reason. Such measure of uncertainty is called expanded measurement uncertainty, K, and it is calculated according to the expression (Benčić and Solarić 2008):

$$K = k \cdot u_c , \tag{3}$$

where:

k – coverage factor, which for the 95.4% probability is 2,
u_c – combined standard measurement uncertainty.

Estimates of standard measurement uncertainty of Type A, standard measurement uncertainty of Type B, compiled standard measurement uncertainty and extended measurement uncertainty are presented as measurement quality parameters. As an estimate of the standard measurement uncertainty of Type B, the measurement uncertainty of the hand-held laser distance meter from the calibration certificate was taken (Fig. 3). Table 5 shows the estimated values of the measurement uncertainty parameters of the measured long course Olympic-size swimming pool lanes distance in the swimming pool complex Svetice.

Table 5. *Estimated values of measurement uncertainty parameters.*

Parameter	Value [mm]
Standard measurement uncertainty of Type A, u_A	0.63
Standard measurement uncertainty of Type B, u_B	0.10
Combined standard measurement uncertainty, u_c	0.63
Expanded measurement uncertainty, K	1.27

3.2. Statistical testing

Geodetic measurements and observations are empirical values that are suitable for statistical analysis, although in most cases amount of data is smaller. Statistical analysis is performed for the purpose of objective and more accurate understanding and presentation of geodetic measurement results. In geodesy, statistical tests are most often used for the purpose of checking the quality of measurements or the results of computational processing.

Statistical testing also makes it possible to compare the parameters of two basic sets, so that the assumed arithmetic means or variances of the two sets can be compared. Because two series of swimming pool lane distance measurements were performed, standard deviations were calculated for each series of measurements. Based on this data, a statistical test of two standard deviations of probability distributions, known as the Fisher test, was performed.

One sample was selected from each of the two statistical sets distributed according to the normal distribution. Based on these samples, standard deviations of statistical sets s_1 and s_2 were determined with the number of degrees of freedom f_1 and f_2. The test is needed to determine if these sets have the same standard deviation. For this purpose, the null hypothesis and alternative hypothesis are set (Feil 1990):

$$H_0 : \frac{\sigma_1}{\sigma_2} = 1 , \tag{4}$$

$$H_a : \frac{\sigma_1}{\sigma_2} > 1 , \tag{5}$$

Hypothesis H_0 can be tested on a sample basis using test statistic F, which contain sample variances s_1^2 and s_2^2, which are distributed according to Fisher's distribution (Feil 1990):

$$F = \frac{s_1^2}{s_2^2}. \tag{6}$$

Hypothesis H_0 is accepted if the value of the ratio of variances s_1^2 / s_2^2 calculated from the samples satisfies the condition (Feil 1990):

$$F = \frac{s_1^2}{s_2^2} < F_{f_1;f_2;1-\alpha} . \tag{7}$$

Fractile $F_{f_1;f_2;1-\alpha}$ for a certain significance level α is taken from statistical tables (Pavlić 1970). If the variances of the samples s_1^2 and s_2^2 have different values, when calculating the test statistic F, a larger variance should be included in the numerator because the number of degrees of freedom cannot change the order.

Table 6 shows the input parameters for conducting the Fisher test, that are used to calculate the test statistic and fractile. The fractile $F_{29;29;0.95}$ was read from statistical tables with the significance level of 0.05 (Pavlić 1970). The statistical test examines the null hypothesis and, depending on the results of the statistical test, the null hypothesis is accepted or rejected, i.e., the alternative hypothesis is rejected or accepted. According to the data in Table 6, the null hypothesis is accepted with a probability of 95%. Acceptance of the null hypothesis means that the empirical standard deviations of two independent measurement series belong to the same sample, i.e., that the same measurement uncertainty of distance measurements is achieved.

Table 6. *Parameters of statistical test of two standard deviations of probability distributions.*

Parameter	Value
Mean distance standard deviation of 1st measurement series, s_1	0.25 mm
Mean distance standard deviation of 2nd measurement series, s_2	0.25 mm
Number of degrees of freedom in 1st measurement series, f_1	29
Number of degrees of freedom in 2nd measurement series, f_2	29
Test statistic, F	1.00
Fractile, $F_{29;29;0.95}$	1.86
Null hypothesis H_0 is accepted.	

4. Ratio of Time and Distance Measurements Accuracy

Timekeeping technology in sports competitions is a key part of competition and has improved significantly from the mid-20th century to the present day. The second is the base unit of time in the International System of Units (SI) and it is defined as being equal to the time duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the fundamental unperturbed ground-state of the caesium 133 atom (BIPM 2019).

Today, high-tech devices, including high-speed cameras, electronic touch panels, infrared rays, radio transmitters and similar, are used for the precise time measurement at sports competitions. Thanks to advanced technology, clocks in swimming competitions can measure time with an accuracy of 10^{-6} seconds, but many sports federations, including FINA, tend to display time per one-hundredth of a second (URL 7, URL 8). The reason for this is the insufficient level of precision during pool or racetrack construction. The pool should be built exactly symmetrically so that every lane is the exact same length down to fractions of millimeters, so that it would make sense to expresses the time of the competitors in a one-thousandth of a second. Today, swimming pools are typically built to specifications that are within centimeters.

FINA Facility Rules define an admissible difference in the swimming pool length of one centimeter. It is possible to consider how much this maximum tolerance has an impact on the time achieved by swimmers in competitions. If the achieved world record of 20.91 s in the men’s 50 m freestyle in long course swimming, is considered as a reference time and discipline, it follows that a swimmer needs 0.004 s to swim 1 cm in pool distance (Table 7). Since it is four thousandths of a second, and the time in swimming competitions is expressed in one-hundredth of a second, it can be concluded that one centimeter difference in the length of the pool has no effect on the time achieved by swimmers.

If the condition is set that the time in swimming competitions is expressed in a one-thousandth of a second, the pool must be built with a millimeter precision. In Table 7, the ratio of time and distance measurements accuracy is calculated. If the time in swimming competitions was expressed in one-thousandths of a second, the difference in the distances of the swimming pool lanes should not exceed 2.4 mm, if the world record in the men’s 50 m freestyle in long course swimming is considered (Table 7). Given that, an improvement of the world record time in swimming can be expected, in the future it should be considered that the criteria and tolerances for the swimming pools construction should be tightened, and thus increase the accuracy of time measurement up to a one-thousandth of a second.

Table 7. *Ratio of time and distance measurements accuracy.*

World record on 50 m: 20.91 s (freestyle, men)	
Time versus distance	
0.01 s	2.39 cm
0.001 s	2.39 mm
Distance versus time	
1 cm	0.0042 s
1 mm	0.00042 s

5. Conclusion

According to geodetic measurements and statistical analysis of the long course Olympic-size swimming pool lane distances in the swimming pool complex Svetice, it can be concluded that the distances of the pool lanes are within the admissible deviation prescribed by the International Swimming Federation. Distance calibration report was prepared for the purpose of issuing State Office for Metrology certificate of dimensions so that the results achieved by swimmers in that swimming pool could enter the World and European rankings.

In accordance with the permitted deviations from the prescribed dimensions in the FINA Facility Rules, the length of the pools may differ within one centimeter. According to the calculations in this paper, it is obtained that 1 cm of pool length, for the world record in the men's 50 m freestyle in long course swimming of 20.91 s, is 0.004 s in time. This means that if the Olympic-size swimming pool is made in accordance with the Facility Rules, this difference in the lane distances will not affect the time that swimmers achieve in competitions.

If the condition is set that the time in swimming competitions is expressed in one-thousandths of a second, the construction of the pool should be at the millimeter level, which is a special requirement for civil and surveying engineers. Today, distance measuring is the most complex and demanding area in geodesy in terms of the number and variety of measurement instruments, especially due to the development of electronic distance meters. During precise distance measurement with electro-optical distance meters, it is very important to accurately measure the atmospheric parameters of the air through which the electromagnetic wave passes because the measured distances need to be corrected for the influence of various errors, corrections and reductions. More about precise distance measurements in the form of consideration of measurement errors, corrections and reductions in precise distance measurement for future measurements when the criteria for expressing time at sports competitions are tightened, can be read in Benčić and Solarić (2008), Zrinjski (2010), Barković et al. (2016), Zrinjski et al. (2019).

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Precizna izmjera i analiza duljine plivačkih staza olimpijskog bazena

SAŽETAK. U radu je analizirano precizno mjerenje duljina plivačkih staza olimpijskog bazena u bazenskom kompleksu Svetice u Zagrebu. Geodetska izmjera duljine 10 uzdužnih plivačkih staza bazena obavljena je ručnim laserskim daljinomjerom. Računskom obradom ustanovljeno je da su duljine plivačkih staza unutar dopuštenih odstupanja od dimenzija koje je propisala Međunarodna plivačka federacija. Analizom rezultata određeni su statistički pokazatelji mjerenih duljina bazena. Kao parametri kvalitete mjerenja iskazana su standardna mjerna nesigurnost A-vrste, standardna mjerna nesigurnost B-vrste, sastavljena standardna mjerna nesigurnost te proširena mjerna nesigurnost. Iskazan je odnos točnosti mjerenja vremena na plivačkim natjecanjima i duljine bazena. Ustanovljeno je da maksimalno dopušteno odstupanje od propisanih duljina plivačkih staza bazena nema utjecaj na rezultate koje ostvare plivači na natjecanjima.

Ključne riječi: olimpijski bazen, precizno mjerenje duljina, ručni laserski daljinomjer, mjerna nesigurnost.

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