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Results of Many Years' Measurements Conducted at the Czech State Long Distances Measuring Standard Koštice

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Abstract. Currently, electronic total stations based on the principles of laser long-range distance measurement are used for collecting geospatial information. As time goes, in the process of using the electronic total stations, their technical parameters vary, necessitating periodic calibration of the instruments. Calibration of the long-range distance measurement laser component of the electronic total stations is carried out at specialized baselines and consists in testing the constant component of an electronic total station, determining the scale error and determining the cyclic error. In the territory of the Czech Republic, two geodetic baselines are operated, the National Calibration Baseline Hvězda and Koštice. Koštice is the Czech State Long Distances Measuring Standard, where electronic total stations are calibrated. From 2017 to 2020, about 600 electronic total stations by different manufacturers Leica Geosystems, Trimble, Topcon, Sokkia, Nikon, Pentax, South and Geomax were calibrated. The total number of measurements performed under the program in all combinations has equaled about 40000. In this paper, results of analysis many years' measurements performed at the geodetic baseline Koštice from 2017 to 2020 with electronic total stations manufactured by Leica Geosystems are presented. In total, 9186 measurements between the baseline sections 1–2, 1–3, 1–4, 1–5, 1–6, 1–7 and 1–8 have been analyzed. For each section, measurements have been detected which did not pass the Grubbs test criterion (the Smirnov – Grubbs test). Altogether, 261 outliers have been detected, totaling 3 % of the total number of measurements. After excluding the detected outliers with the algorithm of the parametric version of least squares optimization, the length of each section of the baseline was found, and the accuracy of the results obtained was evaluated. The calculated values of the length of the baseline sections are in generally good agreement with the results of the measurements performed at the geodetic baseline Koštice by the specialists from the laboratory of the Bundeswehr University in Munich (Germany) and the results of similar measurements conducted at the same baseline by the specialists from the Research Institute of Geodesy, Topography and Cartography (Czech Republic). For section 1–5, based on the results of both verifications, differences have been obtained exceeding the permissible values of the accuracy of determining baseline characteristics. This may be related to the fact that there are displacements of certain pillars, which mainly have a periodic character and depend on the season. To allow more specific assumptions regarding instability of certain pillars, it is recommended to verify the lengths of the baseline sections once in three months, according to the program in all combinations, which will allow comparison of the values of the confidence limits of the baseline section lengths and putting forward hypotheses regarding variations in the position of individual centers, so that the deviations revealed should be included into the residual uncertainty of length measurement.

Keywords: geodetic baseline Koštice, Smirnov – Grubbs test, algorithm of the parametric version of least squares optimization, displacements of pillars

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Результаты многолетних измерений на линейном базисе Коштице

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Реферат. В настоящее время для сбора геопространственной информации широко используются электронные тахеометры, основанные на принципах лазерной дальнометрии. В процессе эксплуатации изменяются их технические

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параметры и возникает необходимость периодической калибровки. Она осуществляется на специальных линейных базисах и состоит в поверке постоянной составляющей электронного тахеометра, определении ошибки масштаба и циклической ошибки. На территории Чешской Республики действуют два линейных базиса – Гвезда и Коштице. Последний является национальным государственным эталоном длины дальних расстояний, на котором осуществляются поверки электронных тахеометров. С 2017 по 2020 год здесь выполнена калибровка порядка 600 тахеометров различных фирм (Leica Geosystems, Trimble, Topcon, Sokkia, Nikon, Pentax, South и Geomax), общее количество измерений во всех комбинациях около 40000. В статье представлены результаты анализа многолетних измерений, проведенных на линейном базисе Коштице тахеометрами фирмы Leica Geosystems. Исследованы 9186 измерений между секциями базиса 1–2, 1–3, 1–4, 1–5, 1–6, 1–7 и 1–8. По каждой секции выявлялись измерения, которые не прошли заданный критерий Смирнова – Граббса, обнаружен 261 выброс, что составляет 3 % всех измерений. После исключения выбросов с помощью алгоритма параметрической версии МНК-оптимизации определена длина каждой секции базиса и выполнена оценка точности полученных результатов. Вычисленные значения длин секций в целом хорошо согласуются с результатами измерений, проведенных на линейном базисе Коштице Лабораторией геодезии Военного университета Мюнхена (Германия) и Научно-исследовательского института геодезии, топографии и картографии. По секции 1–5 в ходе обоих сравнений получены разности, превышающие допустимые значения точности определения характеристик базиса. Это может быть связано с тем, что по отдельным пунктам наблюдаются смещения, которые носят в основном периодический характер и зависят от времени года. Для более конкретных предположений о нестабильности отдельных пунктов рекомендуется проводить поверку длин секций базиса один раз в три месяца по программе во всех комбинациях, что позволит сопоставлять значения доверительных границ длин секций базиса и выдвигать гипотезы о колебаниях положения отдельных центров. В дальнейшем это позволит включать полученные смещения в остаточную неопределенность измерения длины.

Ключевые слова: линейный базис Коштице, тест Смирнова – Граббса, параметрическая версия МНК-оптимизации, смещения пунктов линейного базиса

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Introduction

In the modern post-industrial society, obtaining information is a key factor for developing the economy of any country. The quality and relevance of obtaining this information are determined with the help of national meorological services, as well as the organizations-in-charge, which may be invited to evaluate the accuracy, reliability and completeness of the geospatial data obtained.

Currently, to collect geospatial information, linear measurement tools are used, based on laser long-range measurements. Such tools primarily include electronic total stations and ground-based laser scanners. Such measurement tools mainly include electronic total stations and laser scanners. As during time, the technical parameters of instruments change in the process of operation of linear measurement tools, a necessity arises to calibrate them from time to time. Metrological calibration of electronic total stations is performed on the basis of the following regulatory and technical documentation [1–3].

Metrological calibration of electronic total stations is carried out on specialized baselines, which are geodetic installations containing a totality of special structures (pillars) erected in the location and forming intervals the lengths of which are known to the accuracy set. For example, in the territory of the USA, the US National Geodetic Survey, in cooperation with different government institutions, universities, and professional communities, has established about 400 permanently functioning baselines, thanks to which surveyors have access to the local length standard and can verify electronic total stations in any part of the country [4].

The design of baselines is practically similar, the difference mainly caused only by the length and the number of pillars. Table 1 contains the total information with brief description of the structures of certain baselines.

In the territory of the Czech Republic, there are currently two functioning geodetic baselines, Hvězda and Koštice. The Hvězda baseline is 960 m long and consists of 7 pillars. The lengths of all the baseline sections have been measured in all combinations and are characterized by standard uncertainty of 1.0 mm. The Hvězda baseline is mainly used for calibrating electronic distance meters. The Koštice baseline is 1450 m long and consists of 12 pillars. Similarly to the Hvězda baseline, the Koštice baseline is used for calibrating electronic distance meters [17].

Table 1

The details of certain baselines

Name of baseline (country)	Year of establishment	Baseline length, m	Number of pillars	Section lengths, m
Nummela Standard Baseline (Finland) [5]	1947	864	6	24, 72, 216, 432, 864
The baseline of Research Institute of Physical, Technological and Radiometric Measurements (Russia) [6]	–	3275	10	915, 1285, 1294, 1318, 1366, 1531, 1638, 2538, 3275
Chengdu Standard Baseline (China) [5]	1998	1488	12	384, 576, 720, 762, 773, 788, 828, 888, 1008, 1248, 1488
PTB Baseline (Germany)* [7]	–	600	8	50, 100, 150, 250, 350, 500, 600
BEV Geodetic Baseline (Austria) [8]	2006	1080	7	30, 120, 270, 480, 750, 1080
UPV Calibration Baseline (Spain) [9, 10]	2007	330	6	28, 94, 198, 282, 330
Kyviskes Calibration Baseline (Lithuania) [11]	1996	1320	6	100, 360, 1120, 1300, 1320
Javoriv Geodetic Base (Ukraine) [12]	2003	2260	19	5, 10, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 130, 240, 589, 978, 2260
Gödöllö Standard Baseline (Hungary) [13, 14]	1986	864	5	24, 216, 432, 864
Vääna Calibration Baseline (Estonia) [15]	1987	1344	13	374, 376, 380, 384, 408, 432, 480, 576, 768, 960, 1152, 1344
O. P. Suchkov Standard Spatial Base (Russia) [16]	1976	1104	18	24, 48, 72, 96, 120, 144, 168, 192, 408, 420, 648, 660, 888, 900, 1092, 1104

* 60 temperature gauges along the measurement line, 6 air moisture gauges, and 2 atmospheric pressure gauges.

The geodetic baseline Košťice

The geodetic baseline Košťice is located along the motorway Košťice – Libčeves and was constructed between 1979 and 1980 not far from the village of Košťice in the Louny district of the Czech Republic (Fig. 1).

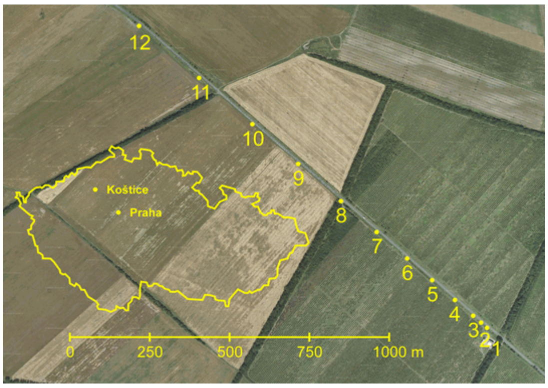

Fig. 1. A schematic of the geodetic baseline Košťice

The geodetic baseline Košťice consists of 12 pillars established to the depth from 5 to 9 m, situated at the distances from 25 to 1450 m. The pillars are equipped with devices for forced centering.

Based on the results of many years' measurements on the geodetic baseline Košťice, displacements of pillars were revealed in the range from decimal fractions of a millimeter to several millimeters per year, with deviations being mainly periodic [18]. Too ensure investigation of periodic deviations, inclinometers have been established on pillars one and three (Fig. 2).

Fig. 2. Pillar one of the geodetic baseline Košťice

On pillar one, the inclinometer PDS-FM3NT-30 by Senceive Ltd (Great Britain) is mounted, and on pillar three, the inclinometer JN 2201 by IFM Electronic GmbH (Germany). Table 2 shows certain technical characteristics of the inclinemeters used.

Table 2

Certain technical characteristics of inclinometers

Parameter	JN 2201	PDS-FM3NT-30
Resolution	0.01°	0.0001°
Repeatability	≤ ± 0.01°	±0.0005°
Angular range	±45°	±90°

In 2006, works were conducted at the geodetic baseline Koštice on international comparison of lengths by a team of the Laboratory of Geodesy of the Bundeswehr University in Munich (BUM) (Germany). Table 3 contains the results of these comparisons [18].

From 2008, the geodetic baseline Koštice is the Czech State Long Distances Measuring Standard, and the National Research Institute of Geodesy, Topography and Cartography (RIGTC), just like the laboratory of the Czech Metrology Institute, takes part in the research project of the Ministry of Industry and Trade of the Czech Republic.

Materials and methods

From 2017 to 2020, calibration of about 600 electronic total stations manufactured by Leica Geosystems, Trimble, Topcon, Sokkia, Nikon, Pentax, South and Geomax was performed at the geodetic baseline Koštice. The total number of measurements performed under the program in all combinations was about 40000, out of which only those measurements were selected for further analysis which were performed with the electronic total stations Leica between baseline sections 1–2, 1–3, 1–4, 1–5, 1–6, 1–7 and 1–8 (Tab. 4).

Table 3

Comparison results

Pillars	Research Institute of Geodesy, Topography and Cartography		Bundeswehr University in Munich		Difference, mm
	Distance between pillars *S*, m	Standard uncertainty σ, mm	Distance between pillars *S*, m	Standard uncertainty σ, mm	
1–2	25.0892	0.5	25.0881	0.4	1.1
1–3	58.0519	0.5	58.0500	0.4	1.9
1–4	133.8831	0.6	133.8810	0.4	2.1
1–5	228.9825	0.8	228.9811	0.4	1.4
1–6	332.9594	1.1	332.9586	0.4	0.8
1–7	459.8596	1.5	459.8584	0.4	1.2
1–8	608.8432	1.9	608.8415	0.4	1.7
1–9	787.0671	2.4	787.0651	0.4	2.0
1–10	977.8891	3.0	977.8827	0.5	6.4
1–11	1199.9900	3.6	1199.9907	0.5	–0.7
1–12	1450.0077	4.4	1450.0112	0.5	–3.5

Table 4

Original data

Baseline section	2017		2018		2019		2020	
	Number of electronic total stations	Number of measure-ments	Number of electronic total stations	Number of measure-ments	Number of electronic total stations	Number of measure-ments	Number of electronic total stations	Number of measure-ments
1–2	66	336	105	483	102	474	64	288
1–3	66	333	105	483	102	474	64	288
1–4	66	318	105	459	102	465	64	288
1–5	66	282	105	393	102	429	64	264
1–6	66	207	105	312	102	342	64	216
1–7	66	204	105	312	102	339	64	204
1–8	66	198	105	297	102	309	64	189
Total	66	1878	105	2739	102	2832	64	1737

Each set of data obtained for different baseline sections (Tab. 4) was analyzed with the Smirnov – Grubbs test at the level of significance $\alpha = 0.05$ [19–20].

After excluding the detected outliers for each set of data with the algorithm of the parametric version of least squares optimization, the length of each verified baseline section was calculated

$$\mathbf{S} = \left(\mathbf{A}^{\mathbf{T}} \cdot \mathbf{K}^{-1} \cdot \mathbf{A}\right)^{-1} \left(\mathbf{A}^{\mathbf{T}} \cdot \mathbf{K}^{-1} \cdot \mathbf{L}\right), \qquad (1)$$

where $\mathbf{A} = \{1_i\}$ is the column vector, consisting of unities; $\mathbf{L} = \{S_i\}$ is the vector of free terms, which are a totality of the measurement results S_i, performed on the processed section; $\mathbf{K}$ is the diagonal covariance matrix of the type of $\mathbf{K} = \mathrm{diag}\{m_i^2\}$, where m_i stands for root mean-square errors of measuring distances S_i with electronic total stations. Index i varies from unity to the number of measurements in a section equal to n.

The precision of determining the section lengths calculated by algorithm (1) was evaluated using the formula

$$m_S = \mu\sqrt{\left(\mathbf{A}^{\mathbf{T}} \cdot \mathbf{K}^{-1} \cdot \mathbf{A}\right)^{-1}}, \qquad (2)$$

where μ^2 is the a-posteriori value of the scale precision index (SPI) [21].

Then the zero hypothesis was verified regarding insignificance of the difference of the a-posteriori value of the SPI μ^2 from its a priori value σ_0^2, theoretically equal to a unity

$$H_0 = \left\{E\left(\sigma^2\right) = \sigma_0^2 = 1\right\}, \qquad (3)$$

where $E(\sigma^2)$ is the average of distribution of the scale precision index (SPI).

The hypothesis was verified with the following test

$$\chi_э^2 = \left(\mathbf{A} \cdot \mathbf{S} - \mathbf{L}\right)^{\mathbf{T}} \cdot \mathbf{K}^{-1} \cdot \left(\mathbf{A} \cdot \mathbf{S} - \mathbf{L}\right) \qquad (4)$$

and by the 5 % χ^2-distribution with the degree of freedom (n – 1)

$$\chi_T^2 = \left[\chi_{\alpha/2;\,n-1}^2;\ \chi_{1-\alpha/2;\,n-1}^2\right]. \qquad (5)$$

When $\chi_э^2 \notin \chi_T^2$, the zero hypothesis was rejected.

Results

Out of 9186 measurement values obtained by the specialists of RIGTC when calibrating the Leica electronic total stations, between sections 1–2, 1–3, 1–4, 1–5, 1–6, 1–7 and 1–8, according to the Smirnov – Grubbs test, 261 outliers were detected, which constitutes 3 % of the total number of measurements. After excluding the detected outliers, the lengths of eight sections 1–2, ..., 1–8 were found with the algorithm of the parametric version of least squares optimization (2) for the measurements made in 2017–2020 and the measurements made in the period from 2017 to 2020. Table 5 contains the results of calculating the section lengths and evaluation of the accuracy of the obtained values.

Then the obtained values of the section lengths were compared with the results of measurements performed at the Koštice baseline, at international comparison of lengths performed by the specialists of the Laboratory of Geodesy of the BUM and of the RIGTC. The comparison results are shown in Tab. 6.

Table 5

The calculated baseline section lengths, m, and their SPI, mm

Pillars	2017		2018		2019		2020		2017–2020	
	S	m_S	S	m_S	S	m_S	S	m_S	S	m_S
1–2	25.0906	0.1	25.0907	0.1	25.0896	0.1	25.0914	0.1	25.0903	0.5
1–3	58.0492	0.1	58.0505	0.1	58.0495	0.1	58.0510	0.1	58.0501	0.5
1–4	133.8797	0.1	133.8810	0.1	133.8799	0.1	133.8808	0.1	133.8805	0.5
1–5	228.9783	0.2	228.9791	0.1	228.9795	0.1	228.9801	0.2	228.9795	0.5
1–6	332.9576	0.2	332.9593	0.2	332.9592	0.1	332.9602	0.2	332.9592	0.5
1–7	459.8582	0.2	459.8604	0.2	459.8606	0.2	459.8604	0.2	459.8600	0.6
1–8	608.8404	0.2	608.8423	0.2	608.8429	0.2	608.8447	0.2	608.8427	0.6

Table 6

The results of comparison of baseline section lengths

Pillars	The average value for 2017–2020	BUM (2006)	RIGTC (2007)	Differences, mm		m_2, mm	m_3, mm	m_4, mm	Allowance 2–3	Tolerance 2–4
				2–3	2–4					
	Section lengths, m									
1	2	3	4	5	6	7	8	9	10	11
1–2	25.0903	25.0881	25.0892	2.2	1.1	0.5	0.4	0.5	1.3	1.4
1–3	58.0501	58.0500	58.0519	0.1	–1.8	0.5	0.4	0.5	1.3	1.4
1–4	133.8805	133.8810	133.8831	–0.5	–2.6	0.5	0.4	0.6	1.3	1.5
1–5	228.9795	228.9811	228.9825	–1.6	–3.0	0.5	0.4	0.8	1.3	1.8
1–6	332.9592	332.9586	332.9594	0.6	–0.2	0.5	0.4	1.1	1.3	2.4
1–7	459.8600	459.8584	459.8596	1.6	0.4	0.6	0.4	1.5	1.4	3.2
1–8	608.8427	608.8415	608.8432	1.2	–0.5	0.6	0.4	1.9	1.4	3.9

In Tab. 6 the permissible values of differences in columns 2–3 and 2–4 (d^{perm}) were formed at the level of significance $\alpha =$ 0.05 in supposition of the fact that these differences have standard normal distribution: $d^{perm} = 1.96 m_d$, where the values $m_d = \sqrt{m_2^2 + m_{3(4)}^2}$.

The calculated values of the section lengths and shown in Tab. 6 (column 2) are generally in good agreement with the measurement results (column 3), performed at the Koštice baseline by the specialists of the Laboratory of Geodesy of the BUM and the results of similar measurements (column 4) performed at the same baseline by the specialists of RIGTC. For section 1–5, based on the results of both comparisons, differences were obtained, exceeding the permissible values of the precision of determining the baseline characteristics. This may be related to the fact that for certain pillars, deviations were observed, which were, as noted above, mostly periodic.

To allow more specific assumptions regarding instability of certain pillars, it is recommended to verify the lengths of the baseline sections once in three months, according to the program in all combinations, which will allow comparison of the values of the confidence limits of the baseline section lengths and putting forward hypotheses regarding variations in the position of individual centers, so that the deviations revealed should be included into the residual uncertainty of length measurement.

CONCLUSION

The studies conducted on the results of the works performed by the specialists of the Research Institute of Geodesy, Topography and Cartography (the laboratory of the Czech Metrology Institute), as well as comparison of these results with the materials obtained by the specialists of the Laboratory of Geodesy of the Bundeswehr University in Munich (Germany), allow us to agree with the previously made assumptions regarding certain displacement of individual pillars at the Koštice baseline. Therefore, the specialists of the Engineering Geodesy and Metrology Department of the Research Institute of Geodesy, Topography and Cartography of the Czech Republic perform repeated measurements of the section lengths of the baseline once every two months according to the program in all combinations, thus determining the relevant standard lengths of each baseline section.

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