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CALIBRATION OF ACCURATE ELECTRO-OPTICAL RANGE FINDERS BY THE MEANS OF LASER-DOPPLER INTERFEROMETER

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Abstract

The precision of short range electro-optical rangefinders has been improved significantly. This fact made it applicable to perform microgeodetic measurements in mechanical engineering, requiring extreme high precision. But there is a strong need for regular calibration of these instruments — possibly by applications of even more precise laser-Doppler interferometers — those the paper deals with.

Keywords: rangefinder, calibration, linear interferometer.

Introduction

Development of industrial manufacturing technology, spreading of robot-technology and the tight technological connection of automatic manufacturing lines require a high-accuracy assembling-checking basic networks. The primary condition of establishing accurate, so called micro-geodetic networks is that the accuracy of distance measurement in case of short distances (less than 30 m) should correspond to the accuracy obtained by angular measurement. For this reason we concluded an examination of MEKOMETER 5000 and DI 2002 accurate electro-optic rangefinders, having common characteristic of 0.1 mm accuracy for distance indication.

The calibration of electro-optic rangefinders generally means periodical and regular re-determination of the following technical parameters:

- carrier wavelength and average refraction index
- measuring frequency, or modulation wavelength
- instrumental constant and its reliability
- distance dependency of instrumental constant
- short distance linearity examination

The present paper deals with the linearity examination in case of calibration of geodetic electronic rangefinders accepted to have the highest

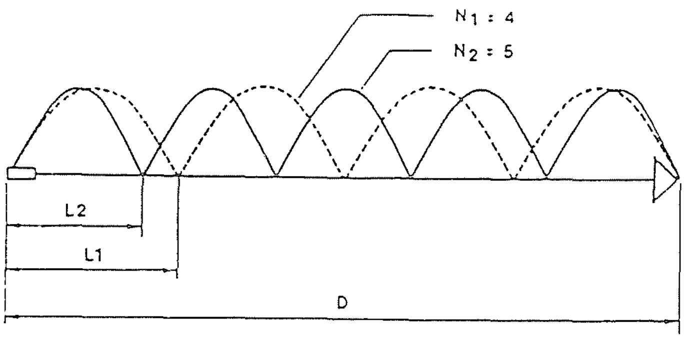


Fig. 1. Two adjacent 'zero-point'

accuracy in their category. As other articles published earlier (SZALÁDI, 1984 and KRAUTER–SZALÁDI, 1987) confirm that the Laboratory of the Institute of Geodesy, Photogrammetry and Surveying have already been involved in other questions of calibration procedures.

Since the distance measurement resolution of electronic rangefinders — constituting the subject of examination — falls into the mm magnitude, it is advisable to use, for short distance range linearity examination, a laboratory instrument having at least one order of magnitude higher accuracy reading. Among the presently available distance measuring instruments, only optical interferometers can be applied in the desired 1 – 50 m measurement range. For performing linearity examination, an LMS 100 laser-Doppler interferometer — manufactured by Carl Zeiss — had been used. Its principle of operation is identical to the HP laser-Doppler interferometer's.

Laboratory Examination of MEKOMETER 5000

MEKOMETER 5000 the electro-optical rangefinder is using the method of measuring frequency change for distance determination. The advantage of this type of operation is that the result of distance measurement is not effected by the periodical errors, coming from the phase difference measurement. The instrument's basic principle of operation is that the oscillator producing the measuring frequency modulates the electro-optical crystal in a given range by a constant change of 161.744 Hz steps, by the help of a syntheser. The laser light passing through the modulator crystal will be elliptically polarised.

The laser light reflecting from the prism passes through the electro-optical crystal again. If the distance travelled by the light is integral multiple of the modulating wavelength, the reflected, elliptically polarised light leaving the crystal will be linearly polarised again and the photodetector placed after the analysator — being perpendicular to the polarisation plane — indicates light minimum. If we measure the value of modulation frequency in two adjacent light minimum positions, the distance can be calculated from the frequencies measured *Fig. 1.*

In every case, measurement starts with internal calibration performed automatically. During the program controlled measurement, the syntheser sets the starting frequency value at the lower limit of the measuring frequency-bandwidth and looks for the first zero point (light minimum position). At this spot the value of f_1 frequency will be measured and saved.

Thereafter the frequency of the next (adjacent) zero point will be measured and the Df frequency difference will be calculated. With the knowledge of the Df value, further zero points can be pre-calculated. On these places the instrument performs so called coarse measurement, adjusts the calculated Df value based on the measurements and afterwards the f_2 frequency value will be measured and saved at one of the zero points, situated in the middle of the bandwidth. Continuing rough measurement for the determination of Df frequency difference, an other frequency measurement will be performed at the upper limit of the frequency band: which results the f_3 measuring frequency value. Fine measurement means multiple repetition of frequency measurement.

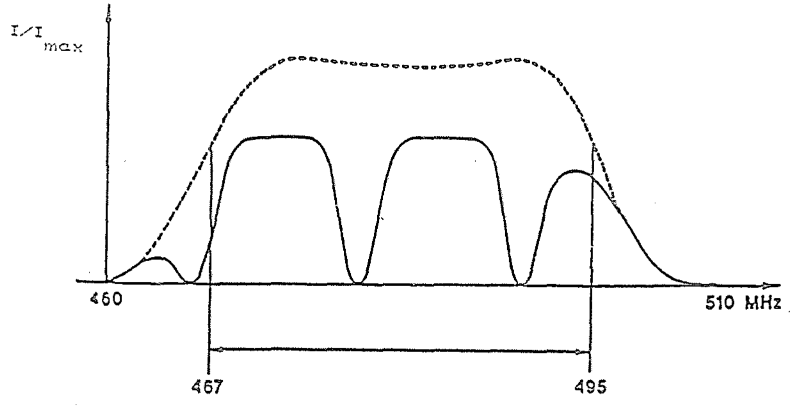


Fig. 2. The modulation frequency range

Fine measurement consists of 5 measurement series, while one sequence includes $2^8 = 256$ measurements. After finishing the measurement, the adjusted Df frequency difference and the f_1, f_2, f_3 frequency values will be known. The modulation wave numbers connected to the frequency values are the following:

$$N_1 = \mathrm{RND}\ \frac{f_1}{Df},$$

$$N_2 = \mathrm{RND}\ \frac{f_2}{Df},$$

$$N_3 = \mathrm{RND}\ \frac{f_3}{Df}.$$

The program examines the values of the f_1/Df; f_2/Df and f_3/Df quotients. If one of the calculated values shows bigger deviation from the integer number than ± 0.25, the program leaves that value out and gives an error message. After determining the modulation wave number, the distances will be as follows:

$$D_1 = N_1 \cdot \frac{c}{2f_1},$$

$$D_2 = N_2 \cdot \frac{c}{2f_2},$$

$$D_3 = N_3 \cdot \frac{c}{2f_3},$$

and the end result is:

$$D = \frac{D_1 + D_2 + D_3}{3}.$$

The measuring frequency has the appropriate accuracy only in a range, depending on the crystal modulator. In the best possible case, this range is between 460 – 510 MHz, but during measurement this range narrows down to the 467 – 495 MHz band *Fig. 2.* The difference between the real and optimum bandwidths effects the short distance measurements.

Modulation and phase detection are effective only in the frequency range of 467 – 495 MHz. The bandwidth of the optimum frequency band slightly depends on the distance measured. The amount of zero points associated with the different distance values varies. On the following figures, distribution of the possible zero points against distance and modulation frequency is presented. The horizontal lines at 467 and 495 MHz indicate the borders of optimal operating range. *Fig. 3* presents the amount of theoretically possible zero points between 0 – 3 m. *Fig. 4* demonstrates the same for the distance range of 20 – 30 m.

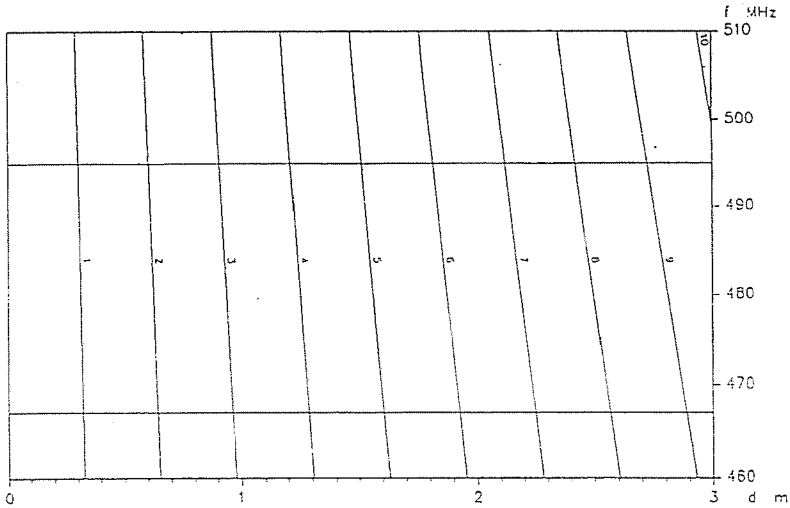


Fig. 3. Distribution of N values against distance and frequency for 0 – 3 m

Fig. 5 illustrates the magnified distance range, where distance measurements cannot be performed. The difference between theoretical (optimum) and real frequency ranges as well as between the unmeasurable, but related to the above distances can be seen.

Based on the above Figures it can be seen that minimum position can be found at a frequency value situated outside of the borders of optimum bandwidth, but still inside the operating range of the modulator. In this case, measurement still can be performed, but the accuracy of the results is uncertain, because of having smaller modulation depth than required.

During short distance (less than 30 m) measurements, the software suggested by the manufacturer was used. Since determination of distances under 10 meters in case of this instrument can be done only by using optional procedure (for example: a method applied by the European Organisation for Nuclear Research CERN), our examination measurements were limited to the distances between 10 – 30 m. The instrument arrangement necessary for performing the measurements is shown on *Fig. 6*.

An LMS-100 type interferometer, manufactured by Zeiss, a 3 m long optical bench and a surface reflecting flat mirror were used in the assembly. The rigidly assembled prisms of the rangefinder and of the interferometer were mounted on the precisely carriage part of the optical bench. This arrangement allowed us to execute comparison distance measurements in 3 m range, applying 10 cm intervals. The computer controlled measurement program made it possible to present the distances — obtained by the

Table 1
The calibration results of the ME 5000

n	1	2	3	4	5	6	7	8	9	10	11	12
1	20.344738	10	4	7	85	2 – 13	—	—	—	—	—	—
2	20.444914	3	4	7	6	1 – 34	100.176	100.18	100.22	100.22	–4	–4
3	20.544963	3	3	6	58	2 – 03	100.049	200.23	100.00	202.22	5	1
4	20.648800	3	4	7	18	2 – 01	99.917	300.14	99.95	300.17	–3	–3
5	20.744975	3	4	7	25	1 – 32	100.095	400.24	100.02	400.19	8	5
6	20.844961	4	4	7	80	1 – 54	99.986	500.22	100.04	500.23	–5	–1
7	20.944924	3	4	7	58	1 – 57	99.963	600.19	99.93	600.16	3	3
8	21.045008	3	4	7	36	1 – 41	100.084	700.22	100.06	700.22	2	0
9	21.144844	3	4	7	13	1 – 06	99.836	800.11	99.98	800.20	–14	–9
10	21.244902	3	4	8	74	2 – 21	100.058	900.16	99.97	900.17	9	–1

where: n — is the serial number of measurements
1 — is the measured distance in [meters]
2 — is the repetition number of distance measurements
3 — is the number of zero points in the optimum frequency band
4 — is the amount of zero points in the total frequency range
5 — is the maximum deviation of repeated measurements in [microns]
6 — is the length of time of measurement in [minute-second]
7 — is the distance difference [10 cm] measured with interferometer [mm]
8 — is the summary value of intervals [mm]
9 — is the distance difference [10 cm] measured by the rangefinder
10 — is the summary value of intervals [mm]
11 — is the difference between 7 – 9 in 0.01 mm unit
12 — is the difference between 8 – 10 in 0.01 mm unit

rangefinder — with the accuracy of 0.01 mm. These values were compared with the results got from interferometric measurement.

The data of *Table 1* (a part of a total measurement sequence) present well that the deviation of intervals, or of summarised distance values, exceed the value of 0.1 mm only in a few cases (in less than 15% of measurements). In the course of determining repetition number of the individual distance measurements, we examined whether these bigger deviation results can be considered to be identical, or not, which means we had to examine whether the same normal distribution is associated with the higher deviating values as with other ones.

The zero hypothesis $H_0 = x_{\max,\min}$ was given under the same distribution condition of other measurements.

Statistics:

$$T = \frac{x_{\max} - a}{\sigma} \qquad \text{or} \qquad T = \frac{x_{\min} - a}{\sigma},$$

Table 2
The calibration results of the DI 2002

N°	True distance [mm]	Measured distance [m]	Diff. [1/10 mm]	Linearity (measured minus true) [1/10 mm] −2 −1 0 1 2
1	2900.20	22.1715		
2	2800.13	22.2715	−0.7	*
3	2700.23	22.3714	−0.7	*
4	2600.12	22.4715	−0.8	*
5	2500.01	22.5718	1.1	*
6	2400.09	22.6716	−0.1	*
7	2300.21	22.7714	−0.9	*
8	2200.14	22.8715	−0.6	*
9	2100.21	22.9715	0.1	*
10	1999.83	23.0718	−0.7	*
11	1900.06	23.1716	−0.6	*
12	1800.18	23.2715	−0.2	*
13	1700.11	23.3716	0.1	*
14	1600.16	23.4716	0.4	*
15	1500.14	23.5715	−0.6	*
16	1400.14	23.6716	0.1	*
17	1300.08	23.7716	0.2	*
18	1200.19	23.8715	−0.1	*
19	1100.12	23.9717	1.2	*
20	1000.12	24.0716	0.2	*
21	900.08	24.1716	−0.2	*
22	800.03	24.2716	−0.7	*
23	699.94	24.3717	−0.6	*
24	600.22	24.4715	0.2	*
25	500.09	24.5716	−0.1	*
26	400.19	24.6715	−0.1	*
27	300.60	24.7710	−1.0	*
28	200.05	24.8716	−0.5	*
29	100.08	24.9716	−0.2	*
30	0.00	25.0717	0.0	*

where: a — is the sample average, determined based on measurements
σ — is the standard deviation of measurement results

Examining all the measurement results, according to the above, there were only two measurements — related to the same distance — to be eliminated from the repeated measurement results. It was also examined whether correlation can be proved among the extreme deviation of measurements repeated for the same distance, the length of time associated with the measurement and the amount of possible zero points. Correla-

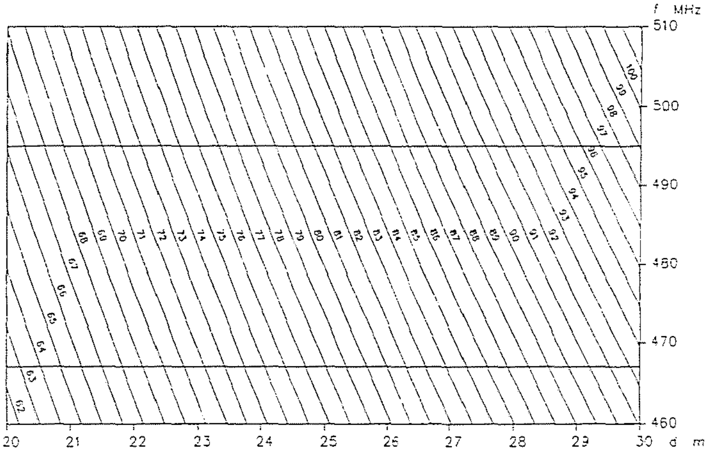


Fig. 4. Distribution of N values against distance and frequency for 20 – 30 m

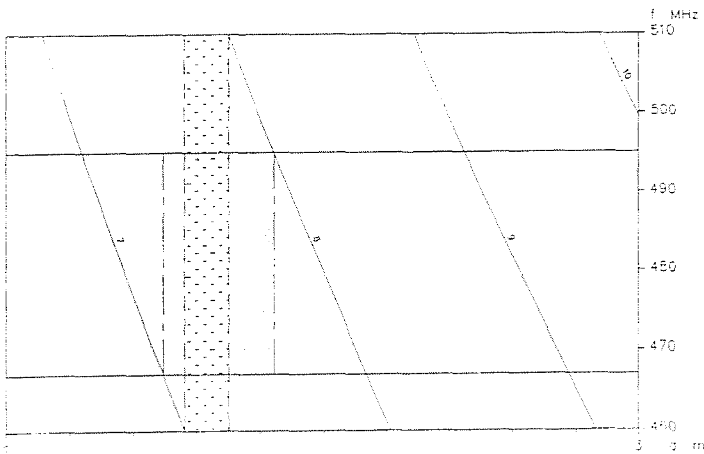


Fig. 5. Distribution of N values against distance and frequency with the unmeasurable distance range

tion coefficient in each case remained under 0.3, so the correlation was not proved. Results of processing in the whole examination range are the following:

- average deviation of distance differences [10 cm]: $\pm 3.4\,\mu$m, standard deviation: $\pm 67.9\,\mu$m,

- average deviation of summarised distance values: $\pm 2.6\,\mu m$, standard deviation: $\pm 41.2\,\mu m$.

Based on the examination results, it can be stated that a mean error of better than ± 0.1 mm can be measured in the range under examination, by using MEKOMETER 5000 electro-optic rangefinder.

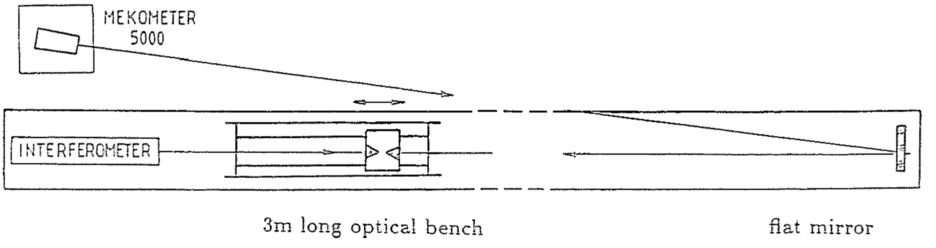


Fig. 6. The layout of the calibration setup

Of course this accuracy can be reached only in case the instrument is controlled by an outside computer, which means that the accuracy of the reading is ± 0.01 mm and measurements are performed with at least 3 times repetition. If deviation exceeds ± 0.1 mm, number of repetitions has to be increased and outstanding value(s) has (have) to be examined, whether the same normal distribution is associated with them as with the other values. We experienced that standard deviation of distance differences of 10 cm is 50% higher on the average than of the standard deviation of summarised measurements, but regular error was not revealed in the range examined. Evaluating the results we have to take into consideration the following condition: the examination was based on comparing distance differences, so it is valid for distance difference determination. Determination of absolute accuracy of distance measurement — which includes also determination of instrumental constant — was not set as an aim.

Laboratory Examination of LEICA DI 2002

Based on the quick development of precision technology, the newer generation of rangefinders are becoming more and more accurate. The DI 2002 rangefinder — manufactured by LEICA — outstands even from among these instruments with its small size, weight and with the accuracy of difference determination of 0.1 mm.

Some of the technical parameters of this instrument are the following:

- measuring range under medium atmospheric conditions (light haze 15 km visibility, gentle atmospheric motion)

with 1 prism	2500 m,
with 3 prisms	3500 m.

- mean error of distance measurement (manufacturer's data):

in the total measurement range	±1 mm+1 ppm,
from 1 m up to 120 m	±0.6 mm

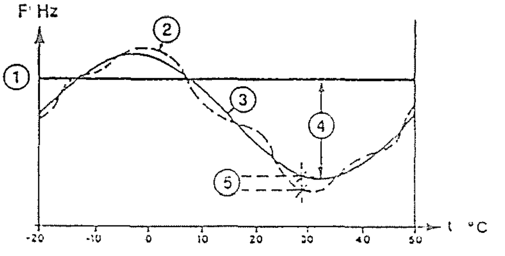


Fig. 7. The temperature-frequency correction function
where: 1 — is the nominal value of the modulation frequency [50 MHz]
2 — is the proper measuring frequency
3 — is the correction curve stored in the instrument
4 — is the frequency correction taken into account during measurement
5 — is the residuum frequency deviation causing scale-error, which means a less than 1 mm/km distance measurement error

The base frequency of the rangefinder working on the traditional way of phase comparison is 50 MHz, which corresponds to the 3 m scale. This small scale by the help of increasing the accuracy of phase measurement and by applying a new frequency stabilising procedure, assures the appropriate measurement accuracy. For producing the value of measuring frequency, the quartz oscillator has to be calibrated in the whole operating temperature range (−20°C ... +50°C). The temperature-frequency correction connection (the equation of improvement 'function') is stored in memory unit inside the instrument. In case of distance measurement, according to the continuously measured internal temperature, the measuring frequency will be modified and will reach a nominal value on the basis of the corrections *Fig. 7*.

Temperature determination inside the instrument and its application results that the acclimatisation temperature of the instrument will be increased in case of measurements — making the most of the instrument's accuracy. According to the Operating Manual, a 2 minutes waiting is required for the equalisation of 1°C temperature difference. The instrument was examined similarly to MEKOMETER 5000 rangefinder. The examination was carried out in the range of 4 ... 31 m with 10 cm distance intervals. We utilised the ability of the instrument for calculating the mean value and the standard deviation of the repeated measurements. This way each result is the arithmetic mean of 5 repeated measurements.

Table 3

The mean deviation and the standard deviation of the calibration results for the DI 2002

n	x	σ		
1	−0.07	0.6	−2.6	+0.4
2	0.02	0.6	−0.8	+1.6
3	−0.05	0.6	−1.4	+0.4
4	0.05	0.6	−0.7	+1.6
5	−0.03	0.5	−1.4	+0.8
6	−0.05	0.6	−1.7	+0.6
7	0.02	0.5	−1.0	+1.2*
8	0.10	0.9	−2.5	+1.4
9	−0.02	0.8	−1.4	+1.4

* It is in the *Table 2*

It has to be mentioned that we did not experience bigger deviation than of 0.2 mm, during the 270 distance measurements performed. Our measurements were evaluated on two ways:

- on one hand the summarised distances inside the 3 m range
- on the other hand the 10 cm difference values were compared to the interferometric measurements.

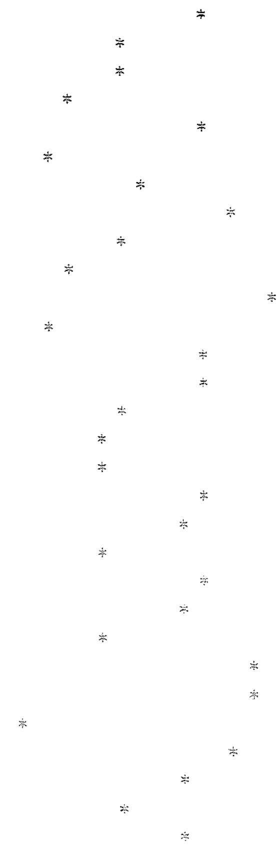
Table 2 demonstrates that the deviation of summarised distance differences is unexpectedly small. There are only three cases, when deviation value reached, or exceeded 0.1 mm. *Table 3* presents the parameters of the measurement results of the 9, 3 m long etaps.

The mean of the average deviation of these 9 etaps is $x = -0.03$, while standard deviation is $\sigma = \pm 0.6$ (both values are given in 1/10 mm).

Table 4 presents the distance differences and their deviations determined in the 10 cm intervals (deviations are given only in graphical form). Data including the whole examination range are collected in *Table 5*.

Table 4
The measurement results in 10 cm intervals and their deviation from the interferometric values

N°	True distance [mm]	Measured distance [m]	Diff. measured [mm]	Diff. true [mm]	100 mm distance (measured minus true) [1/10 mm] −2 −1 0 1 2
1	2999.97	10.1860			
2	2899.89	10.2861	100.1	100.08	
3	2800.10	10.3859	99.8	99.79	
4	2700.09	10.4859	100.0	100.01	
5	2599.90	10.5860	100.1	100.19	
6	2499.78	10.6862	100.2	100.12	
7	2399.67	10.7862	100.0	100.11	
8	2299.86	10.8860	99.8	99.81	
9	2199.64	10.9863	100.3	100.22	
10	2099.63	10.0863	100.0	100.01	
11	1999.53	11.1863	100.0	100.10	
12	1899.92	11.2861	99.8	99.61	
13	1799.87	11.3860	99.9	100.05	
14	1699.83	11.4861	100.1	100.04	
15	1599.68	11.5863	100.2	100.15	
16	1499.96	11.6860	99.7	99.72	
17	1399.80	11.7861	100.1	100.16	
18	1299.84	11.8860	99.9	99.96	
19	1199.88	11.9860	100.0	99.96	
20	1099.90	12.0860	100.0	99.98	
21	999.64	12.1862	100.2	100.26	
22	899.79	12.2861	99.9	99.85	
23	799.91	12.3860	99.9	99.88	
24	699.65	12.4862	100.2	100.26	
25	599.96	12.5860	99.8	99.69	
26	499.96	12.6861	100.1	100.00	
27	399.90	12.7860	99.9	100.06	
28	300.09	12.8859	99.9	99.81	
29	199.93	12.9861	100.2	100.16	
30	100.19	13.0858	99.7	99.74	
31	0.00	13.1860	100.2	100.19	



The mean of the average deviation of these 9 etaps is $x = -0.046$, while standard deviation is $\sigma = \pm 0.8$ (both values are given in 1/10 mm).

Comparing the results of the two different examinations, it can be concluded that the distance differences measured by 10 cm intervals show higher deviation in average values than the summarised distance values. The same applies for standard deviation. It is interesting that each higher deviation value was always followed in a 20 – 30 cm range by a simi-

Table 5
Average deviation and standard deviation in the whole examination range

n	x	σ		
1	–0.06	0.7	–1.8	+1.8
2	–0.09	0.7	–1.6	+1.5
3	0.10	0.8	–1.6	+1.9*
4	0.02	0.8	–2.1	+1.7
5	–0.16	0.8	–2.2	+1.2
6	0.04	0.8	–1.6	+2.0
7	0.00	0.8	–1.8	+1.9
8	–0.02	0.9	–1.6	+2.2
9	–0.04	0.8	–2.4	+2.1

* It is in the showed example

lar size, but reversed sign deviation. These deviations will fall out from the summarised results. It is worth comparing the examination results of MEKOMETER 5000 and DI 2002. By comparing the measurement results of equal length etaps, it can be determined that the accuracy of DI 2002 is almost as good as of the MEKOMETER 5000 accurate electro-optical rangefinder's.

Examination results are the following:

	MEKOMETER 5000	DI 2002
— average deviation in 10 cm	+3.4 μm	–4.6 μm
— standard deviation in 10 cm	±67.9 μm	±80.2 μm
— mean of average deviation (sum. distances)	+2.6 μm	–3.3 μm
— standard deviation of average deviations	±41.2 μm	±60.1 μm

Based on the above results, the distance measurement accuracy of ±0.1 mm can be reached also by using DI 2002 type rangefinder. The required accuracy can be obtained by determining — according to the above — the instrument constant and the number of repetitions.

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