VPLIV UMETNE OSVETLITVE INVARSKIH NIVELMANSKIH LAT NA IZMERO Z DIGITALNIMI NIVELIRJI

THE INFLUENCE OF ARTIFICIAL ILLUMINATION OF INVAR LEVELLING RODS ON THE MEASUREMENTS WITH DIGITAL LEVELS

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IZVLEČEK

Odčitek na kodirani nivelmanski lati je določen z obdelavo slike črtne kode nivelmanske late, ki jo zazna CCD-senzor, vgrajen v digitalnem nivelirju. Kakovost določitve odčitka na nivelmanski lati je odvisna tudi od osvetlitve kodirane razdelbe na nivelmanski lati. V slabih razmerah uporabljamo umetno osvetlitev nivelmanske late. V članku je obravnavan sistematični pogrešek kot funkcija kota, pod katerim je črtna koda nivelmanske late umetno osvetljena. Predlagan je postopek izmere in analiziran vpliv navedenega sistematičnega pogreška na rezultat izmere. Rezultati preizkusa so pokazali, da osvetlitev črtne kode nivelmanske late ni ustrezna, če je kot osvetlitve večji od 45 °. Na podlagi testiranj se je izkazalo, da znaša pri kotu osvetlitve 55 ° napaka približno 0,02 mm, kar je dvakrat toliko kot ločljivost, ki jo navaja proizvajalec digitalnega nivelirja.

ABSTRACT

Since the digital levels operate on the principle of image processing of the bar code of levelling rod, recorded by a CCD sensor, the proper lighting (i.e. illumination of the bar code) is important to achieve accurate results. The prevention of inappropriate lighting conditions is important for the correct recording of the image of bar code section. This paper examines the systematic error as a function of the angle of incidence at which an bar code is illuminated by artificial lighting in low light conditions. Further, the procedure of measurements and the analysis of results for the identification of such errors is proposed. The results of experimental measurements highlight the inappropriateness of bar code illumination at an angle of incidence of more than about 45 °. From the practical measurements, it was found that the angle of incidence 55 ° corresponds to an error of about 0.02 mm, which is twice as much as the resolution of the height measurement determined by the manufacturer.

KLJUČNE BESEDE

precizni nivelman, digitalni nivelir, kodirana invar nivelmanska lata, sistematični pogreški niveliranja

KEY WORDS

precise levelling, digital level, bar code rod, precise levelling rods, systematic errors in levelling

1 INTRODUCTION

Nowadays, digital level instruments are used for various applications because of their accurate, rapid and automated process of measurement. Random and systematic errors are present in precise levelling as in any measurement. The knowledge of causes of these errors and methods of their elimination or reduction enable to choose a measurement methodology that provides the desired accuracy. The reading of digital level instrument operates on the principle of recording an image of the part of bar code visible in the field of view of the instrument using a CCD sensor. In most cases, subsequent comparison with an identical part of the whole scale of bar code rod stored in the memory of instrument is then carried out. The manufacturers that produce digital levelling instruments developed their own code and processing methods (Ingensand, 1999; Schneider and Dixon, 2002; Radcliffe, 1999; Grattan et al., 2003). The issue of the influence of the rod illumination when measuring by digital level instruments is quite broad. We can encounter it in the comparison of levelling rods (Woshitz, 2003), or wherever the lighting conditions are worse. The accuracy of the measurement depends on the accuracy of the recording of the bar code by CCD sensor and is therefore affected by the quality of the image. The rod illumination is an important factor. Problems in the recording of the bar code occur in different lighting conditions. In this regard, some results of tests focused on the examination of illumination intensity (Ježko, J., 2014; Atroschenkov et al., 2016), the extent of coverage of the bar code at the place of code scanning by the instrument (Seto, et al., 1999), the method of illumination (Gassner and Ruland, 2006), or other effects (very intensive, inhomogeneous light intensity, or low-frequency illumination, spectrum of the light) (Schneider and Dixon, 2002; Leica Geosystems, 2006; Schmid, 1995; Ingensand, 1999), has already been realised and published. Insufficient illumination of levelling rods under worse lighting conditions can be solved by using self- luminous levelling rods. Testing, accuracy, an overview of available types, or design solutions, are given in (Brunner and Woschitz, 2004; Fuhrland, 2006). In cases where self-luminous levelling rods are not available, and the rod must be illuminated by another light source, errors that are related to the way of illumination of the bar code by artificial lighting source may be reflected in the results.

2 THEORETICAL ASPECTS

2.1 Production method of bar code - bar code structure

The errors in reading from the illumination of bar code at large angles of incidence, are effected with the physical structure of bar code. In the manufacturing process at first, the invar tape is covered with a black layer, to which a yellow layer is applied. Subsequently, the yellow upper layer is partly removed forming the bar code of rod using high energy laser (Fischer and Fischer, 1999). Due to this process, code elements of yellow colour have a certain thickness, thus protruding above code elements of black colour around 50 micrometres (Szczutko and Frukacz, 2011). In an oblique illumination of the bar code from above or below, the instrument registers a distortion of the section of bar code due to the shadow effect on individual code elements.

2.2 Physical analysis of the effect

The theoretical analysis of the invar barcode illumination from physical point of view is illustrated in Figure 1, which represents the ideal in real, the yellow element is not an absolutely square stone, and planes A and B are not perfectly smooth.

The element of solid angle $d\Omega_A$, at which the element dA of the surface A can be seen from the point S at the distance r (Figure 1), can be calculated as:

$$\Omega \;= \frac{dA \cdot \cos}{\quad}, [\mathrm{sr} = \mathrm{m}^2/\mathrm{m}^2], \tag{1}$$

where δ_A is the angle formed between the axis of the element of solid angle $d\Omega_A$ (i.e. the beam r_A) and the normal line n_{dA} of the element dA.

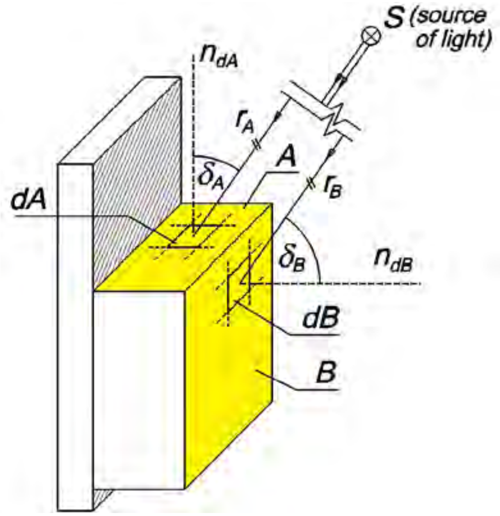

Figure 1: A scheme for the calculation of a solid angle $d\Omega_{A}$, at which the surface dA can be seen from the point S.

For $\delta_A = 0°$, a maximum of the luminous energy is incident on the surface A. The size of the solid angle Ω_A (and thus the amount of luminous energy incident on the surface A) decreases with an increasing angle δ_A. On the contrary, at the front surface (surface B – Figure 1), the size of the solid angle Ω_B (and thus the proportion of incident and subsequently reflected luminous energy to the CCD sensor) increases with an increase in the angle δ_B. The quantity of luminous flux $d\Phi_A$ incident on the surface A depends on the size of the element of solid angle $d\Omega_A$. The ratio of $d\Phi_A$ and $d\Omega_A$ may be expressed as luminous intensity I_A (Hentschel, 1987):

$$I_A = \frac{d\Phi_A}{d\Omega_A}, [\mathrm{cd} = \mathrm{lm/sr}]. \tag{2}$$

When illuminating the levelling rod, the changes in the amount of incident and reflected light between the front and side surfaces occur. Considering the same size of the surface elements $dA = dB$, approximately the same distance $r_A = r_B$ from the light source S, and the same type of light source $d\Phi_A = d\Phi_B$ by fitting the equation (1) into (2), the ratio of luminance can be defined as:

$$\frac{I_A}{I_B} = \frac{\cos\delta_A}{\cos\delta_B}, [\text{ - }]. \tag{3}$$

The graphical dependence of this ratio on the angle of illumination δ_A (where $\delta_A + \delta_B = 90°$) is shown in the following Figure 2. The intensity of reflected light from surface elements dA and dB for the illumination at an angle $\delta_A = \delta_B = 45°$ is the same, i.e. the ratio $I_A / I_B = 1$. By lowering the angle of illumination

δ_A, the intensity I_A starts to exceed the intensity I_B, their ratio increases sharply and the dependency curve gets an exponential character (Figure 2).

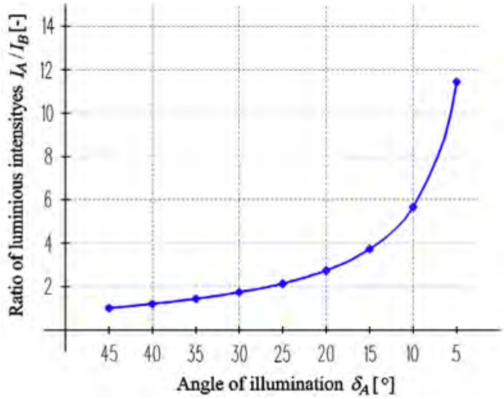

Figure 2: The ratio of luminance I_A/I_B of surface elements *dA* and *dB* depending on the angle of illumination d_A.

From Figure 2, the increasing ratio of reflected light intensity by surfaces A and B towards the CCD sensor of a levelling instrument with an increasing angle of incidence of light is evident. The significant difference in the illumination of areas A and B is evident in the detailed display and comparison of the same sections of the bar code of the levelling rod, which is shown in Figure 3.

2.3 Influence of illumination error

The measured values will indicate that there is a distortion of the bar code area recorded by the instrument when the rod is illuminated from below (Figure 3 c) so that it appears as if the rod was shifted down. A reverse effect occurs when the rod is illuminated from above (Figure 3 a). Thus, the instrument records the illuminated area of the bar code as if the rod was shifted slightly upwards in comparison with reality.

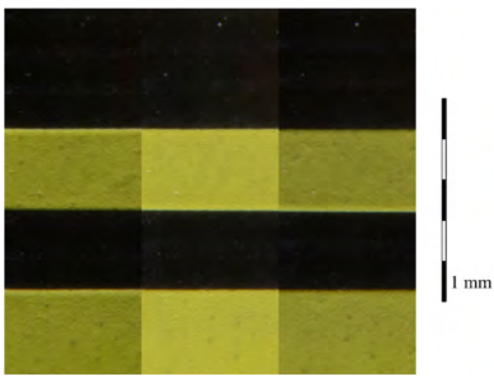

Figure 3: The colour shift of the interface between the yellow and black segments of a bar code rod caused by the illumination a) from above, b) from the centre, c) from below.

The main reason for this effect is likely to be the light incident on the side surfaces of yellow layer of the bar code, which subsequently caused (Figure 3) extension of the yellow part border towards the light source, by its thickness of the applied yellow colour (50 micrometers). All pictures were recorded at the same resolution. Therefore, when all three pictures were opened in photo-editing software, they could be easily opened one over the others (as different layers) and subsequently cropped to the desired area.

The three side-by-side images of the illuminated bar code rod shown in Figure 3 were captured by a DSLR camera using 200 mm focal length from a distance of 3 m from the rod. Complete darkness was maintained during the taking of the photos, using only the spotlight lamps as light sources, which were turned on and off remotely. The degree of this colour shift can be related to the amount of light incident on these surfaces and the amount of reflected luminous energy towards the CCD sensor of the instrument.

2.4 Systematic influence of illumination errors on height difference

In general, for the height difference determined by the geometrical levelling from the midpoint, it is valid:

$$\Delta h = b - f. \tag{4}$$

Since the errors in the reading caused by an oblique illumination of the bar code are very small, and therefore difficult to identify, the methodology of the measurements in a one instrument set-up (Δh, i.e. a foresight and a backsight) with the bar code illumination by reverse - opposing lighting was chosen, leading to a bias of the measured height differences by the double error caused by the illumination according to Figure 4. The measurement procedure was designed to simulate the measurement of a levelling line measured from the initial survey point in both directions „forward and backward". On the base of series reading b and f we can evaluate the precision of mean of b and f, compute the difference ε and statistically evaluate the precision of this difference.

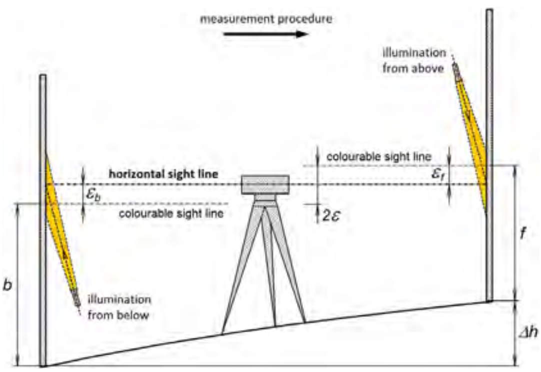

Figure 4: The schematic representation of the readings including errors e_i, depending on the direction of illumination.

From Figure 4 follows:

$$\Delta h = b + \varepsilon_b - (f - \varepsilon_f), \tag{5}$$

where:

Δh – levelling height difference weighted by errors of illumination,
b – bar code reading for the backsight,
ε_b – error of the reading for the backsight line caused by the illumination from below,

f – bar code reading for the foresight; in case of proper illumination (angle of incidence = 0 °) $f = b$,

ε_f – error of the reading for the foresight line caused by the illumination from above.

If the angle at which the bar code rod is illuminated from above and below is approximately equal, we assume:

$$\varepsilon_b \cong -\varepsilon_f = \varepsilon. \tag{6}$$

Moreover, the resulting relation for the measured height difference can be defined as:

$$\Delta h = b - f + 2\varepsilon. \tag{7}$$

These issues arise when bar code of levelling rods are illuminated by spotlights with a narrow beam of light. In practice, this may occur when dealing with large overall height differences, for example, the verification of the stability of water storage dams, when levelling lines are directed through revision tunnels of dams (Figure 5). Repeated measurements and the sum of individual levelling height differences lead to the propagation of errors of illumination, when these errors, even though negligible, but gradually decrease of the accuracy of determining the height difference. The illumination error 2ε is systematic error and the influence 2ε on overall of height difference Δh_{AB} is:

$$\delta_{\Delta h_{AB}} = n \cdot 2\varepsilon, \tag{8}$$

where: n is number of instrument stations.

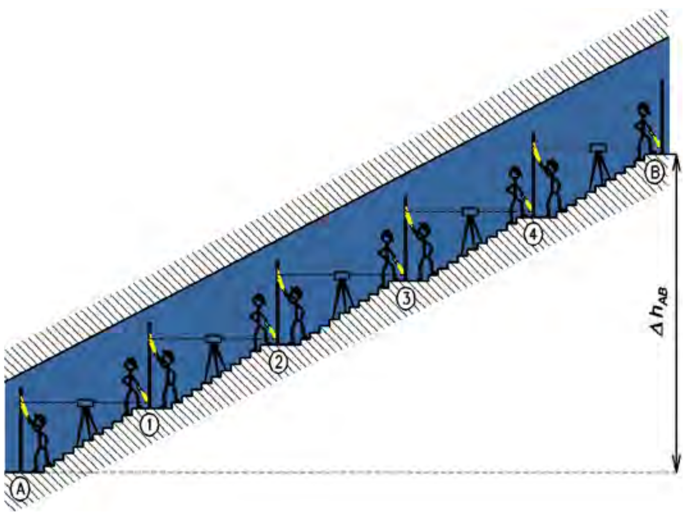

Figure 5: The method of illumination of bar code rods in geometrical levelling from the midpoint between the rods in low light conditions

3 EXPERIMETAL MEASUREMENTS

Two types of electronic levelling instruments were used to realise the experimental measurements: Leica DNA03 ($\sigma_{ISO\text{-}LEV} = 0.3 mm/km$ (Leica Geosystems, 2006)) and Topcon DL-101C ($\sigma_{ISO\text{-}LEV} = 0.4 mm/km$ (Topcon Corporation, 1994)). Resolution of height measurement (last digit) is 0.01mm for both instruments. The digital level instruments were placed in a dark room at a distance of 3 m from the bar code rod. Readings on the bar code rod were executed at a stable temperature, with no flow or turbulence of air layers. The distance instrument – rod of 3 m was chosen in the first series of measurement considering the lowest reading capacity of the used instruments. In the second series of measurements, the distance instrument - rod was lengthened. During the measurement, our attention was focused mainly on the greatest possible elimination of external influences and possible sources of errors, so that only the error caused by illumination is reflected in the results. The line of sight of the instrument was set symmetrically between the two light sources. Two types of GU10 (halogen 50W / 760 lm with $\lambda = 585nm$ (warm white light) and LED 4W / 260 lm with $\lambda = 445nm$(cold white light)) were used as a light source to represent different types of standard hand-held lamps. The bar code was illuminated alternately, i.e. once from above and once from below after each reading of the code by the instrument (Figure 6), while the bar code and the instrument did not change their position during the measurement.

Figure 6: Illumination of the bar code; left - from above, right - from below.

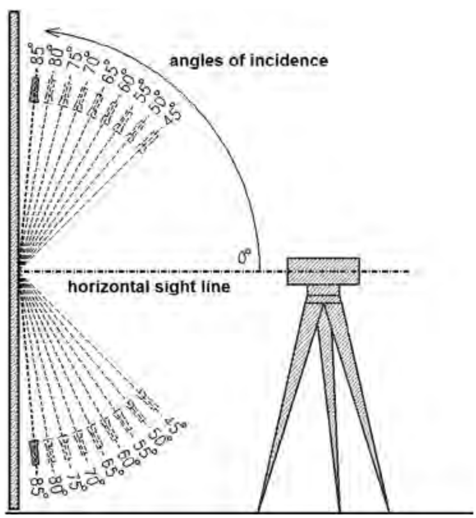

Figure 7: The position of lamps illuminating the bar code.

The measurements were divided into 9 series, where the angle of light beam, at which the scale of bar code was illuminated, was changed for each set of measurement. The angle of incidence was changed in interval from 45 ° to 85 ° from the horizontal sight line (Figure 7). The illumination angle of incidence was set up using a protractor for all measurements. The measurement of one set took about 10 minutes, while 20 values, i.e. 10 reading in the same illumination (e.g. from above) to specify the cumulative illumination errors, were recorded. From practical measurements at the 0 ° angle of incidence, the error was $\varepsilon_b = -\varepsilon_f = \varepsilon = 0$. At the angle of incidence from 5 ° to 40 ° was the value $2\varepsilon \leq$ 0.010 *mm* and applies the equations: $\varepsilon_b \cong -\varepsilon_f = \varepsilon$ and $2\varepsilon = 0$. Significant errors were observed from the angle of incidence of 45 °.

3.1 Results of experimental measurements

Two types of levelling instruments and two types of illumination at nine possible angles of incidence of illumination between 45 ° and 85 ° were used. Each series of measurement started according to Figure 4, i.e. by reading at the levelling rod illuminated from below. For each combination, 20 readings of the bar code were obtained, resulting in 10 differences used for the calculation of average, mean, and standard deviation of error of illumination, according to:

The average error of illumination: $\overline{2\varepsilon} = \frac{1}{n}\sum_{i=1}^{n} 2\varepsilon_i$, (9)

The mean deviation of the error of illumination: $d_{2\varepsilon} = \frac{1}{n}\sum_{i=1}^{n} \left| 2\varepsilon_i - \overline{2\varepsilon} \right|$, (10)

The standard deviation of the error of illumination: $\sigma_{2\varepsilon} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n} (2\varepsilon_i - \overline{2\varepsilon})^2}$. (11)

Results in Table 1 are given only for the distance of 3 m.

Table 1: The error of illumination (Leica DNA 03 and Topcon DL-101C instruments) using halogen and LED light at different angles of incidence.

Angle of incidence	Illumination error *2ε* from distance 3 m [mm]											
	Leica DNA03 (halogen)			**Leica DNA03 (LED)**			**Topcon DL-101C (halogen)**			**Topcon DL-101C (LED)**		
	Average	*Deviation mean*	*Deviation standard*	*Average*	*Deviation mean*	*Deviation standard*	*Average*	*Deviation mean*	*Deviation standard*	*Average*	*Deviation mean*	*Deviation standard*
45 °	0.012	0.003	0.004	0.014	0.005	0.005	0.012	0.003	0.004	0.013	0.004	0.005
50 °	0.014	0.005	0.005	0.016	0.005	0.005	0.013	0.004	0.005	0.018	0.003	0.004
55 °	0.018	0.003	0.004	0.018	0.005	0.006	0.016	0.006	0.007	0.020	0.000	0.000
60 °	0.020	0.000	0.000	0.020	0.002	0.005	0.020	0.000	0.000	0.024	0.005	0.005
65 °	0.026	0.005	0.005	0.033	0.004	0.005	0.041	0.002	0.003	0.028	0.003	0.004
70 °	0.041	0.002	0.003	0.050	0.002	0.005	0.049	0.002	0.003	0.036	0.005	0.005
75 °	0.050	0.000	0.000	0.059	0.002	0.003	0.068	0.003	0.004	0.050	0.000	0.000
80 °	0.080	0.000	0.000	0.082	0.005	0.006	0.087	0.004	0.005	0.069	0.002	0.003
85 °	0.123	0.004	0.005	0.149	0.005	0.007	0.163	0.004	0.005	0.109	0.004	0.006

Averages of illumination error depending on the angle of incidence and their graphical representations are shown in Figure 8.

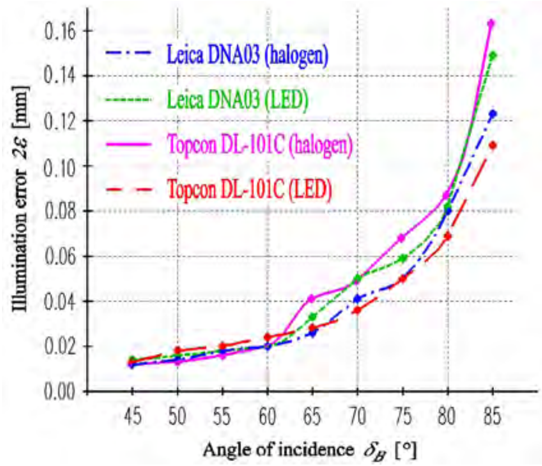

Figure 8: Graphical presentation of dependencies between the height difference measured by digital level instrument DNA03 (Leica), DL-101C (Topcon) and the angle of incidence of the invar bar code rod GPCL2 (Leica), 3m bar code rod of the DL series (Topcon).

For the next series of experimental measurements, Leica DNA03 with two types of illumination at the same angle of illumination of 85°, and from various distances, were used. Each series of measurement started according to Figure 4, i.e. by reading at the levelling rod illuminated from below. For each combination, 20 readings of the bar code were obtained, resulting in 10 differences used for the calculation of average, mean, and standard deviation of error of illumination, according to equations (9), (10) and (11). The maximum distance from which the measurements could be made was 13 m when using a halogen and LED light with the Leica DNA 03 instrument. When using Topcon DL-101C instrument, it was possible to realise the measurement up to the distance of 17 m. Results from the second series of measurements are given in Table 2.

Table 2: The error of illumination (Leica DNA 03 and Topcon DL-101C instruments) using halogen and LED light at the same angles of incidence from different distances.

Distance of bar code rod	Illumination error 2ε (angle of incidence 85 °) from different distances [mm]											
	Leica DNA03 (halogen)			Leica DNA03 (LED)			Topcon DL-101C (halogén)			Topcon DL-101C (LED)		
	Average	*Deviation*		*Average*	*Deviation*		*Average*	*Deviation*		*Average*	*Deviation*	
		mean	*standard*		*mean*	*standard*		*mean*	*standard*		*mean*	*standard*
5 m	0.100	0.005	0.005	0.102	0.004	0.007	0.146	0.005	0.005	0.105	0.004	0.007
7 m	0.102	0.003	0.004	0.108	0.011	0.015	0.148	0.002	0.005	0.126	0.005	0.005
9 m	0.096	0.008	0.010	0.104	0.004	0.005	0.155	0.006	0.007	0.126	0.010	0.013
11 m	0.107	0.007	0.010	0.106	0.010	0.012	0.156	0.006	0.007	0.123	0.012	0.017
13 m	0.116	0.011	0.013	0.120	0.014	0.016	0.171	0.010	0.014	0.144	0.010	0.013
15 m	-	-	-	-	-	-	0.174	0.010	0.013	0.147	0.011	0.015
17 m	-	-	-	-	-	-	0.178	0.011	0.014	0.155	0.012	0.014

3.2 Discussion

When comparing the errors of two instruments regarding to two types of lamps and angle of incidence (Figure 8), the largest variation of the values 2ε can be observed at an angle of incidence of 85 °, where the measured values vary between 0.11 mm to 0.16 mm. A gradual decrease of the values 2ε occurs with a decrease in the angle of incidence. The results show minimum variations (maximum difference 2ε from Table 1 and Figure 8 at the same angle of incident is: $\Delta 2\varepsilon_b = 2\varepsilon_{\max} - 2\varepsilon_{\min} = 0.005mm$) and negligible differences between individual measurements for values of ≤ 60° of the angle of incidence. The evaluation of the results in Figure 4 indicates an apparent increase of the variation of the measured values with increasing angle of incidence. Based on the Table 1 and Figure 8, it can be concluded that curves represent a type of exponential dependence, when a change in the angle of incidence (in the right part of Figure 8) causes significant changes in illumination error 2ε.

From the next series of experimental measurements, it was investigated that with increasing distance, the average error of illumination slightly increases to max. value 0.18 mm, but only to a certain distance (Table 2). By further increasing the reading distance, the instrument could no longer record the reading under the same illumination.

4 CONCLUSION

A demonstration of the influence of the bar code artificial illumination (in low light conditions) on the results of levelling measurements was the main intention of the method of illumination and measurement methodology presented in this paper. In precise levelling in low light conditions the manufacturer of bar code invar rods (NEDO) offers several types of self-luminous levelling rods with a bar code or rods illumination facilities for measurements in these conditions (www.nedo.com).

Our results indicate that the largest errors in reading occur when the bar code rod is illuminated at a very acute angle. Although the errors are relatively small, but not negligible for a single rod reading, its influence can become significant on long levelling runs. Decreasing the angle of illumination reduces the errors. The illumination errors can be negligible for angles of incidence with value 55 ° and smaller. The detected errors are less than 0.02 mm. By increasing the length of sight line, the error 2ε slightly increases, but only to a certain distance (Table 2). This is due to the fact that by further increasing the length of sight line, it is not possible to record the reading on the illuminated bar code staff by the instrument. For that reason, it is important to pay attention to the method of illumination in precise levelling measurements using digital level instruments in low light conditions. The surveyor should ensure a homogeneous and perpendicular illumination of the recorded part of the bar code in the measurement process to limit the influence of the systematic errors in the illumination that are clearly shown in Table 1 and Figure 8.

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