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CALIBRATION OF SURVEYING INSTRUMENTS AND TOOLS – MEANS TO THE QUALITY INCREASE OF DEFORMATION MEASUREMENTS

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ABSTRACT

Purpose This paper describes selected control and calibration procedures of some surveying instruments and tools (digital levels and code bar levelling staffs, total stations and electronic tacheometers, and reflective systems).

Methods The calibration of horizontal circles of optical and electronic theodolites can be carried out under laboratory conditions, e.g. on an automated device for the calibration of optical polygons EZB-3 in the Slovak Institute of Metrology in Bratislava (SIM).

Results The results of testing the influence of lighting when working with a digital levelling instrument are presented. Furthermore, the procedure and results of the calibration of horizontal circles of surveying instruments on a calibration device (Slovak Institute of Metrology in Bratislava) are described in this paper.

Practical implications The result of such calibration is a set of horizontal scale corrective values for particular nominal values of the scale, determined using a series of measurements, and eventually the provision of the parameters of approximating function.

Originality/value The use of a laser interferometer (laser measurement system XL 10 f. RENISHAW) for the calibration of the code leveling rod, respectively of the system calibration (digital leveling device – code late) prepared by the Department of Geodesy, SUT Bratislava with the help of European projects, will then be implemented in a unique facility in the Slovak Republic.

Keywords
calibration, testing, digital level, bar code levelling staff, electronic tacheometer, horizontal circle

1. INTRODUCTION

Currently, in addition to the conventional measurement systems: theodolites, electronic distance meters, total stations and GPS units are the most frequently employed instruments in surveying. The optical levels are gradually replaced by digital automatic levels and conventional invar staffs by bar code levelling staffs. These new levels equipped with a CCD sensor enable the full automation of staff reading and offer new benefits, such as greater accuracy of reading, automatic registration, the elimination of gross errors and mistakes, and the data measured is in electronic form with the possibility of further processing in different software environments.

2. TESTING AND CALIBRATION OF LEVELS AND ANCILLARY EQUIPMENT

Among the most frequently occurring errors in levelling, using digital levels, is the staff graduation error (Hánek, 2001; Melicher, 2001). This error has a systematic character and significantly affects the accuracy of the results of precise levelling measurements, e.g. measurements in the National Levelling Network, measurement of the vertical displacement of building structures etc. The calibration of the levelling staffs means that the influence of this error is minimal. The calibration measurement is performed using, for example, a linear laser interferometer. This method is suitable for levelling staffs with conventional graduation as well as for bar code levelling staffs. Calibration itself can be realized by various arrangements of the calibration equipment, i.e. by placing the levelling staff in a horizontal or vertical position. Below are examples of some calibration equipment – comparators.

2.1. Comparator using a laser interferometer at the Department of Theoretical Geodesy of FCE of SUT in Bratislava

A comparator using a laser interferometer (CLI) with its accuracy and traceability to the national standard of length of the Slovak Republic at the Slovak Institute of Metrology (SIM) represents the most advanced item of metrological measurement of length at the Department of Theoretical Geodesy. Values of all onward comparators up to the parameters of the length baseline in Hlohovec are derived from CLI. CLI was calibrated at SIM by measuring the differences in the frequency of the laser Δf to the national standard of length of the Slovak Republic (laser SIM B2) with extended relative uncertainty $U = 6.8\cdot10^{-11}$ ($P = 0.95$) (Ježko & Bajtala, 2005). CLI allows for the contactless calibration of all linear measures whose scale (lines) can be set up under the adjustable microscope of the comparator. By using CLI invar levelling staffs of varying length, control invar measures and other working measures and standards can be calibrated. It is also possible to carry out verification (calibration) of the foldable levelling staffs (4 m), base staffs, measuring bands etc. (Ježko & Bajtala, 2005). Currently, these laboratories are not in use as they are currently under reconstruction.

2.2. Horizontal comparator for bar code levelling staffs

The core of the laboratory is the 30 m long calibration bench with two moving trucks (Fig. 1), their distance from the reference point is measured by the laser interferometer HP5507B. Levelling staff, located on the moving trucks, is supported at Bessel's points. On the bench an electro-optical microscope is mounted, trucks with fixed levelling staff move under the microscope. This determines the position of all elements of the staff code.

Fig. 1. Horizontal comparator

2.3. Vertical comparator for bar code levelling staff and system calibration

The vertical comparator (Fig. 2) enables the calibration of levelling staff in the vertical plane. The value of movements is measured by a laser interferometer, similar to the horizontal comparator. The vertical comparator can be used for the calibration of levelling staffs in the vertical plane and for, so called, system calibration as well. The advantage of this procedure is during calibration the levelling staff is in the same position as it is in field measurement.

In general, it is assumed that the scale of the measuring system is a scale of staff determined by calibration. Eventually, the properties of a level and levelling staff can vary, and thus in order to control the whole system it is necessary to carry out system calibration. During system calibration the correct values of the readings on the staff are determined, from which it is possible to determine the scale of the whole digital levelling system, the stability of the whole system in time and also to estimate the accuracy of the whole measuring system. A similar system is in use in Japan (The Geographical Survey Institute) and in Slovenia (The University of Ljublana). The vertical comparator for the calibration of levelling staffs in the vertical plane, also enabling system calibration, is in operation in the metrological laboratory of the Technical University in Graz (Austria). The Finnish Geodetic Institute has been performing automatic calibration of levelling staffs by means of a vertical comparator from 1996 and system calibration from 2002. A similar calibration system is also in operation at the Technical University in Ostrava.

Fig. 2. Vertical comparator

2.4. Calibration system at the Department of Surveying of FCE of SUT in Bratislava

The preparation of the calibration system is carried out using a laser measuring system. The linear interferometer is based on a frequency stabilized He-Ne laser of energetic class II (it can be used without special safety equipment). The laser head also contains an optoelectronic sensor of interference field and electronic network in order to process the values measured, i.e. the interpolation of the interference signal with a resolution of up to 1 nm and the compensation of the length expansion of the measured object. The interference system together with the units for environment compensation and with the electronic part of the system enables the measurement of length with a resolution of up to 1 nm (dynamic measurement is also possible), angle measurement in a range of ±10° and the measurement of differences of evenness. The system can be used in order to calibrate invar and bar code levelling staffs, to test electronic distance meters, to observe movements of constructers etc.

The Department of Surveying of Faculty of Civil Engineering at SUT in Bratislava has currently at its disposal the laser measuring system XL 10 co. RENISHAW (Fig. 3, 4), working with an accuracy (P = 95%) of linear measurement 0.5 μm per 1 m of measured length in the entire range of the defined measurement conditions – air temperature from 0 to 40°C and a pressure of 650–1150 hPa in the measured path – with a maximal range of linear measurements of 80 m. This system means that the reading of values of length with a frequency of 50 kHz at maximal speed of length change

4 m/s can be carried out. The attained linear resolution of 1 nm is well-preserved across the whole range of the speed of measurement. The stability of the frequency of the emitted laser wavelength is guaranteed by the manufacturer at $\pm 0.05 \cdot 10^{-9}$ per year and $\pm 0.02 \cdot 10^{-9}$ per hour. Laser XL 10 communicates with the user's computer by means of a USB port.

Fig. 3. Laser head XL 10

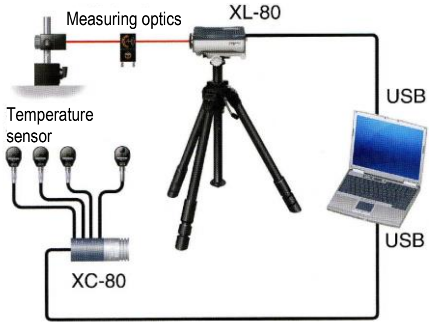

Fig. 4. Measuring system XL 10 f. RENISHAW

The compensating unit XC 80 is one of the key components when ensuring the stated accuracy of measurement within an XL system. The compensating unit enables the measurement of temperature, pressure and relative humidity in the path of the ray and the measurement of the temperature of the object being measured. Based on the data acquired the value of real laser wavelength, entering in real time into the processing of the distance, can be adjusted. In the same way the influence of linear temperature expansion of the measured object (in pursuance of the previously known coefficient of linear temperature expansion and the measurement of the average temperature of an object) can be compensated. Thereby errors are eliminated due to the changes in atmospheric conditions. The time interval of reading is 7 seconds. Three sensors used for material temperature and one sensor used for atmospheric conditions (temperature, pressure, humidity) can be joined to the unit.

3. TESTING THE INFLUENCE OF THE INTENSITY OF ILLUMINATION ON MEASUREMENTS WITH A DIGITAL LEVEL

The results of levelling measurements, performed with digital levels, not only affect the conditions and influences mentioned in the previous chapter, but also the intensity of illumination. Requirements on the intensity of illumination are higher than for optical levels (Hánek, 2001).

3.1. Light and photometric conditions

Light is an essential part of our life and environment and is a fundamental factor that must be considered. From a physical point of view, as a part of electromagnetic waves, light is everywhere, whether in the pure form as a source of energy (sun radiation), this is equally true when considering the achievements of science and technology.

The intensity of light and illumination can be a limiting factor in every area of human activity, including surveying. Modern surveying instruments, used for terrestrial measurement, require in order to operate, not only a source of energy, but also particular photometric conditions in order to recognise the subject of the measurement – the target. Recognition of the subject of measurement with surveying instruments is, in general, provided by the attributes of the observer, the telescope and of the environment between the observer and the target. When working with conventional optical instruments, these properties can be specified in pursuance of:

- photometric conditions (illumination, contrast),
- the geometrical properties of a target (angular size, shape) (Sokol & Michalčák, 1999).

When using digital levels which automatically determine elevation, it is necessary to highlight the fact that the size of the target is defined by a minimal section of the graduation distance, which must be visible during measurement. Illumination E is a derived photometric quantity determined as a ratio between the uniformly distributed luminous flux $\Delta\Phi$, hitting the surface of the object, and the area of this surface ΔS. The illumination unit is lux (lx). The illumination of the area is one lux, if at each square meter of the area there is uniformly distributed luminous flux of one lumen:

$$E = \frac{\Delta\Phi}{\Delta S} \tag{1}$$

For illustration some values of illumination under different conditions are given (Table 1). For the experimental evaluation of illumination portable luxmeter PU 150 with a measuring range up to 100 000 lx, equipped with two sensors: resistive – measuring range up to 40 lx, selenium – measuring range up to 100 000 lx, has been used (Halahyja et al., 1985).

Table 1. Values of illumination under different conditions

Place of measurement	Illumination (lx)
Moon illumination at full moon	0.15 up to 0,20
Illumination of a street	2,00 up to 20
Illumination of a bedroom	up to 50
Illumination of a living room	up to 80
Illumination of an art room	up to 300
Room in the day-time	10 up to 10 000
Direct sun illumination	up to 100 000

3.2. Conclusions from experimental measurements of photometric conditions using the digital level DiNi12

- measuring time under normal daily illumination of (200–3000) lx and more corresponds with the manufacturer data and the time ranges are up to 4 seconds,
- when decreasing the intensity of illumination under 80 lx, the measuring time is increased by as much as double (6 seconds and upwards),
- the threshold value at uniformly artificial illumination (when instrument still measures) is (8 to 5) lx, (at spotlighting minimal values of 10 lx and higher are necessary),
- the illumination of staff graduation by direct sunlight of higher intensity (no diffuse illumination) is indicated by the interruption of measurement – "unreadable staff",

- under daily illumination the most oblique (dispersive) light is most suitable and is measured at (200–400) lx (the variance over repeated readings is ±0,1 mm),
- increased intensity of illumination, direct sun illumination and increased distance of the sights leads to worse results (with a variance in repeated readings of up to 0,6 mm) and prolongs the time of measurement,
- measurement with the digital level DiNi 12 is possible on the ground and in low light conditions, but it is necessary to take into account that under the reduced intensity of illumination below (120–100) lx the accuracy of the measurement results decreases.

4. THE CALIBRATION OF ELECTRONIC DISTANCE METERS AT THE LENGTH COMPARATIVE BASELINE IN THE FIELD

The exploitation of electronic distance meters (EDM) in surveying practice, their rapid development in terms of construction, especially concerning the range and accuracy of measured distances, has led to the formation of a range of new methods and procedures in the area of measurement processing. One of the key areas is the improvement in the accuracy parameters of EDM. The low variance in the measurements when using EDM can often lead to a high level of trust in the results obtained and the factor of change in EDM parameters is often neglected. To the fore appears the reproducibility of distances when repeating measurement at different time intervals (Mičuda & Korčák, 2001).

The manufacturer specifies the accuracy for particular types of instruments by means of standard deviation of the measured distance in the following form:

$$\sigma_d = a + b \cdot 10^{-6} \quad (2)$$

where a represents the additive element and b is the scale element.

These parameters stated by the manufacturer are usually obtained from the processing of multiple measurements in laboratory conditions. During long-term exploitation it is necessary to verify the parameters stated in the field conditions. The user's role is therefore to check the reliability and accuracy of EDM before its exploitation, which should become the norm when using all instruments in surveying. One of the methods of verifying EDM parameters is its calibration on the field length baseline. Such a length comparative baseline – baseline Hlohovec, was built by the Department of Theoretical Geodesy of Faculty of Civil Engineering in collaboration with, then, the IGHP n.p. Žilina plant in Bratislava in 1978 (Mičuda & Korčák, 2001).

4.1. Calibration methodology on the baseline Hlohovec

The calibration procedure on the baseline in Hlohovec (Fig. 5) consists of two steps (Ježko & Bajtala, 2005; Mičuda & Korčák, 2001):

- the realization of the measurement and acquisition of the measured data,
- the processing of the measured data.

For the calibration measurement 5 pillars with necessary centring (***n* = 5**), labelled Z1 – Z5 are used. This configuration enables the measurement of the following number of combinations

$$n(n-1) \quad (3)$$

in this case 10 distances are used for the calibration of the EDM. Full calibration measurement is recommended to be carried out in two series over two days (Mičuda & Korčák, 2001), ideally under different atmospheric conditions.

A series of measurements presents reciprocal distance measurement in every combination. The minimal calibration measurement, which is sufficient for most instruments in surveying practice, consists of one measurement in one series.

Fig. 5. Total station on the baseline in Hlohovec

4.2. The processing of the measured data

Resulting from the processing of the calibration measurements, the values of selected instrument parameters, the confidence interval of these parameters and the testing of the hypotheses about the selected parameters can be determined. The processing procedure starts with the determination of physical reductions (the influence of air temperature, pressure and humidity), the application of mathematical adjustments (the transfer of the slope distance to the reference plane); this includes corrections of direction (misalignment of the baseline points from its axis) and corrections of elevation. Another part of the procedure represents an estimate of the additive constant and an estimate of the parameters of the regression line, representing correction of the EDM, proportional to the measured distance (Mičuda & Korčák, 2001).

The additive constant of EDM can be defined follows

$$c = k + c_1 + c_2 \quad (4)$$

where:

k is a part of the additive constant, caused by the electronic part of the instrument. This part affects the accuracy of the measurement result. Determination of k is possible only in laboratory conditions,

c_1 is a geometrical part of the additive constant,

c_2 is a geometrical part of the additive constant of the reflective system.

The value of $c_1 + c_2$ equals to zero at most EDMs for the reflective system recommended by the manufacturer. In the case of a different reflective system the determination of the value of additive constant is necessary, as its unknown size impacts the measurement and can be seen in the form of a systematic error. Therefore, the additive constant is estimated on the basis of the second linear model (indirect measurement of vector parameter) from the measurement on the baseline (Mičuda & Korčák, 2001).

Using the aforementioned model, estimates of the measured distances and estimates of the additive constant together with the characteristics of accuracy of instrument are obtained. Estimates of the additive constant are valid for the calibrated system: EDM – reflective system. Estimates of the distances, characterised by their covariance matrix, are corrected using the additive constant and can be directly compared with parameters of the baseline. By means of linear regression, considering statistical properties of estimates, search parameters of EDM are determined:

a (additive constant) and *b* (scale constant – proportional to the measured distance) – equation (2).

The Hlohovec geodetic baseline enables the determination of the real value of the additive constant of the EDM – reflective system and the assessment of the accuracy of the distance measurement using a specific system. Determination of the correct value of the measured value is a necessary condition from the point of view of the assurance of metrological traceability – realization of the meter as the unit of distance (Mičuda & Korčák, 2001).

5. CALIBRATION OF HORIZONTAL CIRCLES OF OPTICAL AND ELECTRONIC THEODOLITES

In the past, to assess the quality of horizontal circles and accuracy of the measurement of angles a procedure based on the standard STN ISO 8322 was used. This standard assumes that measurement is carried out using two faces of the telescope, in four ranks and in two series. Accuracy of the measurement of angles or directions is, according to this standard, specified by standard error "m_α" (Ježko & Bajtala, 2005; Ježko, Mokroš, & Tajzler, 2004).

Currently, the process of quality assessment of optical and electronic theodolites, EDM and electronic tacheometers is defined by the following standards (Ježko, 2010):

- STN ISO 17123-3:2010 Optics and optical instruments – Field procedures for testing geodetic and surveying instruments. Part 3: Theodolites.
- STN ISO 17123-4:2013.
- STN ISO 17123-5:2013.

The calibration of horizontal circles of optical and electronic theodolites can be carried out under laboratory conditions, e.g. on an automated device for the calibration of optical polygons EZB-3 in the Slovak Institute of Metrology in Bratislava (SIM). This device is part of the primary standard and hereby the national standard of plane angle in the Slovak Republic. The basis of this device is a 72 edged optical polygon representing the design of directions in a range of 0 to 360°, with a 5° increment and extended uncertainty of transmission to calibrated instrument up to 0.1" (*P* = 95%), depending on the metrological parameters of the calibrated instrument. This device has been used for the calibration of many optical and electronic theodolites, details of which can be seen in (Hašková, 2007; Hašková, Sokol, Ježko, & Mokroš, 2007; Ježko, Mokroš, & Tajzler, 2004; Mokroš, 2006; Mokroš, 2005).

The result of such calibration is a set of horizontal scale corrective values for particular nominal values of the scale, determined by carrying out several series of measurement, and eventually the parameters of the approximating function.

The statistical testing of parameters of normal distribution and analysis of variance is an important part of processing. Detailed information about the testing of normal distribution and ANOVA (Analysis Of Variance) is given in the following literature (Ježko, Hašková, Bajtala, 2005; Ježko et al., 2004). As an example, the results from the calibration of the electronic theodolite Leica TC 800. Graphical representation of the data – corrections of particular places on the horizontal circle can be seen in Figure 6.

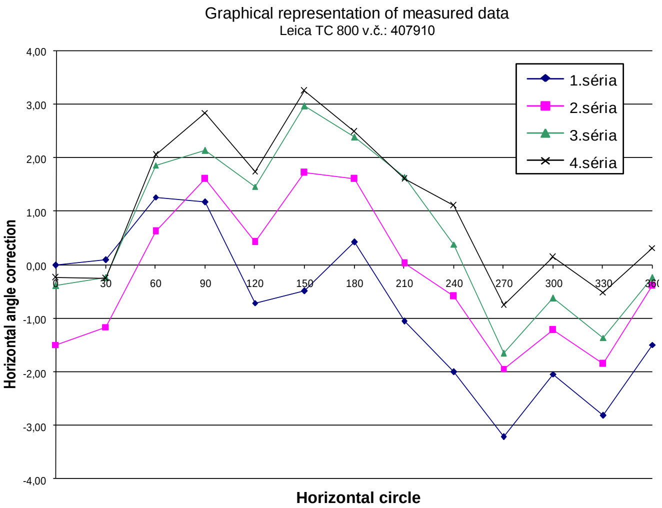

Fig. 6. Values of corrections for four series of measurement from calibration device in SIM

During the approximation of the measured values the cyclic function (sinusoid) (Fig. 7), which is based on the following relationship, was applied:

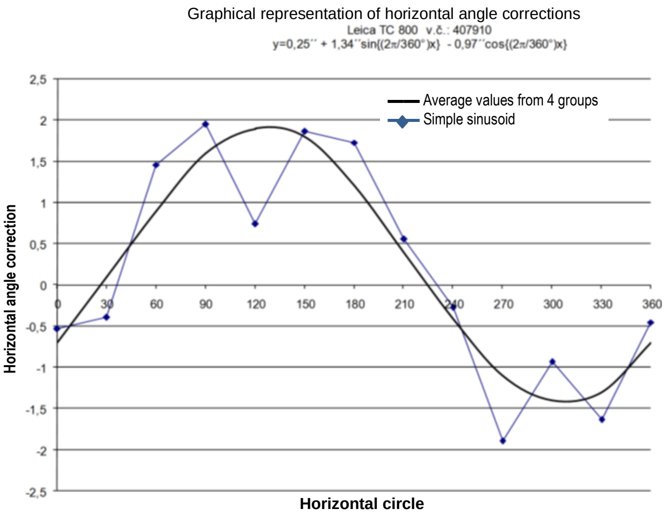

Fig. 7. Calibration curve and the approximating cyclic function

$$y = b_0 + b\,\sin(t + B) \tag{5}$$

where:

$$t = \frac{2\pi}{P}x = \frac{2\pi}{360°}x,$$

x – the rotation of horizontal circle,
b_0 – the coordinate where the axis of sinusoid intersects the y-axis,
b – the amplitude of the sinusoid,
B – the shift of the origin of the sinusoid.

Equation (5) can be written as follows:

$$y = b_0 + b\sin(t)\cos(B) + b\cos(t)\sin(B) \quad (6)$$

After substitution:

$b_1 = b\cos(B)$ and $b_2 = b\sin(B)$

Equation (6) can be written as follows:

$$y = b_0 + b_1\sin(t) + b_2\cos(t) \quad (7)$$

The coefficients b_0, b_1, b_2 can be estimated using the least squares method and their values are listed in the chart. From these coefficients it is possible to re-determine the parameters of equation (5):

$$\tan(B) = \frac{b_1}{b_2}, b = \sqrt{b_1^2 + b_2^2} \quad (8)$$

6. CONCLUSIONS

The calibration and quality control of surveying instruments is an important part of their use in every field of scientific and professional technical work. The use of a laser interferometer (laser measurement system XL 10 f. RENISHAW) for the calibration of the code leveling rod, respectively of the system calibration (digital leveling device – code leveling staff) prepared on the Department of Geodesy, SUT Bratislava with the help of European projects, will begin after the implementation of a unique facility in the Slovak Republic.

The results of the experimental evaluation of lighting quantify the need for the intensity of illuminance using the device DiNi 12 and, in part, also the quality of the results for selected conditions.

The procedures presented and the results of the calibration and inspection of electro rangefinders and theodolites offer additional possibilities and opportunities to ensure quality and verified equipment and printouts for geodetic practice in the field of measuring displacements and deformations.

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