602. Principle and Data Analysis of Vertical Angle Calibration of Geodetic Instruments

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Abstract. Many opto-electronic digital instruments, such as rotary encoders, theodolites, total stations, laser trackers, etc. are used in machine engineering and instrumentation, geodesy, surveying, robotics and other branches of industry. Most of optical-electronic geodetic measuring instruments consist, among the other elements, of the circular scales and angular transducers for angle determination in two perpendicular planes – horizontal and vertical. Accuracy of the instrument mostly depends on the accuracy of these means for angle measurement. Even if calibration of horizontal angle measurement instrumentation can be relatively easily solved implementing rotary tables of different constriction the calibration of vertical angle measurement instrumentation is still a very complicated and not easily solvable task. Here in this paper we present a review and some simple means and methods that can be used in the angle measurement metrology, especially in vertical plane angle calibration. The results of the experimental calibration with the brief errors analysis and possibilities of accuracy increase of tested instrument are also given.

Keywords: vertical angle, angular encoders, calibration, systematic errors, correlations.

1. Introduction

Main standard of measure used for angle measurements or calibration is multiangle prism (polygon) with an autocollimator. The polygon prism features by restricted number of faces, it is, flat angles, usually, consisting from 12, 24, 36 or 72 angles. At the same time, readings from the circular or raster scales display a great number of discrete values on their display units. In fact, most of these values remain without checking during the calibration process due to the restricted number of angles available by the polygon at use. A present scientific and technical background validates the concept of development of the standard measure for calibrating the wide range of angular readings from optical instruments and consisting from thousands of angular values in compliance with the requirements stated in their technical specifications.

Generally there are several groups of plane angle measurement principles (methods) [1,2]:

1. Solid angular gauge method:
   - polygons (multiangular prisms);
   - angular prisms;
   - angle gauges, etc.
2. Trigonometric method (angle determination by means of linear measurements);
3. Goniometric method (plane angle determination by means of a circular scale):
   - full circle (limb, circular code scales etc.);

- non-full circle (sector scales).

Calibration and testing of the geodetic angle measuring instruments has always been a serious problem and if calibration of the horizontal angle measurements could be quite efficiently accomplished using standard precise turn tables (quite widely implemented in metrology and industry), calibration of vertical angle measures required some special instrumentation [3]. Calibration of vertical angle measures of the geodetic instruments was usually performed by a special bench composed of autocollimators attached at the different vertical angles to the calibrated instrument, in this case the entire test bench used to be extremely bulky and able to measure only very limited number of vertical angles [4]. A new approach to the problem was implementation of the precise angle encoder for the creation of vertical angle reference, in this case it was possible to create unlimited number of reference angle values, but the equipment was extremely expensive [5].

Here we present some developments in the flat angle calibration methods and means permitting to assess a large number of angle values or, theoretically, most of the output information from the circular scale's or rotary encoder's readings. The experiment described is based on the trigonometric method (angle determination by means of linear measurements) and requires minimal amount of complicated instrumentation.

2. Implemented principle of vertical angle calibration

Most of geodetic instruments have two angle reading devices installed – for horizontal and vertical angle measurement. A number of methods of calibration of the horizontal angle measurements are implemented on practice, their origin comes from the circular scales and rotary encoders calibration. Here we analyse a proposal for arrangement to create the reference standard for angle measurement suitable for vertical angle calibration purposes in laboratory environment [6].

The principle of proposed vertical angle calibration is based on the trigonometric angle determination. The arrangement for calibration is shown in Fig. 2.

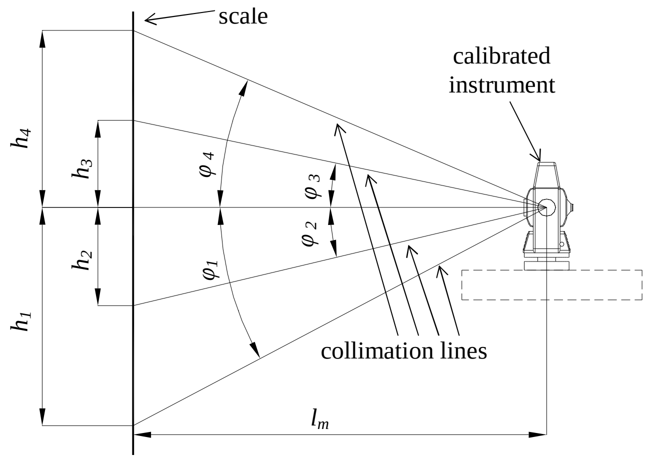

Fig. 2. Arrangement for vertical angle calibration for geodetic instruments

As can be seen from the picture an instrument to be calibrated is placed at a certain known distance (l_m, Fig. 2) from the precise linear scale. The spyglass of the instrument is declined at the angle φ (φ_1, φ_2, φ_3 or φ_4) accuracy of which must be calibrated. The reading h (h_1, h_2, h_3 or h_4) from the scale is taken. The angle of interest is expressed:

$$\varphi = arctg \frac{h}{l_m} \quad (1)$$

where h - the reading from the scale, l_m – distance from the instrument's centre to the reading surface of the scale.

It is difficult to measure with high accuracy, so additional measures must be taken for the calculations. It is accomplished by adding the known length measure l_e of high accuracy. It can be the end gauge, linear incremental transducer, etc. On the second step the instrument is replaced on the distance ($l+l_e$) from the scale preserving the same value φ of instrument's view angle. The position of horizontal axis is replaced from the point O_1 to the position O_2.

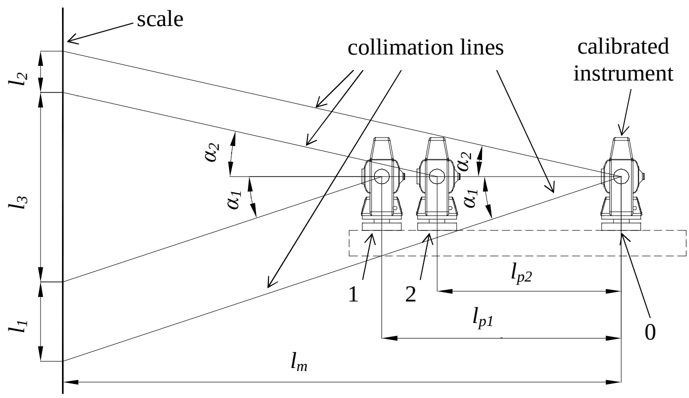

Fig. 3. Determination of the distance from calibrated instrument to the reference measure; 0 – instrument calibration position, 1, 2 – subsidiary calibrated instrument position used for distance determination

For the precise vertical angle measurements the distance from calibrated instrument (tacheometer) and the reference measure (linear scale) has to be determined quite precisely (down to 0.01 mm).

The determination of the distance from calibrated instrument to the reference measure can be determined using the layout shown in Fig. 1. The distance l_m from instrument calibration position (0) to the reference measure (scale) can be calculated by moving the instrument linearly to the subsidiary positions (1, 2) while the same vertical angle (α_1 or α_2) of the calibrated instrument spyglass is being kept. Therefore the readouts of the vertical scale at the same vertical angle and different length to the scale can be made and distances l_1, l_2 and thus l_3 can be determined. The calibrated instrument should move from position 0 to positions 1 and 2 by means of some kind of guide-skid, and the linear movement (l_{p1} and l_{p2}) determined using the linear photoelectrical scale, laser interferometer or even precise linear optical scale (with microscope).

To determine the distance l_m calibrated instrument at the calibration position 0 should be pointed at the certain scale stroke with the vertical angle α_1 and scale readings taken. After that instrument is moved to the position 1 keeping the same vertical angle α_1 till the spyglass collimated to different scale stroke, thus scale distance l_1 determined. After that instrument moved back to the position 0 and collimated to the different scale stroke with vertical angle α_2, the measurement procedure is repeated thus the distance l_2 determined. Distances l_{p1} and l_{p2}

will usually be different since it is almost impossible (in case of visual scale) to collimate exactly to the scale stroke (having different vertical angles α_1 and α_2) having the same horizontal movement. The procedure of two measurements (l_{p1} and l_{p2}) is essential since it is also almost impossible (again in case of simple visual scale) to collimate the tacheometer at the horizontal collimation line to a certain scale stroke.

Having the mentioned measurements performed the vertical angles can be determined (using linear measures, Fig. 1):

$$tg\alpha_1 = \frac{l_1}{l_{p1}}; \quad (2)$$

and

$$tg\alpha_2 = \frac{l_1}{l_{p2}}; \quad (3)$$

where l_1, l_2 – scale measures at the same vertical angle but different linear distance from calibrated instrument to the reference scale; l_{p2}, l_{p2} – linear movement of instrument during measurements.

Also the total measured length of the scale could be expressed (Fig. 1):

$$l_1 + l_2 + l_3 = l_m \cdot tg\alpha_1 + l_m \cdot tg\alpha_2; \quad (4)$$

where l_m – distance from the calibrated instrument to the reference scale.

Therefore the real distance form calibrated instrument to the scale:

$$l_m = \frac{l_1 + l_2 + l_3}{tg\alpha_1 + tg\alpha_2}; \quad (5)$$

Using equations (2) and (3) it could be written:

$$l_m = \frac{l_1 + l_2 + l_3}{\frac{l_1}{l_{p1}} + \frac{l_2}{l_{p2}}}. \quad (6)$$

Therefore the real distance from calibrated instrument to the reference scale can be determined using only linear scale.

3. Results of the experiment

The test of calibration of vertical angle measurements of the geodetic angle measuring instrument (tacheometer) was perform using *Trimble 5503* tacheometer having the manufacturer stated standard deviation (manufacturer often states simply accuracy for general public) of angular measurements of 5″ (arc sec) [7].

The arrangement for the experiment was composed according to Fig. 2; the tacheometer was mounted on the linear slideways and aimed to the linear scale positioned vertically at a distance of approximately 2.5 m for the tacheometer. The industrial laboratory linear scale of f 1 m with the scale strokes at every 1 mm was used. The linear displacement of the tacheometer to be calibrated was performed using the end length gauge of 200 mm. After the measurement and calculation of linear distance from tacheometer to the scale performed according to the previous chapter, it was determined that the distance l equals to 2.4215 m.

The main objective of experiment was to test the calibration method and obtain results of the errors of the vertical angle measurements using *Trimble 5503* tacheometer.

The calibration was performed using 1 m precise linear scale collimating the spyglass to the scale strokes at a pitch of 10 mm and 12 mm. Overall 6 measurements were performed at full reference scale length. The resulting calculated deviations of tacheometer readings are shown if Fig. 3.

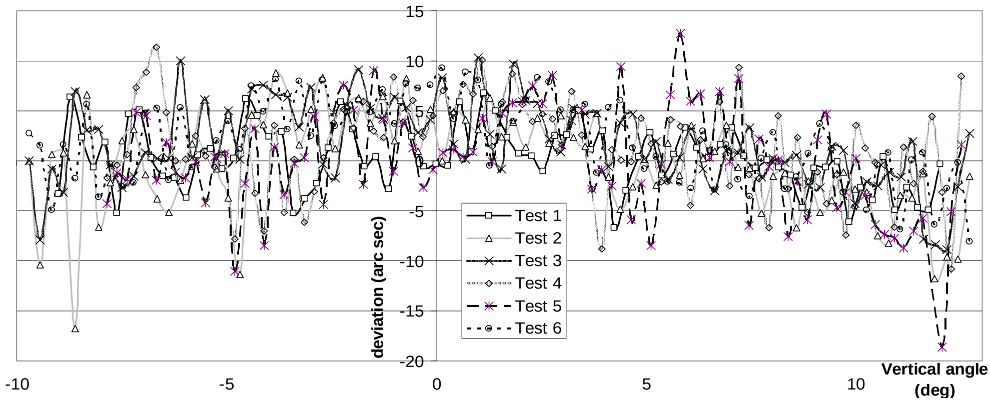

Fig. 4. Deviations of vertical angle readings

From the mentioned test experimentally determined standard deviation of a vertical angle measurements for *Trimble 5503* tacheometer is 4.46″ which almost perfectly matches to the manufacturer stated standard deviation of 5″ [8]. Nonetheless to determine the character of errors, obtain the possible systematic constituent of them and therefore foreseen the possibility of accuracy increase the analysis of data obtained must be performed.

To determine the existence of systematic constituent of errors the correlation analysis of the data was performed. The results of the correlation analysis are presented in Table 1 and Fig 5. In Table 1 the values, which statistically might show some correlations, are marked grey. Generally according to the calculations of correlations there can be no significant correlation tendencies recognized – most of the correlation values do not exceed ±0.25 and are both positive and negative. The largest correlation according to results of calculations exists among the data of Test 1 and Test 2, which could appeared due to the fact that both measurement series were performed under repeatability conditions (same day, same operator etc.), thus systematic errors of measurement could be present (like reflection, temperature etc.), additionally those where the first measurements performed therefore there could occur some biases caused by the operator.

Generally basing on the correlation analysis (Table 1 and Fig 5) it can be stated that no significant systematic errors of measurements can be spotted.

Table 1. Correlations calculation data

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
Test 1		0.4728	-0.0326	0.0403	0.0871	-0.0032
Test 2	0.4728		0.2295	0.0447	0.2152	0.196
Test 3	-0.0326	0.2295		0.132	0.1689	0.0809
Test 4	0.0403	0.0447	0.132		-0.2958	-0.125
Test 5	0.0871	0.2152	0.1689	-0.2958		0.3546
Test 5	-0.0032	0.196	0.0809	-0.125	0.3546	

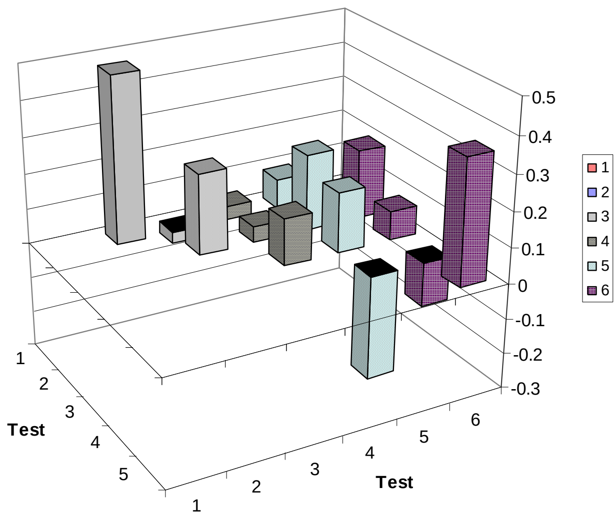

Fig. 5. Correlation of measurements series

Despite the correlation calculation data (Table 1 and Fig. 5) some tendency of errors in all of the measurements could be spotted from Fig. 4 – all of the measurement series deviations numerically increase at the centre of the measurements (i.e. 0° measure or level measurement) and decrease moving further to both ends of measurements. The matter can be obviously noticeable in Fig. 6 where Test 2 (as an example) deviations data are presented (black curve). The character of deviations can be represented by the 2[nd] degree polynomial curve (dotted) having the law described by equation:

$$y = -0.0772x^2 + 0.0265x + 4.374 \,. \qquad (7)$$

where x – vertical angle data (deg), y – correction of the results of measurements.

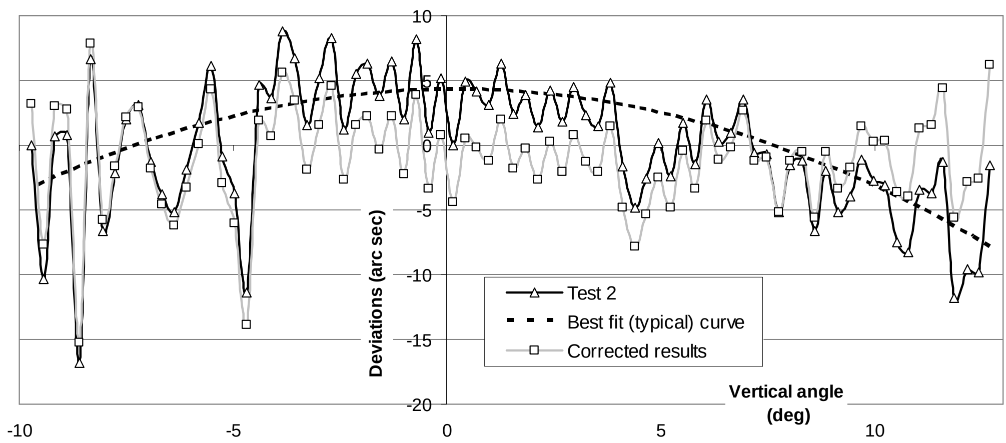

Fig. 6. Example of the obtained deviations with the best fit curve

Implementing the typical (best fit) curve (Fig 6) and its equation (7) the corrected deviations of the measurements could be calculated (grey curve, Fig 6). Having the corrected results of vertical measurements deviations the standard deviation of vertical angle measurements can be calculated. The standard deviation of tests performed after the data were corrected is 3.48″ while the initial value (without the correction of results) was 4.46″. Therefore it can be stated that implementing the equations (7) for calculation of measurements data the accuracy of measurements can be increased by almost one arc second (which stands for roughly 20% of measurement error) other measurement errors have obviously random origin and can hardly be eliminated. The determined possible increase of vertical angle measurements accuracy of almost 1″ (20%) can be addressed to only to tested *Trimble 5503* instrument, further test should be carried on to determine the possibilities of accuracy increase of other instrumentation [9].

It must be noted that despite the possible increase of the accuracy it can hardly be of great interest in everyday implementation of the instrument since the determined systematic constituent of errors is quite small and does not have a great effect on general quality of measurements. Nonetheless the suggested method of calibration can be implemented for the large number of instruments with the task of determining the accuracy of vertical angle measurements and possibly eliminating some systematic errors thus increasing the general accuracy of measurements.

5. Conclusions

1. A simple method of calibration of vertical angle measurements accuracy of geodetic instruments was proposed, similar method of angle measurement calibration could be implemented for all angle measurements, both vertical and horizontal of collimated instruments such as theodolites, tacheometers, etc.;
2. The calibration of accuracy of vertical angle measurement of *Trimble 5503* tacheometer was performed implementing the principle described. According to the results of calibration the accuracy of vertical angle measurements for the mentioned instrument can be increased by almost 1″ (20%);
3. The principle of calibration should be tested on other geodetic instruments to determine the real possibility of implementation of method and increase of the accuracy of tested instruments.

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