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Theoretical aspects of the calibration of geodetic angle measurement instrumentation

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1. Introduction

In geodesy, surveying, machine engineering and other branches of industry there are very widely used instruments that allow precise planar angle measurements. Such instruments are theodolites, digital theodolites, total stations, laser scanners, laser trackers etc. Same as all other measuring instruments these instruments must be tested and calibrated.

Testing of these instruments in Europe is regulated according to ISO 17123-3 [1] and ISO 17123-5 [2]. According to the standards an accuracy of the angle measurement performed by the instrument must be tested in the field conditions using the known length reference measure for the angle measurement (triangulation principle). Using such method it is possible to get only a very restricted number of angular measurements, it doesn't allow collecting a large number of different (desired) tested angular values. On the other hand, angle measuring instruments due to implementation of precise angle encoders display a vast number of discrete values on their display unit during measurement, and these values must also be checked, the accuracy of these values remain unknown even after testing due to limited nature of testing method itself [3].

Throughout calibration of the angle measuring instruments requires a large number of angular values to be compared with the reference values. Such procedure due to its technical complexity is not regulated by any standard in Europe at all. Very few test rigs are used to perform the complex testing and calibration of planar angle for geodetic instruments [4]. Those devices are usually operated by the companies – manufacturers of the measurement equipment and are not available for the wide public and the users of these instruments.

Additionally both marketing representatives of the angle measurement instrumentation and their users (especially in field of geodesy and surveying) are not interested in additional investments in periodical testing and calibration of instrumentation. Such approach eventually leads to high errors in measurements which are especially evident in construction engineering and legal surveying.

It is obvious that the method and instrumentation is needed for testing and calibration of the angle measuring instrumentation. Here in this paper we present the principles of such testing and calibration together with construction of the test bench and methodology intended for such tasks.

2. Calibration of angle measures

There are several methods of calibration of angle measuring instrumentation, nonetheless the method of comparison (of any kind) has been most widely accepted and is considered to be the most effective and less time consuming. Comparison – the method of comparing of the angle measures of tested instrument with the ones provided by the reference means of angle measurement [5-6].

Reference angle can be produced by different types of measuring devices, such devices used in some calibration methods are presented in Table 1 [3, 7, 8].

The first of the methods presented is based on the precise multi-angular prism – polygon [7]. Usually it has

Table 1

Technical specifications of angle measuring methods and devices

	Angle standards of measure	Discretion	Standard deviation	Bias
1.	Polygon – autocollimator	10°, 15°, 30°	0.15″	0.30″
2.	Moore's 1440 Precision Index	15′	0.4″	0.1″
3.	Circular scale- microscope	3°, 4°, 5°	0,2″	~3″
4.	Photoelectric angular encoders	1″, 0.1″	~ 0.3″	~ 1″
5.	Ring laser	0.1″	~ 0.4″	~ 1″
6.	Trigonometric methods (angle determination by means of linear measurements)	1" (highly dependant on linear reference used)	0.01" (highly dependant on linear reference used)	± 0.1″ (highly dependant on linear reference used)

from 12 up to 72 flat mirrors positioned at very precise constant angle to each other, the polygon usually is being turned to a certain position together with the object to be measured and the angle of rotation is registered by the optic instrument – autocollimator. Such a method is very widely applied in measuring technique so in geodesy instrumentation as well. This method has one shortcoming – the discretion of this method is very great, so it is possible to check only a small number of values offered by the calibrating measuring instrument.

The second method presented in the Table 1 uses a very precise tool – Moore's 1440 Precision Index [9, 10]. Moore's 1440 Precision Index is an angular measuring device consisting of two serrated plates joining together to create the angle standard of measure. During measurement the upper disk of the Index is lifted, the lower part rotates with the object to be measured, after that the upper part is lowered back and the readings are taken. The method according to many sources is of high precision - 0.004" (Table 1), although it also has some shortcomings – it is very difficult to automate, also during the lifting of the table (which is necessary technological operation of the method) the calibrated instrument may lose its stability, move and unexpected errors may occur.

The third method is a classical one both in geodesy and in general technique [8, 9, 11]. This method has been very widely used in the past and it requires a highly accurate circular scale and one or more (depending on the measuring method) microscopes (preferably photoelectrical) for the scale readings. The major shortcoming of the method is the need of circular scale of very high accuracy; the scale must be of a large diameter for placing the photoelectric microscopes, it needs a precise manufacturing and a time consuming calibration. Due to a great cost of such processes this method slowly vanishes from the common use being replaced by the rotary encoders.

The fourth method presented is the most widely spread one nowadays, it uses the digital rotary encoders as the reference measure. Using modern high accuracy digital rotary encoder it is possible to achieve a very good result comparable with the classic methods. Using rotary encoders also allows reducing the size of the test bench to minimum and good possibilities for its automatization.

Presently a very modern method of angle measurement has been developed using the "ring laser" as reference measure of angle. The device consists from the split laser beam which rotates into opposite directions and the angle measurement is performed by the comparison of the split beams phase difference, in such way a very high precision is being achieved. This method is slowly taking its place in technique due to its dynamic nature, by now it was mostly widely used in the aircraft navigation systems etc.

Additionally, a method angle determination by means of linear measurements (trigonometric) can be noted. This method implements liner reference with further calculations to determine the measured angle value. Though the method can be quite time consuming a high accuracy can be obtained which highly depend on the linear reference used and possible distance to the reference itself.

To use the described angle measuring methods for the calibration and testing of the geodetic instruments their accuracy must be higher than the accuracy of the instruments being calibrated [9-11]. Standard deviations of the horizontal angle measurement of the most commonly used electronic tacheometers are listed in Table 2.

Assuming the technical specifications of the most commonly used geodetic instruments it can be considered

Table 2

Technical specifications of the most commonly used electronic tacheometers

Instrument model	Standard deviation of angle measurement
Leica	
Leica TPS403/5/7	3", 5", 7"
Leica TPS1201/2/3/5	1", 2", 3", 5"
Leica TPS5000	0.5"
Leica TCA1800	1"
Leica TCA2003	0.5"
Trimble	
Trimble M3	3", 5"
Trimble 3601/2/3/5	1,5", 2", 3", 5"
Trimble 5603/5	3", 5"
Trimble S6 "High precision"	1"
Sokkia	
Sokkia SRX1/2/3/5	1", 2", 3", 5"
Sokkia 130R SET1/2/3/4	1", 2", 3", 5"
Sokkia 30R SET2/3/5/6	2", 3", 5", 6"
Sokkia 200 NET1	1"
Sokkia 100M NET1	1"
Topcon	
Topcon DT202/5/7/9	2", 5", 7", 9"
Topcon GPT3002/3/5/7(L)N	2", 3", 5", 7"
Topcon GPT8201/2/3/5A	1", 3", 2", 5"
Topcon GPT9001/3/5A	1", 3", 5"
Hewlett – Packard	
HP 3820A Elect. Total St.	2"

that all the angle measuring methods listed in Table 1 could be used for their calibration and testing, the difference being in more or less suitable ones for this task.

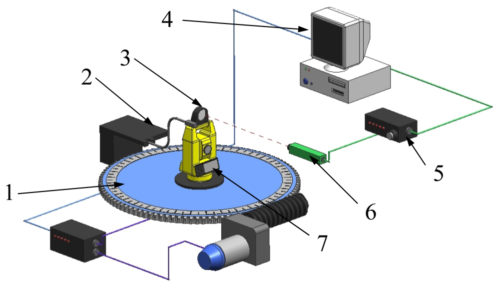
As can be seen from Table 1 and 2, basing on the accuracy requirements most of the most of the angle measuring principles (instrumentation) could be used for testing and calibration of geodetic instrumentation.

3. Results of the experiment

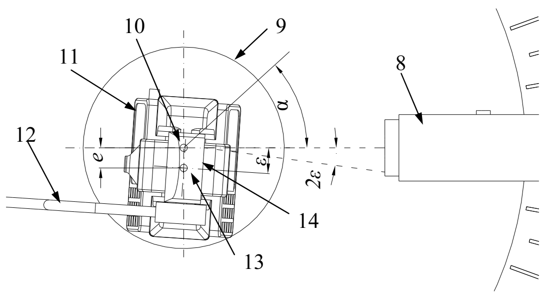
In case of implementation of any of angle measuring principles some special instrumentation and arrangement is needed to perform reliable and high accuracy angle measuring instrument calibration. The arrangement for calibration of horizontal angles is given in Fig. 1, a (implemented in Institute of Geodesy, Vilnius Gediminas Technical University).

The tested/calibrated geodetic device *7* is being mounted on the test rig rotary table *1* and flexibly attached via the holder *2* to the stationary part of test rig; the table is being turned at a desired angular position. The mirror *3* is attached on the top (or any other part) of calibrated device and rotates with the upper part of device. The autocollimator *6* is placed on a stationary part of test rig and pointed to the mirror. The autocollimator transfers the data to a computer *4* where the data of angular position of the rotary table are also transmitted.

The principle of tested/calibrated device angular position determination is shown in Fig. 1, b. After turning the rotary table *9* to a desired angular position (for testing or calibration) α the tested/calibrated device upper (rotary) part *11* due to eccentricity e or looseness in holder joint rotates to an angle ε regarding the initial position (before rotation of the rotary wheel, parallel to longitudinal axis of the rig).



a



b

Fig. 1 Determination of angular position of calibrated device: a) general arrangement; b) principal diagram, *1*, *9* – rotary table, *2*, *12* – holder of calibrated device, *3*, *14* – position determination mirror, *4* – PC, *5* – autocollimator control unit (optional), *6*, *8* – position determination autocollimator, *7*, *11* – calibrated geodetic device, *10* – centre of rotation of the rotary table, *13* – centre of rotation of calibrated device

The mirror *14* (Fig. 1, b) attached to the calibrated device rotates to a same position and it is possible to determine its angular position regarding the longitudinal axis of the rig using the stationary positioned autocollimator *8*. Since autocollimator measurements depend neither on the distance from autocollimator to a mirror, nor on perpendicular movement of it regarding the autocollimators axis, angle ε can be determined. That way the reference angular position of the calibrated device upper (rotary) part regarding its lower part (attached to tribrach) can be calculated:

$$\alpha_{ri} = \alpha_i + \varepsilon_i . \quad (1)$$

Therefore, a precise angle measure of the tested instrument can be determined and compared to the reference one disregarding the eccentricity of instrument attachment to the rig. Such arrangement allows simple and fast replacement of the calibrated instruments.

Since horizontal angle measurement instrumentation have been quite widely implemented in multiple branches of industry, therefore approaches for such testing and calibration have been quite widely developed. Nonetheless vertical angle measurements are applicable practically only to the geodetic instrumentation (and some modern instruments like laser scanners and laser trackers), therefore methods of calibration have to be developed.

The principle of patented (and implemented in Institute of Geodesy) method for calibration of vertical angle measurement systems is based on the trigonometric angle determination. The arrangement for calibration is shown in Fig. 2.

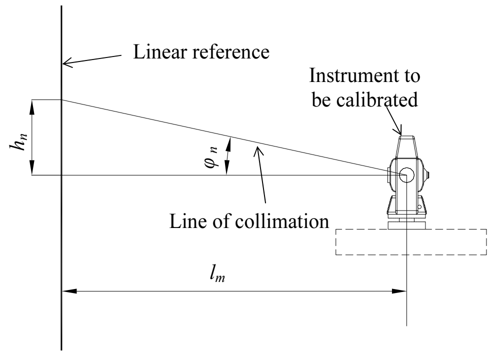


Fig. 2 Principle of trigonometric vertical angle measurement

In this case an instrument to be calibrated is placed at a certain known distance l_m (Fig. 1) from the precise linear reference. Reference 1 meter scale of accuracy of 1μm is placed perpendicularly to the sight axis of the telescope while in horizontal position. The telescope of the instrument is declined at the angle φ_n accuracy of which must be calibrated. The reading h_n from the scale is taken. The angle of interest is expressed:

$$\varphi = arctg\frac{h}{l_m} \tag{2}$$

where h is the reading from the scale, l_m is distance from the instrument's center to the reading surface of the scale. 1 meter scale is graduated in 1.0 mm increments, and every tenth graduation is numbered. Measurement range depends on a horizontal distance between the tacheometer and the reference scale. The closer the scale is the bigger range of vertical angle encoder can be calibrated. However, it is important to ensure that the distance between the reference graduated scale and the tacheometer fits tacheometer's focusing range.

Implementing these approaches the calibration of both vertical and horizontal angle of geodetic measurement equipment can be realized. Since in both cases a large number of angular values can be generated by reference measure, the instrument can be calibrated in the range close to full range of measurements with high density of measures tested.

4. Results of the testing

The preliminary calibration of the geodetic angle measurement instruments was performed according to the methodology described above at Institute of Geodesy, Vilnius Gediminas Technical University.

For precise measurements of horizontal displacements of the instrument high accuracy two axis horizontal table (Fig. 5) was used (ensuring accuracy of movement of up to 1 µm). The industrial laboratory linear 1 m scale of high accuracy with the scale strokes at every 1 mm was used. 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. At this distance the vertical angle encoder can be calibrated in the range of 25 degrees in both faces of the tacheometer. One of the main advantages of this new method is that any mean of the angle can be determined in the range of 37 degrees (if the focusing range is 1.5 m) by changing both horizontal and vertical distances.

The objective of experiment was to test the calibration method and obtain preliminary results of the systematic errors (biases) of the vertical angle measurements using Trimble 5503 (5 arcsec stated st. dev.) and Nikon DTM352 (5 arcsec stated st. dev.) tacheometers. The results of horizontal angle measures calibrations are given in Figs. 3 and 4.

As can be noted from the preliminary graphs (Figs. 3 and 4), both tacheometers produced deviations of measurements showing certain systematic errors of measurement (Typical curves), which could be eliminated from measures thus increasing the final accuracy of measurements. The interesting discovery was that despite the stated accuracy of instruments (5 arcsec stated st. dev.), Nikon DTM352 showed far higher practical accuracy of measurements (though the results should be double-checked during later experiments).

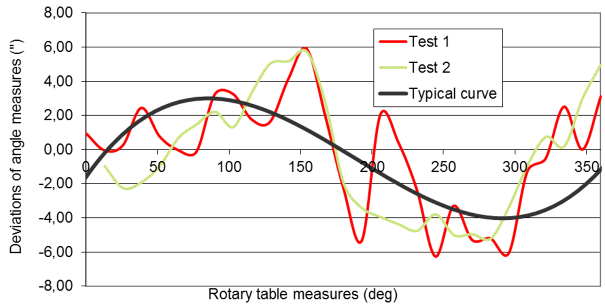


Fig. 3 Deviations of horizontal angle readings of Trimble 5503

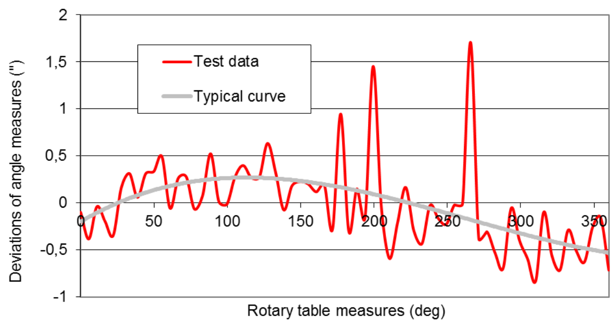


Fig. 4 Deviations of horizontal angle readings of Nikon DTM352

Accuracy of both instruments horizontal angle measurements is sufficient and falls in the stated limits of 5 arcsec st. dev. Results of vertical angle testing experiment of *Nikon DTM352* are given in Fig. 5.

As can be seen from Fig. 5 some of the systematic errors of vertical angle measures can be noted, though more serious and thorough analysis of results is needed. By determination of accurate systematic errors across the range of vertical angle measurements and later numerical removal of determined errors (biases) the accuracy of instrument can be substantially increased.

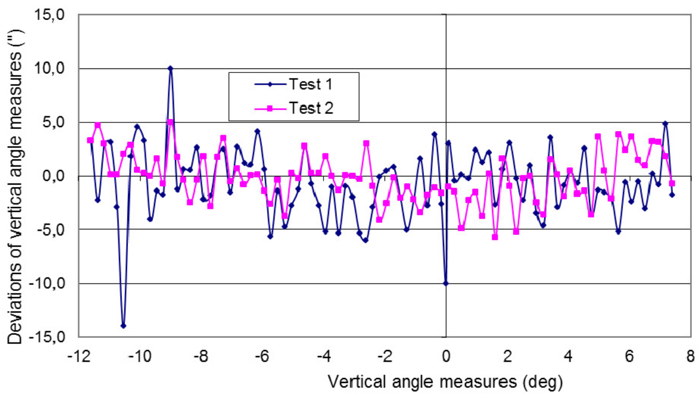


Fig. 5 Deviations of vertical angle readings of Nikon DTM352

5. Conclusions

1. Calibration of angle measuring instrumentation can increase both knowledge on uncertainty of measures (by determination of random errors across the measuring range) and measurement accuracy by determination and subsequent elimination of systematic errors;

2. No calibration of geodetic angle measuring instrumentation is legally required, only outdoor basic testing with error determination at very limited angular values is officially required;

3. The indoor calibration and testing method for vertical and horizontal angles is proposed in the paper;

4. The proposed methods allow precise determination of measurement errors at great amount of angular values thus allowing precisely determine the systematic and random errors;

5. Results of initial testing of the instruments show that (though more thorough testing is needed) the standard deviation of less than 1 arcsec can be achieved.

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TEORINIAI GEODEZINIŲ KAMPŲ MATAVIMO PRIETAISŲ KALIBRAVIMO ASPEKTAI

R e z i u m ė

Daugybė geodezijoje, mašinų gamyboje, statyboje ir kt. naudojamų prietaisų (tacheometrai, teodolitai, lazeriniai skaneriai, lazeriniai sekikliai ir kt.) turi tiesioginio kampų matavimo priemones. Iki šiol nėra oficialaus tokių prietaisų kalibravimo ar patikros visame matavimų diapazone reglamento, nors prietaisai matavimų metu teikia didžiulį kiekį tiek vertikaliųjų, tiek horizontaliųjų kampų matmenų. Straipsnyje apžvelgiamos teorinės tokių kampų matavimo prietaisų kalibravimo prielaidos, o kartu pateikiama galimos naudoti įrangos pavyzdžių.

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THEORETICAL ASPECTS OF THE CALIBRATION OF GEODETIC ANGLE MEASUREMENT INSTRUMENTATION

S u m m a r y

There are multiple instruments directly implementing the principle of angle measurements (horizontal and vertical) for its functioning, used in geodesy, surveying and machine building (like tacheometers, theodolites, laser scanners, laser trackers etc.). As for the moment, there is no official reglamentation regarding calibration and testing of such instrumentation in entire range of the measurements, though instrumentation produce a huge number of both horizontal and vertical angular values during its normal implementation. In the paper the theoretical assumptions of such instrumentation testing and calibration together with examples of some practical tests are given.

Keywords: vertical angle, calibration, systematic errors, random error, calibration method.

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