

New setup for calibration of vertical angle measuring systems

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Abstract. Precision instrumentation is the key factor in quality assurance in various fields of industry. Precision angle measurements performed by using total stations is a field showing a lot of potential. Horizontal angle measuring system calibration is well documented and researched field however vertical angle measuring system calibration tends to lack proper investigation. This paper deals with the analysis of modern calibration methods of vertical angle measuring systems after which the new arrangement for vertical angle calibration of the total station is presented. The principle of the vertical angle calibration using special equipment is described. The primary results of the research are presented in this paper as well as advantages and weaknesses of this new setup approach are discussed.

I. Introduction

Precision angle measurements and instrumentation are few of the main factors ensuring quality in most fields of industry – civil engineering and survey, machinery, laboratory measurements, etc. Total stations are very widely used in the field of geodesy. Moreover their ability of measuring angles because of the good optics and angle measuring systems can be used in laboratory measurements too. Total stations are very commonly used because of the ability to perform horizontal angle, vertical angle and distance measurements using only one instrument. There are two angle encoders embedded into total stations for horizontal and vertical angle measurements. Therefore, there is a need to calibrate these instruments in order to define its systematic errors, eccentricity of the encoders, etc. like any other angle encoder. As previous research showed, most of the methods in angle metrology deal with the flat angle calibration [7]. However, calibration of vertical angle measuring systems is a challenging task for scientists.

Main methods for vertical angle measuring system calibration are analyzed below in the paper. Analysis of means and methods for angle calibration led to a conclusion that angle calibration should be performed using standard means such as Moore's Precision Index, polygon or other reference mirror and an autocollimator. For vertical angle calibration it is quite difficult to combine such instrumentation in a vertical plane. Therefore, an apparatus with the special frame which allows the horizontal position of the total station while performing the measurements was created at Korea Research Institute of Standards and Science.

II. Vertical angle calibration methods

There are only a few comparators designed for vertical circle calibration. Such vertical circle comparator (VCC) was created as the standard in order to perform precise calibration of vertical angle measuring system of robotic total stations and laser trackers in ESRF, France. This comparator is designed to measure vertical angles in the range of $90^{\circ} \pm 45^{\circ}$ and $270^{\circ} \pm 45^{\circ}$ because this is the range mostly used while performing calibration of vertical angle measurements. An instrument to be calibrated is placed against the vertical circle comparator and the reflector is mounted on the adjustable part of the comparator. During the calibration procedure vertical circle readings are compared with the vertical displacements of its spherically mounted retro-reflector which are measured by the interferometer. The horizontal distance between comparator and the total station is measured by using distance meter calibration bench. While changing the position of the reflector different vertical angles can be measured. The VCC calibration procedure compares the total station's vertical circle readings with the angles determined based on vertical displacements of its reflector and the calibrated distance between the VCC and the device to be calibrated. The uncertainty of vertical angle measuring system calibration was determined to be $\pm 1.4''$. However, the drawback of this method is that this comparator is designed to calibrate vertical angle measuring systems of the robotic total stations, therefore, minimal distance is 2.5 m which reduces the vertical angle calibration range to $\pm 23.75^{\circ}$. The expanded uncertainty of vertical angle measuring system calibration using this vertical circle comparator is $1.65''$ ($k=2$) [4,5,6].

Another method for vertical angle measurement system calibration developed by Leica, Switzerland is based on the mirror and autocollimator measurements. Practically, this principle was implemented by fixing a special mirror to the telescope of a total station which is mounted to special high precision theodolite testing machine on the top of the reference horizontal rotary encoder. This machine has two reference indexes (in horizontal and vertical planes) and a frame which enables autocollimator rotation around the total station to be calibrated in a vertical plane. TS's vertical encoder readings are compared to the reference vertical high precision indexing table readings. This method is implemented only by using special fully automatized Theodolite Testing Mashine (TPM) based on a principle theodolite in theodolite which fulfills the condition of orthogonality of the axes. The standard deviation of 0.058" for horzional angles and 0.091" is possible to achieve by this unique due to its structure and precision machine [2, 3].

At National Metrology Center in Singapore the vertical angle calibration method where indexing table and a collimator is used was developed. A special fixture is used to ease the alignment process and minimise effect from compound angle. The expanded uncertainty obtained by this method is 2.0" ($k=2$) and the vertical angle calibration range of $90\pm 30^\circ$ is possible to achieve [8].

III. Proposed setup for vertical angle calibration

The proposed angle measuring system is based on a well-known and reliable angle measuring technique described in standards, latest angle metrology related papers and official reports of famous metrology institutes. The main principle of angle calibration is comparison of reference angle and measured angle. The reference angle can be obtained by using various techniques and instrumentation. One of the main techniques used for horizontal angle measuring system calibration of total station is comparing measured angle with the reference angle created by the indexing table. After aligning and leveling all devices to be used in calibration, total station is fixed to the apparatus and attached to the indexing table. The system is set to its initial position and the telescope of the total station with the mounted mirror is pointed to the autocollimator. The indexing table is rotated by an eligible angle. Afterwards, the telescope of the total station is returned to its previous position and pointed to the same target. The main component of this angle measuring system is a special apparatus fixed on the top of Moore's 1440 Precision Index. This apparatus has a special weight balanced structure to fit the total station in a horizontal position. The special mount for fixing total station's tribrach is installed in this system as well as six adjustment screws, three on each side of the frame to support and level a total station. The main parts of this angle measuring system for the calibration of vertical angle measuring system of a total station are shown in Fig 1.

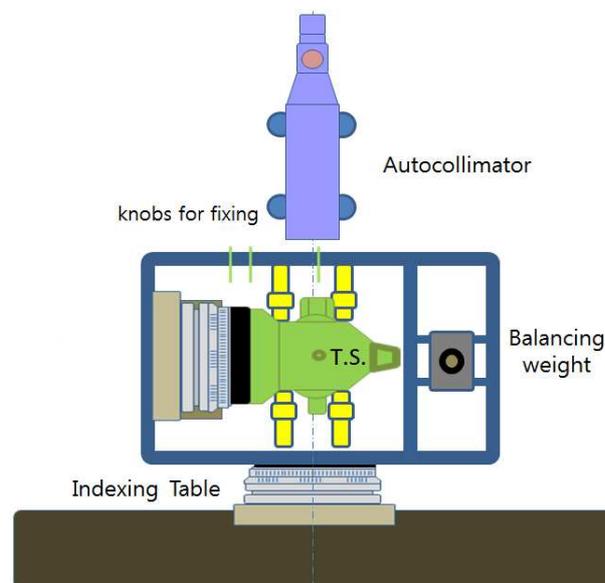


Fig.1. Components of the vertical angle measuring system.

This method was investigated by performing a practical approach which is discussed further in the paper.

A. The practical approach

Special granite surface plate stand was filled with the sand for stabilization in order to minimize vibrations which could affect measurement results. The leveled total station is mounted horizontally to the apparatus on the indexing table. The mirror and its mount is fixed to the telescope of the total station and the telescopes of both the total station and the autocollimator are aligned and coaxially pointed to each other as it is shown in **Fig.2**. After the alignment, the angle measuring system, total station and the electronic autocollimator are set to the initial position. The indexing table is rotated by a desired angle with the apparatus and fixed. Then the telescope of the total station is turned backwards by the same angle. Autocollimator readings show the angle of changed mirror position which means that there was a mismatch between the angles of the indexing table and the total station. The procedure is repeated 12 times (6 times clockwise and 6 times counter - clockwise) in the range of 40° to 140° and 220° to 320° and the readings of total station vertical angle as well as autocollimator are taken.



Fig.2. Electronic autocollimator pointed to the mirror fixed on the telescope of the total station

Fig.2. shows the setup of instrumentation for the vertical angle measurement system calibration with the mirror and the autocollimator. In this approach it is very important to fix the mirror on the telescope very precisely as well as align both devices to be on the same sight axis. If this condition is not fulfilled then measurement uncertainty will increase due to biaxial change of mirror position. After reducing vibration of granite plate stand, the effect was noticeable in stable readings of the electronic autocollimator. The measurement procedure was time saving because the telescope of the total station was turned to the initial position defined by the vertical angle reading displayed on the total station's display . However, time consuming alignment of the devices and difficulties of precisely mounting the mirror on the total station's telescope are the weaknesses of this approach.

IV. Experiment results

After performing the measurements primary results were obtained.

In this method the total station, indexing table and the autocollimator are three main error sources influencing the magnitude of the uncertainty. The combined uncertainty of the correction value (B) can be expressed as the sum of squares of the uncertainty due to the indexing table $u^2(\theta_{I.C})$, uncertainty due to the total station $u^2(\theta_{TS})$ and uncertainty due to the autocollimator $u^2(\theta_{AC})$ multiplied by their sensitivity coefficient squares (c_i):

$$u_c^2(B) = c_{I.C}^2 u^2(\theta_{I.C}) + c_{TS}^2 u^2(\theta_{TS}) + c_{AC}^2 u^2(\theta_{AC}) \quad (1)$$

Uncertainties due to the total station and the autocollimator have two more components each. Therefore, uncertainties due to resolution and repeatability of both instruments have to be included in whole uncertainty budget. Moreover, in this method a special attention should be paid to the uncertainty due to the telescope shift of the total station while is it used in horizontal position. In this setup the total station is used horizontally, however it was designed to measure in vertical position. In this position there could be a possible shift of the telescope and inner vertical angle measuring system components. Upon a query, manufacturer of the total station affirmed the presents of the special mechanisms embedded in the total station for compensation of such influence and the measurement errors due to position of the total station are negligible. Uncertainties due to the indexing table ($U(\theta_{I.Cal})$) and due to the autocollimator ($U(\theta_{ACcal})$) can be evaluated using type B uncertainty evaluation method .

The final equation for the combined uncertainty of the correction value describing uncertainty budget is:

$$U_c^2(B) = c_{I.C}^2 u^2(\theta_{I.Cal}) + c_{TS}^2 u^2(\theta_{TSres}) + c_{AC}^2 u^2(\theta_{ACcal}) + c_{AC}^2 u^2(\theta_{ACrep}) + c_{AC}^2 u^2(\theta_{ACres}) \quad (2)$$

The uncertainties of nominal angle and repeatability of the total station were eliminated because nominal angle was the same during the measurements and there was no uncertainty due to repeatability of TS due to pointing the telescope to exactly the same position defined by the vertical angle reading of the total station. The uncertainty due to alignment of the devices was considered negligible according to the autocollimator readings of both axes. In this case the uncertainty due to the shift of the TS telescope was neglected, however it might need further investigations proving the stability of inner components while changing the position of total station. The best way to evaluate the uncertainty when all individual data sets have their own uncertainties is to determine pooled standard uncertainty as shown in (3):

$$s_p = \sqrt{\frac{\sum_{i=1}^N s_i^2}{N}} \quad (3)$$

where: s_i – standard uncertainty of every data set,
 N – number of data sets, $N=11$.

The uncertainty due to repeatability of the autocollimator ($u(\theta_{ACrep})$) can be evaluated as a ratio of pooled uncertainty (s_p) and square root of the number of observations in a data set ($n=6$) using type A uncertainty evaluation method:

$$u = \frac{s_p}{\sqrt{n}} \quad (4)$$

Uncertainties due to the limited display resolution of the total station ($U(\theta_{TSres})$) and due to the limited display resolution of the autocollimator ($U(\theta_{ACres})$) have rectangular distributions and is expressed as follows:

$$u(\theta_{res}) = \frac{R}{2\sqrt{3}} \quad (5)$$

where: R- display resolution of the device. The display resolution of angle reading of total station $R_{TS}=0.1''$ and the display resolution of the autocollimator $R_{AC}=0.05''$.

The uncertainty budget influencing the measurement accuracy is shown in Table 1.

Table 1. Uncertainty budget.

Source of uncertainty	Standard uncertainty $u(x_i)$	Sensitivity coefficient c_i	Uncertainty contribution $u(x_i) \cdot c_i $	Probability distribution	Degrees of freedom ν	Effective degrees of freedom ν_{eff}
Uncertainty due to the Indexing table $u(\theta_{I.Cal})$	0.05"	1	0.05"	Normal	∞	
Uncertainty due to the limited display resolution of the total station $u(\theta_{TSres})$	0.029"	1	0.029"	Rectangular	∞	
Uncertainty due to autocollimator $u(\theta_{ACcal})$	0.2"	1	0.2"	Normal	∞	
Uncertainty due to repeatability of the autocollimator $u(\theta_{ACrep})$	0.049"	1	0.049"	t-(Student's)	5	
Uncertainty due to limited display resolution of the autocollimator $u(\theta_{ACres})$	0.014"	1	0.014"	Rectangular	∞	
Uncertainty of the correction value $U_c(B)$	0.262"			Normal		6

The expanded uncertainty of this setup is $U_{95\%}=0.52''$ ($k=2$).

As it is shown in Fig.3 there is a slight difference between standard deviation values of the measurements performed in face I and face II of the total station. The average standard deviation of face I is 0.22" while of face II is 0.33". Although there is a visual symmetry in the distribution of standard deviation values, the bigger error is noticeable in face II measurements. Such a difference can be a result caused by an influence of vibration or the slight tilt of the mirror mounted on the telescope of the total station. The possibility that this error of vertical angle measuring system of the total station can be caused due to the shift while the device was in a

horizontal position cannot be absolutely ignored, however it needs further investigations. Fig.3. also shows the range in which angle calibration of vertical angle measuring system of the total station can be done. Comparing to other previously analyzed vertical angle calibration methods, this enlarges the measurement range up to $90^\circ \pm 50^\circ$ and $270^\circ \pm 50^\circ$ and it is one of the main advantages of this setup.

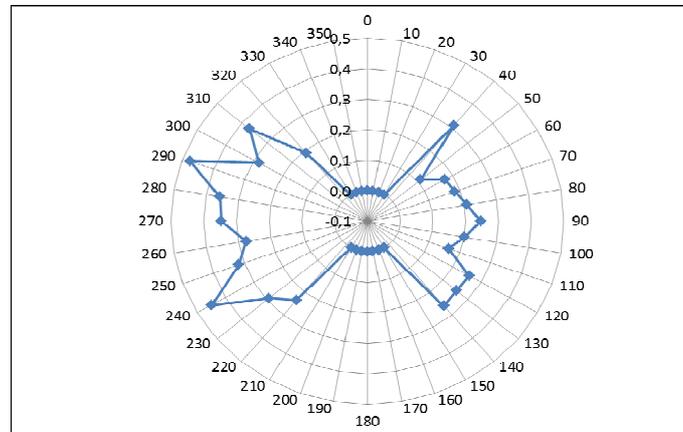


Fig.3. Standard deviation of the measurements at 10° pitch.

It is very important to perform further research in order to investigate the behavior and measurement accuracy of vertical angle measuring system while the total station is in horizontal position. This could be one of the main uncertainty sources as well as limited display resolution and the repeatability of the devices.

This setup is time saving and uncertainty reducing because readings are read directly from the electronic output of the devices. Although the vibration is reduced, the procedure of the mirror mounting on the telescope and alignment of the devices might be time consuming.

V. Conclusions

The new setup for vertical angle measuring system calibration along with the methodology is presented in the paper. The measurement error sources are analyzed as combined uncertainty components such as uncertainties due to indexing table and autocollimator, limited display resolution and repeatability of the devices. Expanded uncertainty of the setup $U=0.52''$ ($k=2$) was evaluated. The calibration range of vertical angle measuring systems was expanded up to $90^\circ \pm 50^\circ$ and $270^\circ \pm 50^\circ$ which is wider than in previously analyzed methods. Uncomplicated time saving measurement procedure makes this method user-friendly, however time consuming alignment and lack of possibility to cover whole calibration range of the vertical angle encoder of the total station needs further research.

References

- [1] Evaluation of measurement data – Guide to the expression of uncertainty in measurement. 2008. Joint Committee for Guides in Metrology. 134 p. JCGM 100:2008.
- [2] Lippuner, H.; Scherrer, R. Die neue Theodolit-Prüfmaschine TPM-2 von Leica Geosystems. Allgemeine Vermessungs-Nachrichten : AVN; Zeitschrift für alle Bereiche des Vermessungswesens Vol. 112, No. 5 (2005), p. 170-176, 2005.
- [3] Lippuner, H. Device for checking or calibrating the angle - dependent alignment of a high - precision test piece. US Patent No. US0236746 A1, Alexandria, Virginia, 2006.
- [4] Martin, D. 2010. Instrument calibration at the ESRF. In proceedings of XXIV FIG International Congress 2010, Sydney, Australia.
- [5] Martin, D.; Chetwynd, D., G. Angle calibration of robotic total stations and laser trackers. In Proceedings of the XIX IMEKO World Congress, p. 1893 – 1898. ISBN 978-963-88410-0-1, 2009.
- [6] Martin, D.; Gatta, G. Calibration of Total Stations Instruments at the ESRF. XXIII FIG Congress Proceedings, Munich, Germany, p. 1-14. ISBN 87-90907-52-3, 2006.
- [7] Rybokas, M; Šiaudinytė, L.; Giniotis, V. New approach to precision angle calibrations means and methods. In proceedings of Metrologia 2011, Natal, Brazil. Instituto Nacional de Metrologia, ISBN 9788586920080.
- [8] Tan, S. L.; Chao, Z.; Wang, S. The Industry and Us – NMC's Experience. APMP workshop "Collaboration and Support for Industry in Dimensional Metrology", Osaka, Japan, 2011.