# DETERMINATION OF VARIATION COMPONENTS FROM GEODETIC MICRONETWORK ADJUSTMENT

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**Abstract**
This paper deals with the design of a procedure to determine the accuracy of a total station. It is based on the surveying of a geodetic micronetwork and subsequent evaluation of the measured data using the created software tool. The calculation works on the principle of least squares adjustment with the application of the Förstner method of estimation of variation components. In addition, the calculation is enriched by the possibility of determining residual errors of the prism constants.

**Keywords**
Automatic targeting, Förstner method, least square adjustment, standard deviation, total station

# 1 INTRODUCTION

In connection with the continuous rapid development of technology and the increasing demands of users on the equipment used, manufacturers are constantly coming up with new product innovations. They bring a wide range of options and services that make the work easier and more precise. However, despite the technological developments which bring high precision instruments into the field of engineering surveying, it is still necessary to keep the realistic quality of the results in mind and not to consider the requirement of measurement accuracy as a foregone conclusion. Precise work and reliability of results are a priority in the industry.

Nowadays, the automatic targeting function of robotic total stations has become a standard feature. The automatic targeting function eliminates meter errors during manual targeting and helps to obtain more accurate results. However, no measurement is error-free, and therefore, when using this feature, it is important to remember that even automatic targeting may have its shortcomings and ultimate accuracy needs to be verified.

The accuracy of robotic total stations is usually specified according to the technical standard ISO 17123: Part 3 [1] and Part 4 [1]. At the same time, the accuracy defined in this way is verified in accredited calibration laboratories. However, the procedure for determining standard deviations of the measured quantities according to this standard consists in determining the accuracy of the individual measured quantities separately (horizontal directions, zenith angles, slope distances). The procedure does not cover the application and evaluation of automatic targeting. This situation necessitates a proposal for a novel approach to ascertain the precision of the automated targeting of total stations. The outcomes will encompass all the typical influences prevalent during the measurement procedure.

The proposed testing and evaluation method was developed in collaboration with Ing. H. Braunová who is dealing with this topic in her forthcoming PhD thesis. The whole procedure was tested on a Leica Nova TS60 total station.

For more detailed information on this topic, please refer to the thesis [3], on which this text is based.

# 2 METHODOLOGY

The concept of the proposed method consists in the measurement of a local spatial geodetic microgrid (a network of small dimensions with distances up to approximately 150 m) and its subsequent adjustment using the least squares method in the developed software. The calculation is being/has been performed iteratively by comparing the apriori and aposteriori unit's standard deviation. In each step of the iteration, standard deviations of the individual groups of measurements (horizontal directions, zenith angles and slope distances) are determined according to the Förstner method and then they are used as the input accuracy in the next step of the iteration. This fact brings the main advantage of the method described above, namely the elimination of the influence of the human factor on the adjustment results when choosing the apriori accuracy of the measured quantities at the beginning of the calculation. In addition, the calculation is enriched with the possibility of determining the magnitude of residual errors of the prism constants of the prisms located on the individual points of the network.

The testing of the proposed method is presented in the following sections.

## Apparatus and aids used

The accuracy of the automatic targeting was tested on a Leica Nova TS60 robotic total station. Its technical parameters are given in Tab. 1.

Tab. 1 Accuracy of the Leica Nova TS60 total station as per the manufacturer [4].

| **Leica Nova TS60** | |
|---|---|
| **Angle accuracy (standard deviation ISO 17123-3)** | *0.5 '' (0.15 mgon)* |
| **Distance accuracy, prism (standard deviation ISO 17123-4)** | *0.6 mm + 1 ppm* |

The Leica GMP101 mini prisms served as targets at every point of the micronetwork (Fig. 3). For Leica instruments, the prism constant is +17.5 mm [5].

## Scheme of the micronetwork

A geodetic micronetwork comprising four points with forced centering on concrete pillars and two points stabilised in a concrete block (also with forced centering), was chosen for the experiment. Stabilising the points prevented potential errors caused by soil movement or tripod twisting. The distances between the points in the network ranged from about 20 m to 120 m. The maximum elevation between the points was approximately 4 m. A scheme of the micronetwork is shown in Fig. 1, the real environment in Fig. 2.

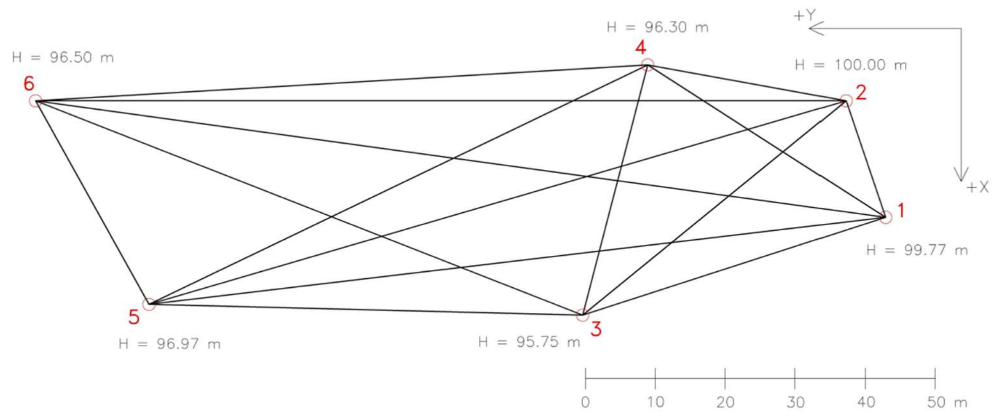


Fig. 1 Scheme of the micronetwork.


Fig. 2 Leica Nova TS60 at point 6.

Fig. 3 Leica mini prism at point 3.

## Geodetic micronetwork surveying procedure

Prior to commencing measurements, the utilized instruments and tools were acclimatized to the ambient air temperature for an hour. In addition, the total station was brought to the operating temperature by taking about 30 series of measurements to 2 points in the network, during which the readings stabilized. Next, a tribrach was attached to each pillar and leveled precisely. Then, a total station or a carrier with a prism was inserted. It is recommended to have this set of carriers with a prism on each point of the network to prevent any confusion of the prisms between pillars; therefore, six tribrachs, carriers, and prisms were necessary. When inserting a carrier and a prism into the tribrach, care was taken to ensure that the carrier was oriented in the same way each time to prevent errors resulting from tool eccentricity. Its effects on the measurements were discussed by the author of this thesis [6]. It is advisable to select six prisms of identical type to ensure that varying sizes or types do not impact the homogeneity of the network. This guarantees statistical accuracy of measurements across all variables.

Measurements were then taken at each survey station, targeting all visible points. At each pillar, the warp of horizontal directions, zenith angles and slope distances to other network points were measured in 5 groups (method: observation method in rows and groups). Throughout the measurements, the targets were carefully routed to the total station.

During the measurement process, the ambient temperature and air pressure were observed: the measured values were regularly entered into the total station to introduce the correct physical corrections. The atmospheric conditions were suitable during the measurements: cloudy, temperature 4–7 °C.

Since it is known that inaccuracies in the adjustment results are also caused by the differing construction heights of the instrument and the target prism with the carrier, it was proposed to consider all survey stations as free stations in the calculation. This solves the discrepancies between the construction heights of the instrument and the prism assemblies used. Formally, there were 12 points in the network consisting of 6 survey stations and 6 targets. Though they were nearly identical in physical appearance, they were adjusted separately in practice (since the essence of the experiment was to determine the accuracy of the measured quantities and not to determine the coordinates of the points, we did not have to worry about doubling the number of points in the network). The measurement procedure with this modification has been retained. Throughout the measurement, the heights of both the instrument and all targets were inputted as zero values into the total station.

The last recommended (yet not necessary) step in the proposed measurement procedure is to determine the distance which gives the network a dimension between 2 (or more) points. An ideal instrument for this task may be a high precision laser tracker, such as the Leica AT500. As such an instrument is not easy to obtain, a method has been devised for our purposes of determining this distance by measuring horizontal directions, zenith angles and slope distances from at least 3 suitably selected free stations to 2 points in micronetwork. The distance between the selected points can be calculated from the measured values and the height between the two points. This distance is more accurate than the lengths measured by the total station when surveying the micronetwork [7]. In addition, a total station with the best distance accuracy on the Czech market was used to test the proposed method. The distance defining the micronetwork dimension was determined between points 2 and 6.

## Data processing and evaluation

The process of evaluating the measured data and determining the resulting estimates of standard deviations for the measured slope distances, horizontal directions, and zenith angles of total stations, by utilizing automatic targeting, is based on the PES1234 application (Instrument Evaluation System 1234, by Hana Váchová) [3].

The application has been developed in the MATLAB R2022a programming environment. After starting the application, it is necessary to load the measurement notebook in the MAPA2 format or in a predefined text file, see the application manual [3]. The application then calculates the approximate coordinates of the network points in the local coordinate system from the measured values (or they can be uploaded directly to the application in a predefined text file). Finally, it is necessary to select the apriori accuracy of the measured quantities to define the position of the network in space and, if necessary, to specify the distance defining the dimension of the network. The resulting values are then saved in a text file in the selected folder on the computer. Detailed instructions for installing and operating the application are attached to the thesis [3] (Annex 5) which this text is based on.

The basic principle of data processing is the iterative least squares adjustment. The math model uses three kinds of observation equations. Equations for horizontal directions and zenith angles are in the standard form. The equations for slope distances are modified to allow for compensation of residual errors in the sum constant of the prism. This means that the residual errors in the sum constants are treated as unknown in the equalization. More details can be seen in [3], [7]. I mention the principle of the Förstner method used to estimate the variational component in more detail [8].

In the Förstner method, the apriori standard deviations of the measured variables are changed at each step of the iteration and used in the calculation of the weight matrix. Iteration is performed until the magnitude of the aposteriori unit standard deviation $s_0$ is sufficiently close to the magnitude of the apriori unit standard deviation $\sigma_0$. This condition Eq. (1) has been used in the present software:

$$|\sigma_0 - s_0| < 0.0001. \tag{1}$$

The basic idea of the Förstner estimator is to determine the number of redundant measurements for each group of measured variables separately. In contrast to the classical least squares adjustment where all effects are mixed and thus only the aposteriori accuracy estimate characterising the network as a whole is calculated, in the case of the Förstner method the aposteriori standard deviation for the measured slope distances $s_0^{sd}$, for the horizontal directions $s_0^{\varphi}$ and for the zenith angles $s_0^{\zeta}$ can be determined separately.

The first step after the actual adjustment of the spatial network is the calculation of the so-called redundant matrix $\boldsymbol{R}$, Eq. (2):

$$\boldsymbol{R} = \boldsymbol{I} - \boldsymbol{A}\,\overline{\boldsymbol{Q}}_{xx}\,\boldsymbol{A}^{T}\boldsymbol{P} \tag{2}$$

where $\boldsymbol{I}$ is a unit matrix with dimensions $n$ x $n$, and $n$ is the number of measurements. $\boldsymbol{A}$ is a matrix of partial derivatives of each observation equation by each unknown, $\boldsymbol{P}$ is a diagonal weight matrix expressing the precision of each measurement, and $\overline{\boldsymbol{Q}}_{xx}$ is the part of the matrix expressed as Eq. (3):

$$\boldsymbol{N}^{-1} = \begin{bmatrix} \boldsymbol{A}^{T}\boldsymbol{P}\boldsymbol{A} & \boldsymbol{B}^{T} \\ \boldsymbol{B} & \boldsymbol{0} \end{bmatrix}^{-1} = \begin{bmatrix} \overline{\boldsymbol{Q}}_{xx} & \overline{\boldsymbol{Q}}_{kx}^{T} \\ \overline{\boldsymbol{Q}}_{kx} & \overline{\boldsymbol{Q}}_{kk} \end{bmatrix} \tag{3}$$

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Each element on the diagonal of the redundancy matrix represents the contribution of a particular measurement to the total number of redundant measurements in the network. Based on this fact, it is possible to quantify the contribution of each group of measurements to the number of redundant measurements, and thus to determine the contribution of the measured slope distances $r_{sd}$, horizontal directions $r_{\varphi}$, and zenith angles $r_{\zeta}$.

It is then possible to calculate an aposteriori estimate of the accuracy of the measured slope distances $s_0^{sd}$ [m], horizontal directions $s_0^{\varphi}$ [gon] and zenith angles $s_0^{\zeta}$ [gon] using the contributions thus determined, Eq. (4):

$$s_0^{sd} = \sqrt{\frac{\sum(vv)_{sd}}{r_{sd}}}, \qquad s_0^{\varphi} = \sqrt{\frac{\sum(vv)_{\varphi}}{r_{\varphi}}}, \qquad s_0^{\zeta} = \sqrt{\frac{\sum(vv)_{\zeta}}{r_{\zeta}}} \tag{4}$$

The calculated estimates of the standard deviations according to Eq. (4) are further used as the apriori precision going into the adjustment, and the whole calculation is repeated. The mathematical formulae in this section are taken from [9], [10]. For a more detailed understanding of all relations, refer to [3].

The apriori standard deviations of the measured values were set according to the estimates declared by the manufacturer of the instrument used. The angular standard deviation for the Leica Nova TS60 total station is given by the manufacturer as 0.15 mgon [4]. The accuracy of the measured lengths per prism is given as 0,6 mm + 1 ppm [4]. Based on the magnitudes of the distances in the targeted micronetwork (approx. 20 m to 120 m), the apriori accuracy of the measured slope distances was given as 0,7 mm.

All measured data were adjusted in the developed application according to the proposed calculation procedure. The adjustment of the measured data was performed in two modes. In the first mode, the calculation was performed without using the distance defining the network dimension (DDND). In this case, only the standard deviations of the measured variables are the result of the adjustment. In the second mode, the DDND was used in the adjustment calculation. In this case, in addition to the standard deviations of the measured quantities, the residual errors of the prism constants are also the output of the adjustment.

One of the aspects studied was the number of points necessary and their configuration in the geodetic micronetwork to obtain reliable estimates of the accuracy of the measured quantities. Therefore, the experiment proposed to evaluate the measured data using 4–6 points in the network in different configurations.

# 3 RESULTS

Tab. 2 shows the adjusted standard deviations of the Leica Nova TS60 total station measurements. These values were obtained from an adjustment calculation in which the DDND dimension was not defined. Tab. 3 shows the contribution of each group of measurements to the redundant number of measurements in the network. Both tables show the equalised values when 6, 5 or 4 network points are used in the calculation.

Tab. 2 Resulting values without using the DDND, Leica Nova TS60.

| | **6 points** | **5 points – without point:** | | | | **4 points – without points:** | | |
|---|---|---|---|---|---|---|---|---|
| | | **1** | **3** | **4** | **5** | **3, 4** | **1, 5** | **4, 5** |
| $s_0^{sd}$ **[mm]** | *0.16* | *0.15* | *0.13* | *0.15* | *0.13* | *0.12* | *0.11* | *0.10* |
| $s_0^{\varphi}$ **[mgon]** | *0.11* | *0.11* | *0.11* | *0.10* | *0.10* | *0.09* | *0,10* | *0.10* |
| $s_0^{\zeta}$ **[mgon]** | *0.15* | *0.16* | *0.14* | *0.15* | *0.15* | *0.12* | *0.15* | *0.13* |

Tab. 3 Contributions of measurement groups to the redundant number of measurements without using the DDND.

| **measured groups** | **6 points** | **5 points – without point:** | | | | **4 points – without points:** | | |
|---|---|---|---|---|---|---|---|---|
| | | **1** | **3** | **4** | **5** | **3, 4** | **1, 5** | **4, 5** |
| $r_{sd}$ | *140.8* | *91.4* | *90.9* | *91.4* | *91.9* | *52.6* | *52.2* | *52.2* |
| $r_{\varphi}$ | *132.2* | *86.6* | *87.1* | *86.6* | *86.1* | *50.4* | *50.8* | *50.8* |
| $r_{\zeta}$ | *139.0* | *91.0* | *91.0* | *91.0* | *91.0* | *53.0* | *53.0* | *53.0* |
| **total** | *412.0* | *269.0* | *269.0* | *269.0* | *269.0* | *156.0* | *156.0* | *156.0* |

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Tab. 4 shows the resulting adjusted values (standard deviations of the measured quantities and residual errors of the prism constants) obtained from a calculation in which the DDND was applied between points 2 and 6.

Tab. 4 Resulting values using the DDND, Leica Nova TS60.

| | 6 points | 5 points – without point: | | | | 4 points – without points: | | |
|---|---|---|---|---|---|---|---|---|
| | | 1 | 3 | 4 | 5 | 3, 4 | 1, 5 | 4, 5 |
| $s_0^{sd}$ [mm] | *0.14* | *0.08* | *0.14* | *0.14* | *0.08* | *0.09* | *0.06* | *0.06* |
| $s_0^{\varphi}$ [mgon] | *0.11* | *0.12* | *0.11* | *0.11* | *0.11* | *0.09* | *0.10* | *0.09* |
| $s_0^{\zeta}$ [mgon] | *0.15* | *0.16* | *0.14* | *0.15* | *0.15* | *0.12* | *0.15* | *0.13* |
| $c_1$ [mm] | *0.02* | - | *-0.08* | *0.14* | *0.22* | *-0.74* | - | *0.47* |
| $c_2$ [mm] | *0.02* | *-0.78* | *0.00* | *0.04* | *0.24* | *-0.27* | *-0.21* | *0.33* |
| $c_3$ [mm] | *0.08* | *0.08* | - | *0.11* | *0.24* | - | *0.12* | *0.29* |
| $c_4$ [mm] | *0.15* | *0.19* | *0.05* | - | *0.31* | - | *0.24* | - |
| $c_5$ [mm] | *0.23* | *0.31* | *0.10* | *0.29* | - | *-0.14* | - | - |
| $c_6$ [mm] | *-0.11* | *0.76* | *-0.19* | *-0.19* | *-0.15* | *-0.27* | *0.22* | *-0.17* |

Tab. 5 shows the resulting standard deviations of the residual errors of the prism constants in the different configurations.

Tab. 5 Resulting standard deviations of residual errors of prism constants using DDND, Leica Nova TS60.

| | 6 points | 5 points – without point: | | | | 4 points – without points: | | |
|---|---|---|---|---|---|---|---|---|
| | | 1 | 3 | 4 | 5 | 3, 4 | 1, 5 | 4, 5 |
| $s_{c_1}$ [mm] | *0.06* | - | *0.08* | *0.08* | *0.05* | *0.09* | | *0.05* |
| $s_{c_2}$ [mm] | *0.04* | *0.07* | *0.05* | *0.05* | *0.04* | *0.04* | *0.12* | *0.04* |
| $s_{c_3}$ [mm] | *0.04* | *0.03* | - | *0.04* | *0.04* | - | *0.06* | *0.04* |
| $s_{c_4}$ [mm] | *0.04* | *0.03* | *0.04* | - | *0.03* | - | *0.03* | - |
| $s_{c_5}$ [mm] | *0.05* | *0.04* | *0.06* | *0.05* | *0.03* | *0.05* | - | - |
| $s_{c_6}$ [mm] | *0.04* | *0.08* | *0.05* | *0.05* | - | *0.04* | *0.12* | *0.03* |

Tab. 6 records the contributions of each measurement group to the redundant number of measurements in the network in different configurations.

Tab. 6 Contributions of measurement groups to the redundant number of measurements using the DDND.

| measured groups | 6 points | 5 points – without point: | | | | 4 points – without points: | | |
|---|---|---|---|---|---|---|---|---|
| | | 1 | 3 | 4 | 5 | 3, 4 | 1, 5 | 4, 5 |
| $r_{sd}$ | *136.4* | *86.5* | *87.9* | *87.8* | *87.4* | *49.9* | *49.7* | *49.9* |
| $r_{\varphi}$ | *131.6* | *87.5* | *86.1* | *86.2* | *86.6* | *50.1* | *50.3* | *50.1* |
| $r_{\zeta}$ | *139.0* | *91.0* | *91.0* | *91.0* | *91.0* | *53.0* | *53.0* | *53.0* |
| **total** | *407.0* | *265.0* | *265.0* | *265.0* | *265.0* | *153.0* | *153.0* | *153.0* |

Tab. 7 compares the accuracy of the Leica Nova TS60 total station obtained from the proposed experiment with the accuracy specified by the manufacturer. The resulting accuracies of the measured quantities are given as the average standard deviations of the horizontal direction, zenith angle and slope distance from the adjustment standard deviations characterising the accuracy of the network surveying with 5 and 6 points using the DDND (see Tab. 4).

Tab. 7 Comparison of the calculated accuracy of the measured quantities with the value given by the manufacturer.

| | slope distance [mm] | horizontal direction [mgon] | zenith angle [mgon] |
|---|---|---|---|
| **declared accuracy [4]** | *0.70* | *0.15* | *0.15* |
| **accuracy from adjustment** | *0.12* | *0.11* | *0.15* |
| **the difference** | *-0.58* | *-0.04* | *±0.00* |

# 4 DISCUSSION

Comparing the resulting values between the configurations in Tab. 2, excluding any point (or even multiple points) has almost no effect on the resulting standard deviations. The differences between the standard deviations for all configurations are minimal (the maximum variance is 6 hundredths of a mm for the slope distance).

This is similar to the resulting accuracies in Tab. 4: the standard deviation values are stable across all configurations. Comparing the magnitudes of the adjusted residual errors of the prism constants in this table, the differences between the resulting values from the different configurations are already more apparent. At first glance, it is clear that the largest discrepancies reach the values determined by the adjustment of the measurements between the 4 network points. This may be due to the lower number of redundant measurements. It is also evident that when point 1 is not used in the adjustment, the residual error results of the prism constants at points 2 and 6 show outliers compared to the other situations. This is probably due to an inappropriate configuration where changing the distance by the prism constant moves the point practically in one direction. Moreover, in such a situation, important angles that ensure the stability of the network are missing in the adjustment calculation. A partial indicator of the accuracy of the residual errors of the summation constants can be their standard deviations, see Tab. 5. When point 1 is excluded from the calculation (values in column 3 of the table), the standard deviations of points 2 and 6 are twice as large as those of the other points. However, further investigation is needed to draw further conclusions.

If we compare the resulting values between Tab. 2 and Tab. 4, we find a difference only in the values of the standard deviations of the slope distances. When the network dimension is defined and the residual errors of the prism constants adjusted, the value of the resulting accuracy of the measured slope distance slightly improves. This modification has no effect on the angular accuracy for a given configuration and instrument.

Several conclusions can be drawn from the results obtained. If the user defines the size of the network by a DDND and therefore needs to determine the accuracy of the measured quantities and the residual errors of the prism constants by adjustment, it is necessary to aim and adjust a network containing at least 5 points (or rather 6 points). A suitable configuration of the points is also essential. If the user only needs to determine the standard deviations of the measured quantities by adjustment, 4 points in the network are sufficient. However, in such a situation, the resulting accuracy may be affected by the error introduced by the prism constants.

However, it is important to note that determining the distance that defines the network dimension using the proposed method is not ideal (the distance provides less accuracy than we need). A better solution would be to use the high precision laser tracker mentioned previously.

A comparison of the resulting standard deviation values with the accuracy stated by the manufacturer of the tested instruments in Tab. 7 shows that the precision of the slope distance determined by the experimental procedure is significantly higher than the accuracy stated by the manufacturer. The reason for this may be that systematic errors in the measured distance did not manifest themselves when the network was surveying since it is the same for all distances. At the same time, I believe, instrument manufacturers report lower accuracies for slope distance measurements than what total station's distance meters achieve (thus avoiding inaccuracies that can arise, for example, from a large residual error in the prism constant of the prism used). At short distances (approx. up to 50 m) the Leica distance meters show a real systematic error in tenths of a millimetre [11]. The standard deviation of the measured horizontal direction also shows a better accuracy than that given by the manufacturer. In the case of the measured zenith angle, the calculated accuracy is the same as the one given by the manufacturer.

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# 5 CONCLUSION

This paper presents an experimental method of determining estimates of standard deviations of total station measurements using automatic targeting. The essence of the procedure is the use of the Förstner method for estimating variation components.

The proposed method consists of a detailed procedure for surveying a geodetic micronetwork and includes instructions for evaluating the measured data. The evaluation procedure consists in using the developed software tool PES1234 (by Hana Váchová) [3]. The application works on the principle of iterative least squares adjustment of measurements obtained by terrestrial surveying of the local geodetic network. Using the Förstner method, new estimates of the standard deviations are calculated at each iteration step for a group of measured horizontal directions, zenith angles and slope distances.

The proposed procedure was used to test the data measured by the Leica Nova TS60 total station. The results showed that the accuracy of the total station achieved by the experimental procedure was comparable or better than the accuracy declared by the manufacturer of the instrument. As part of the tests, residual errors of the prism constants of the prisms used were also determined. Their values can play a significant role in more precise surveying operations and should be considered when analysing the accuracy of a total station.

The experiment demonstrates that the Förstner method of estimating variation components allows a clear and unambiguous determination of the precision for any group of measurements. In conclusion, the idea that the chosen solution procedure provides the possibility of determining the standard deviations of all measured variables at once by a single measurement test can be confirmed.

The proposed method can be used by end users when they need to test a total station themselves (i.e. when they need to determine the accuracy of the total station measurement and when they need to determine the magnitudes of the residual errors of the prism constants depending on the reflecting prisms used) in a different way from what is done during regular checks in calibration laboratories. The results can be expected to depend on the conditions of the experiment and should therefore be carried out under conditions as close to the expected use of the instrument as possible.

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