Scale Determination of Digital Levelling Systems using a Vertical Comparator

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Summary
A procedure known as ›system calibration‹ can be used to check the behaviour of digital levelling systems. We designed an experiment to show that in addition system calibration is capable to determine the scale of the levelling system. The experiment consisted of a staff calibration at Bundeswehr University Munich and a system calibration at Graz University of Technology, using the same 3 m invar staff and a brand-new Trimble DiNi12. The scale value was found to be 15.5 ± 0.3 ppm determined by staff calibration, and 15.0 ± 0.3 ppm determined by system calibration. Thus we were able to experimentally prove that system calibration using short sighting distances yields the composite scale value of the whole levelling system (staff and level) with a standard uncertainty of about 1 ppm.

Zusammenfassung
Die Systemkalibrierung wurde bisher nur zur Bestimmung der Eigenschaften von Digitalnivellier-Systemen eingesetzt. In dieser Arbeit stellen wir die Resultate einer Vergleichsmessung vor, mit der wir zeigen konnten, dass die Systemkalibrierung auch den Maßstab des gesamten Systems liefern kann. Das Experiment bestand aus einer Lattenkalibrierung an der Universität der Bundeswehr München und einer Systemkalibrierung an der Technischen Universität Graz. Dabei wurde dieselbe 3 m Invarlatte und ein brandneues DiNi12 verwendet. Der Maßstab der Latte ergab sich aus der Lattenkalibrierung mit 15.5 ± 0.3 ppm, der Maßstab des Systems aus der Systemkalibrierung mit 15.0 ± 0.3 ppm. Damit konnte gezeigt werden, dass der Maßstab des Systems (Nivellier und Latte) mit der Systemkalibrierung bei kurzen Zielweiten mit einer Standardunsicherheit von etwa 1 ppm bestimmt werden kann.

1 Introduction

During the last two decades geodetic instruments became fully electronic and as a consequence smaller, lighter, more automatic and more efficient. This development pushed back the precision mechanics content, and in turn the manufacturing process was changed. Now, the manufacturer calibrates the equipment and stores specific parameters in the instrument to appropriately correct the measured quantities. In general, the user does not know anything about the tolerated imperfections of the mechanics and the associated internal corrections. In most cases he does not even want to know about them. As a consequence of this development the importance of the proper calibration of geodetic equipment is experiencing a necessary revival (Heister and Staiger 2001).

1.1 Digital Levels

Automation took also place in the field of levelling. Currently, there are four different types of digital levels on the market (Leica, Sokkia, Topcon and Trimble [former Zeiss]). The coded staff and the level form the levelling system. The main components of a digital level are the optical telescope, the compensator, the CCD array, the micro controller and, of course, the software running on it (see fig. 1).

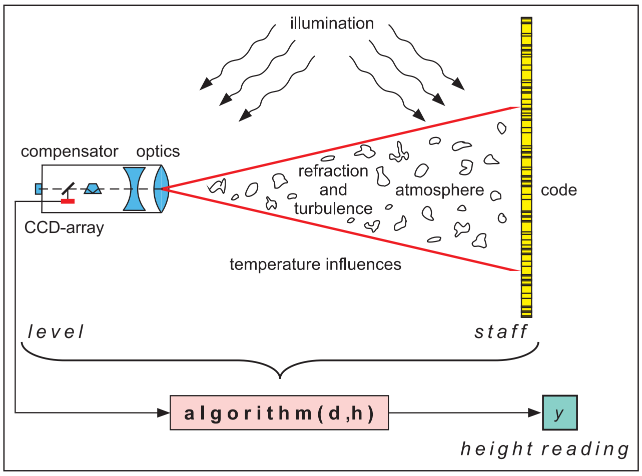

Fig. 1: The digital level as a measuring system

The staff reading is calculated by evaluating the image of the coded staff, which was projected onto the CCD. Different measurement techniques have been developed with related codes. Algorithms used for the calculation of the staff reading are correlation, geometric averaging and Fourier analysis. An overview of the different measurement techniques is given by Ingensand (1999).

Today, instruments of three manufacturers are used in high precision levelling. Commonly, 3 m long staffs are used whereby the code is etched on an invar band. For a comprehensive correction of the height readings the individual scale value of the staff, the actual temperature of the invar band, and its coefficient of thermal expansion must be known.

1.2 Staff Calibration

The calibration of levelling staffs has a long tradition. First, etalons and optical methods were used, then interferometers became the standard for length measurements and the automation of the calibration process took place. It was based on the idea to measure the position of the graduation lines on the staff with an opto-electronic microscope under the control of the interferometer (Schlemmer 1975). The result of the calibration was the scale value of the staff and the individual correction for each graduation line. Subsequently, the readings were corrected using these values. A review of staff calibration is given by Rüeger and Brunner (2000).

1.3 System Calibration

In the measurement process using a digital level the whole system (see fig. 1) is involved. The scale value of the system is also influenced by the scale value of the level (e.g. aging effects of the CCD) and the behaviour of the system, which may change, if the staff face is damaged (e.g. scratched code elements). Therefore ›system calibration‹ has been considered the proper technique to calibrate the level and the staffs together (Heister 1994). The basic idea is to make a height reading with the digital level, then move the staff by a known amount followed by another height reading and so on. Comparing the heights determined by the level to the true values of the motions, information about the behaviour of the levelling system can be derived (Brunner and Woschitz 2001). Obviously this requires an adequate ›machine‹ which performs the movements and provides the true displacement values.

1.4 Outline

Critics have expressed their doubts about the usefulness of system calibration and insist on the separate staff calibration. We considered it sufficient to concentrate on the determination of the scale value of one staff (Zeiss) only, for proving the capability of system calibration. For this purpose first a staff calibration was carried out using one of the most accurate facilities, which is operated at the Bundeswehr University Munich (UniBwM). Subsequently, a system calibration was carried out at the Graz University of Technology (TUG) using a Trimble DiNi12. The two calibration facilities are described in section 2. A description of the test procedure and the results are the main part of section 3. An analysis of the independently derived results is presented in section 4.

2 Description of Calibration Facilities

2.1 Horizontal Comparator for Staff Scale Determination

The horizontal comparator for staff scale determination is situated in the Geodetic Laboratory at UniBwM. The temperature (~ 22 °C) and humidity (~ 45 %) of the laboratory are controlled with an uncertainty of 0.2 °C and 5 %, respectively, within a span of 2–3 hours. The ›heart‹ of the laboratory is the 30 m long comparator bench with two movable carriages which are controlled by the laser interferometer HP5507B. The staff is mounted on the two carriages (see fig. 2) and supported in the ›best points‹ (see positions p1 and p2 in fig. 6b), which results in a minimum change of length of the invar band. To adjust the staff with respect to the laser beam of the interferometer, a triangulation sensor is used. At one side of the bench an electro-optical microscope (Zeiss MPV Compact) is mounted (see fig. 3). The mounted staff moves beneath the microscope, which measures the edges of all code elements. The accuracy of automatic edge detection is $0.7\,\mu m + L * 0.4\,\mu m$, with L being the position on the staff in meters. Details about the construction and the achievable accuracy are discussed by Heister (1988).

Fig. 2: The horizontal comparator for staff calibration at UniBwM

Fig. 3: Electro-optical micro-scope for edge detection

2.2 Vertical Comparator for System Calibration

Within the last decade, the Geodetic Metrology Laboratory (GML) was established at the Graz University of Technology. The laboratory is climatically controlled with a temperature of 22.0 °C ± 0.5 °C and a humidity of 50 % ± 10 %. One of the calibration facilities in the GML is its vertical comparator.

The basic concept of a vertical comparator is to mount the levelling staff in the position of use, i. e. vertically. To be able to calibrate 3 m long invar staffs, it was necessary to extend the laboratory using two shafts. Now, there is enough space for the 6.5 m high frame and the carriage attached to it. The carriage with the mounted staff is moved under control of a laser interferometer (HP10889B). Abbe's comparator principle was strictly adhered to as shown in fig. 4. The level can be positioned on a 30 m long concrete bench. So, the sighting distances can be chosen from 1.5 m to 30 m. In the GML the staff illumination is achieved by special light bulbs which radiate light covering the range of the spectral response of all four types of digital levels.

Further details about this vertical comparator are described by Brunner and Woschitz (2001). A schematic overview is shown in fig. 4, and impressions of the facility are given in fig. 5. We have assessed the precision of this vertical comparator to be ± 4 µm.

3 Test Procedure and Results

In this section we describe the use of the two different comparators for the determination of the scale value of the staff and of the levelling system. For the main investigation reported in this paper, we used a Trimble DiNi12 digital level and only one staff with Zeiss code.

3.1 Staff Calibration

A calibration procedure (using the horizontal comparator described in section 2.1) of the levelling staff consists of two separate runs. In every run the edges of all code elements (265) of the staff are detected, beginning at the staffs base plate and proceeding to its upper end. Between the first and second run, the staff is demounted and mounted again.

The measurements of each run are reduced to the reference temperature (20 °C), assuming a standard thermal expansion coefficient of the invar band of + 0.75 ppm/°C (Maurer and Schnädelbach 1995). Then the scale value of the staff is determined from a linear regression model applied to the observations y_i in eq. (1):

$$y_i + e_i = \alpha + \beta \cdot x_i \qquad (1)$$

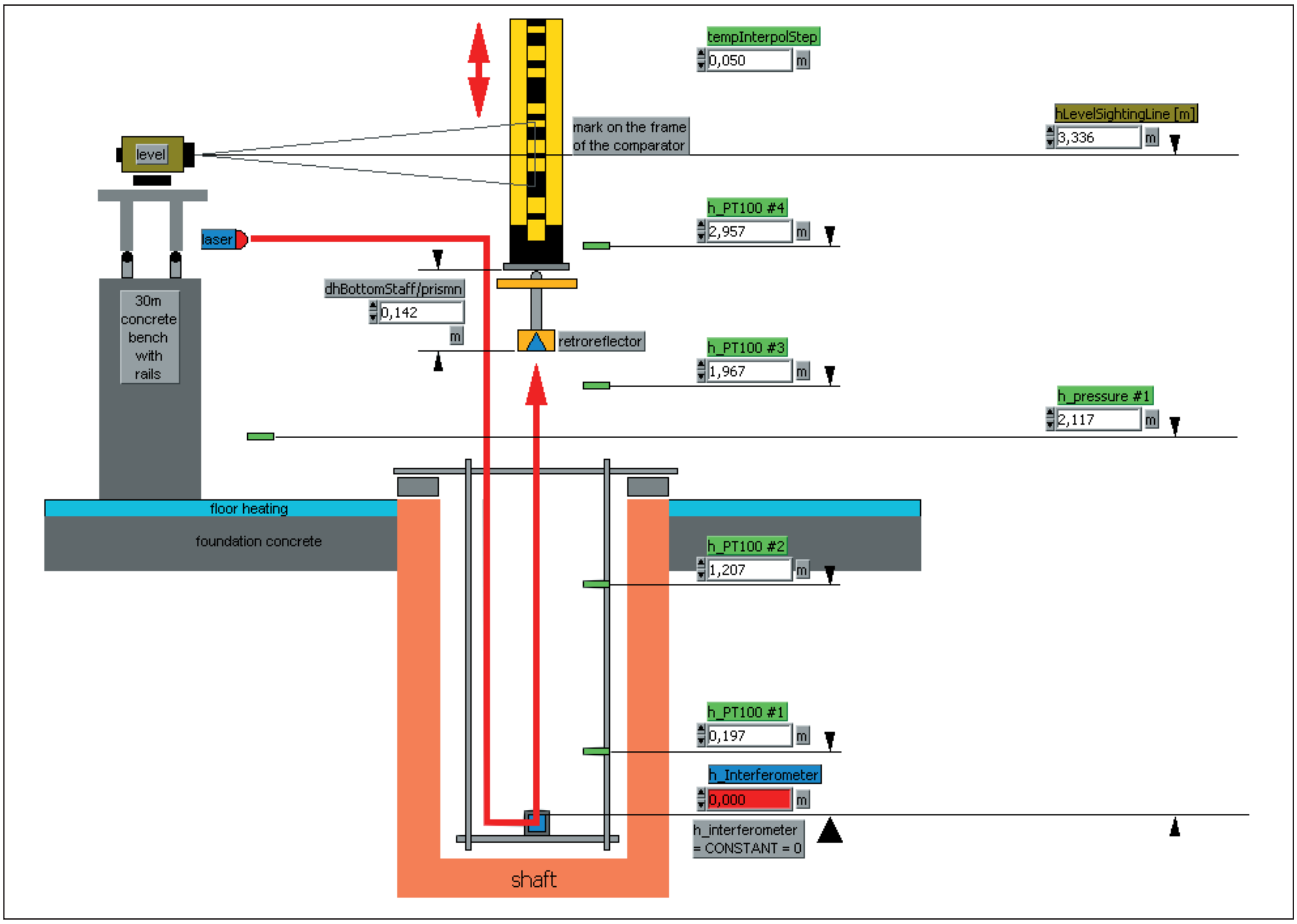

Fig. 4: Scheme of the vertical comparator at the GML-TUG

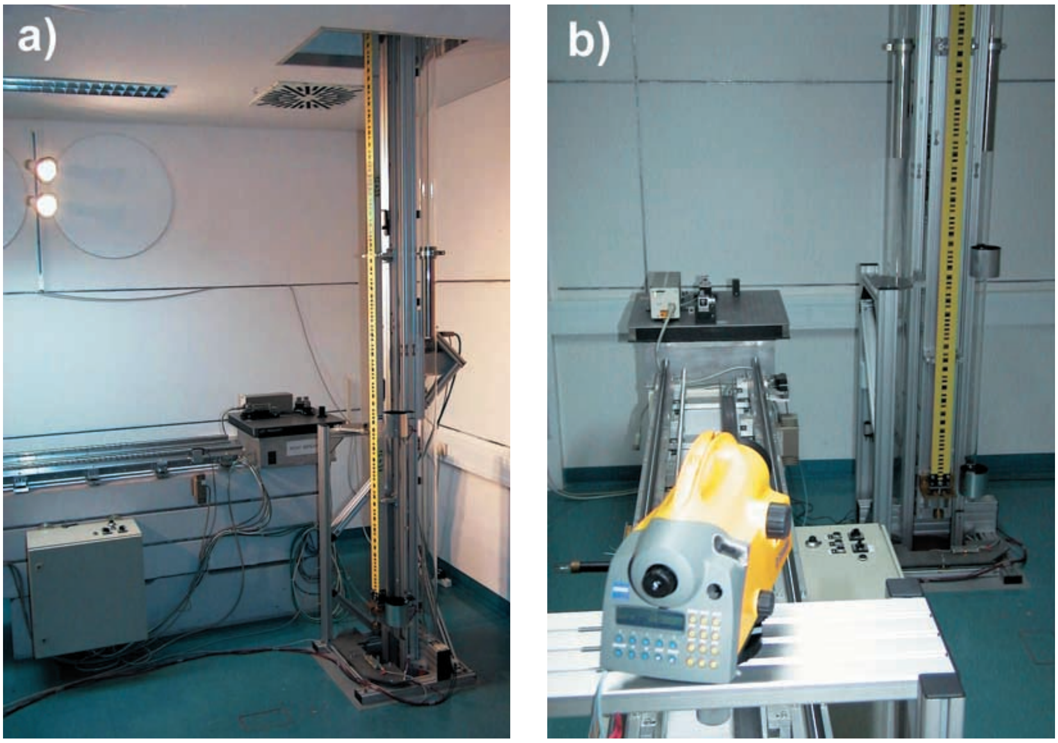

Fig. 5: The vertical comparator (a) with staff illumination and (b) as seen from the level's position

for all measurements $i=1,2,\ldots,n$. The parameters defining the linear regression are the intercept α and the slope β, which is actually the scale value to be estimated. The mid positions of every pair of edges of the known code are introduced as the true values x_i into the model. The differences between these known values and the interferometer values are the observations y_i. The noise of the measuring process is modelled by e_i. The unknown regression coefficients are computed using the least squares method. Tab. 1 shows the results of the staff calibration of the coded Zeiss staff (S.No. 15439).

measurement run	#1	#2
scale value [ppm]	15.2	15.9
σ_{scale} [ppm]	0.3	0.3
σ_y [µm]	3	3

Table 1: Numerical results of staff calibration at UniBwM for a coded Zeiss staff (S.No. 15439)

The calculated scale value of the staff deviates by more than 15 ppm from 0. The reason for this difference is unknown. It can be assumed that this scale value does not result from the manufacturing process (Fischer and Fischer 1999), but is most likely the result of tough field use. Nevertheless every height measured with this staff is affected by these 15 ppm and thus the field data need to be corrected appropriately. The residuals $\tilde{e}_i$ of the first calibration run are shown in fig. 6a.

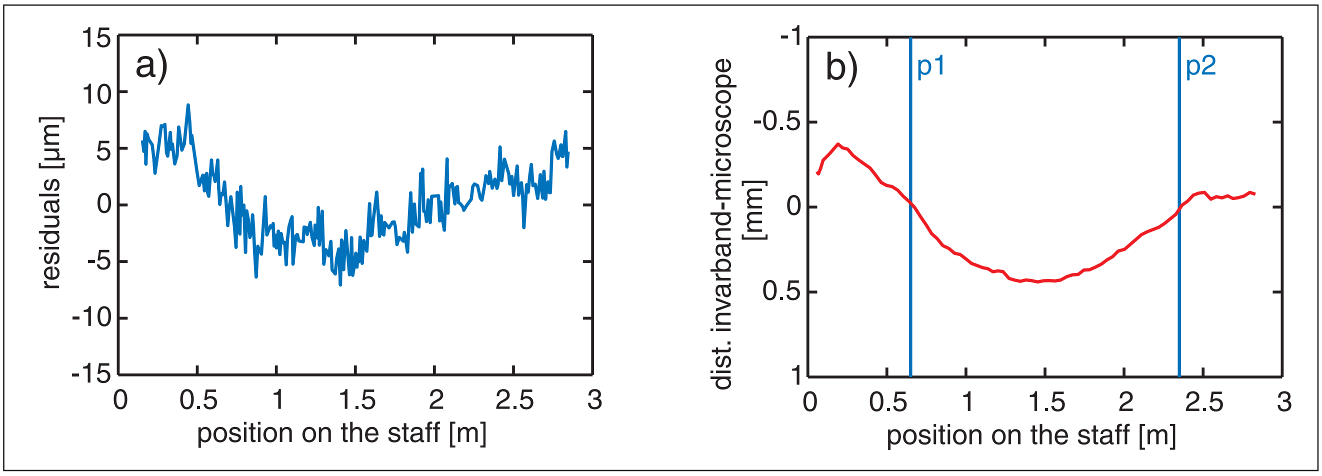

Fig. 6: First measurement run at UniBwM: (a) residuals of the positions of the code elements; (b) height position of the invar band

3.2 System Calibration

Following the calibration at UniBwM, the staff was transported to Graz for the system calibration. We wanted to avoid a possible superposition of the scale value of the level (e. g. aging effects of the CCD) with the scale value of the staff, and therefore we used a brand-new Trimble DiNi12 (S.No. 700376, SW-Ver. 3.31) for the system calibration, assuming that this new level has no significant scale value.

Here, we shall report about the system calibration (using the vertical comparator described in section 2.2) at two sighting distances, i. e. 3.3 m and 8.3 m. These distances were chosen to be smaller and larger than 6 m. At this distance the calculation mode of the Trimble level changes (Trimble 2001). The calibration at every sighting distance consists of two calibration runs. Between them the staff is demounted and mounted again.

To avoid systematic errors of the level, which usually occur at the ends of a staff, the calibration was carried out using staff readings between 0.15 m and 2.85 m only. Every calibration run consisted of two parts: (a) the forward measurements from the lower to the upper end of the staff and (b) the backward measurements, from the upper to the lower end. The backward measurements were shifted by half the sampling interval (Rüeger and Brunner 2000). The sampling interval was chosen – rather arbitrarily – as $I/12$, where I is the length of the CCD projected to the code at a sighting distance of 3 m. Note, that Rüeger and Brunner (2000) suggested to use $I/3$. In our case $I/12$ equals 21.833 mm. Every position was calculated as the mean of three individual height readings. Both measurements, (a) and (b) together yielded 247 positions at the staff.

sighting dist.	3.3 m		8.3 m	
measurement run	#1	#2	#1	#2
scale value [ppm]	15.0	14.9	15.0	14.8
σ_{scale} [ppm]	0.3	0.3	0.4	0.4
σ_y [µm]	4	4	5	5

Table 2: Numerical results of the system calibration of Trimble DiNi12 and staff S.No. 15439 at two sighting distances at TUG

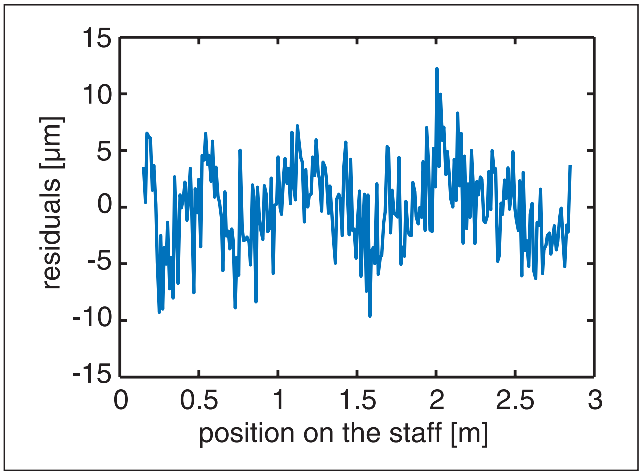

Fig. 7: Residuals of the first measurement run at a sighting distance of 3.3 m

Before estimating the scale value using the linear regression model, the measured heights were reduced to the reference temperature (20 °C). For this purpose the thermal expansion coefficient of invar was assumed as above (+ 0.75 ppm/°C). The scale values, estimated from the combined forward and backward measurements, are listed in tab. 2. Note, that the scale value determined by system calibration is a composite value of the scale values of the staff and the level. However, this is definitely an advantage, as it is exactly this composite value which is needed to correct the levelling data obtained during field work.

As an example the residuals $\tilde{e}$ of the first calibration run at the 3.3 m distance are shown in fig. 7. Note that $\tilde{e}$ is now mainly the levelling noise as the interferometer values are at least an order of magnitude more accurate.

4 Analysis of the Results

The scale values determined by staff and system calibration are listed in tab. 3. There are no significant differences in the scale values determined by the two calibration methods. However, a slight difference was to be expected, because the different calibration techniques use the horizontal or vertical position of the staff. Maurer and Schnädelbach (1995) published the differences between the determinations of the mean scale values of a vast amount of staff calibrations in horizontal and vertical positions. They stated that scale values determined by vertical staff calibrations are on average about 0.9 ppm smaller than for horizontal staff calibrations, but the range of the values is more than 10 ppm.

The scale values obtained from the system calibration at the 3.3 m and the 8.3 m position are almost identical. This indicates, that the calculation method of the level, which changes automatically depending on the distance, has no influence on the scale value of the system.

The goal of this paper was to prove that the scale value of the levelling system can be accurately determined as part of the system calibration. Therefore system calibrations using long sighting distances were not considered, as systematic effects, such as the drift of the compensator or periodical oscillations, have a stronger influence on the height readings with increasing sighting distance. As a result, the estimated scale value would be contaminated by such effects.

In section 3.2 we argued, that system calibration determines the composite value of the scales of the staff and the level. Thus, the dependency of the scale value on

	staff calibration		system calibration (DiNi12)			
			sighting dist. = 3.3 m		sighting dist. = 8.3 m	
measurement run	#1	#2	#1	#2	#1	#2
scale value [ppm]	15.2	15.9	15.0	14.9	15.0	14.8
σ_{scale} [ppm]	0.3	0.3	0.3	0.3	0.4	0.4
σ_y [µm]	3	3	4	4	5	5

Table 3: Comparison of the scale values obtained by staff and system calibration for levelling staff S.No. 15439

	staff calibration		system calibration							
instrument	–		DiNi12		DiNi11 #1		DiNi11 #2		DiNi10	
S.No.	–		700376		106755		114766		212032	
SW-Ver.	–		3.31		3.31		3.31		2.30	
meas. run	#1	#2	#1	#2	#1	#2	#1	#2	#1	#2
scale [ppm]	15.2	15.9	15.0	14.9	14.2	14.3	14.5	14.3	16.9	16.7
σ_{scale} [ppm]	0.3	0.3	0.3	0.3	0.3	0.3	0.5	0.4	0.3	0.4
σ_y [µm]	3	3	4	4	4	4	6	5	4	4

Table 4: Comparison of the scale values determined by system calibration using the same levelling staff (S.No.15439) and levels DiNi10, DiNi11 and DiNi12 at a distance of 3.3 m with the scale values derived by staff calibration

the level actually used was investigated. We calibrated another three Zeiss instruments (two DiNi11 and one DiNi10) with the same levelling staff (S.No. 15439). For all three instruments the same system calibration procedure, as described for the DiNi12, was used, but only at a sighting distance of 3.3 m. All resulting scale values are listed in tab. 4 including the software version of the levels.

The scale values determined using both DiNi11 instruments are slightly smaller than those determined using the DiNi12. Comparing the two DiNi11, the results of the DiNi11 #2 show a larger standard deviation for the scale value. The reason for this result is probably the higher noise value of DiNi11 #2, as shown in fig. 8. Nevertheless, the residuals (fig. 8) are within a range of ± 10 µm which is an excellent result considering that the resolution of the staff reading is 0.01 mm.

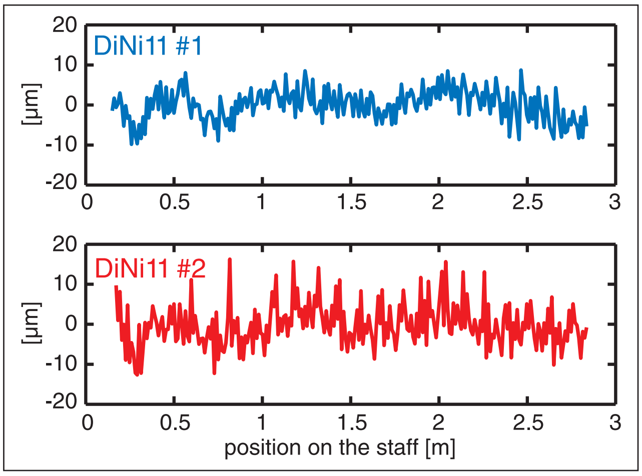

Fig. 8: Residuals of the first measurement run of DiNi11 #1 and DiNi11 #2 at a sighting distance of 3.3 m

The scale value associated with the DiNi10 is 2 ppm larger than the scale values of the DiNi11/12 levelling systems. Reasons for this difference might be the older software version or an inherent scale value of the level, which is the oldest of the selected levels.

5 Conclusion

We have shown that the scale value of a staff can be determined both by staff calibration and by system calibration (assuming the level has no scale value). Staff calibration determines the scale of the staff only. However, the scale value determined by system calibration is a composite value of the staff scale and an additional scale, caused by the level. This is definitely an advantage, as it is exactly this composite value which is needed to correct the levelling data obtained during field work.

Once the scale value is determined, the measured heights, h^{meas}, have to be corrected for the following systematic effects

$$h^{corr} = h^{meas} \cdot [1 + m^{sys} + \alpha^{inv} \cdot (t^{inv} - t^{ref})] \qquad (2)$$

where m^{sys} is the scale value of the levelling system (i. e. level and staff), α^{inv} is the coefficient of thermal expansion of invar, t^{inv} the temperature of the invar band of the staff, and t^{ref} the reference temperature (generally 20 °C) for which m^{sys} was determined.

In our opinion, it is not necessary to determine the coefficient of thermal expansion for every individual levelling staff. It seems to be sufficient to determine the coefficient representative for a batch of staffs.

We were able to prove, that system calibration of levelling systems using short sighting distances is capable to yield the composite scale value of the whole levelling system with a standard uncertainty (Heister, 2001) of about 1 ppm.

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