Scale Determination of Digital Levelling Systems Using a Vertical Comparator

Helmut WOSCHITZ and Prof. Fritz K. BRUNNER, Austria and Prof. Hans HEISTER, Germany

Key words: digital levels, staff calibration, system calibration, scale of levelling staff.

ABSTRACT

For high precision levelling digital levelling systems use 3m long staffs, where the code is etched on an invar band. The scale of the code is a function of the actual temperature of the invar band and a constant scale value. The latter is traditionally determined by ‘staff calibration’.

Using digital levels the scale value could also be influenced by a scale value of the level (e.g. aging effects of the CCD). To check the behaviour of the whole levelling system a procedure known as ‘system calibration’ can be used. Thereby height readings are taken at different positions on the staff and compared with their ‘true values’, which are obtained by a laser interferometer. Critics have expressed their doubts about the usefulness of system calibration and they insist on the separate staff calibration.

Therefore we investigated the determination of the scale value of the staff by system calibration. For this purpose a staff was calibrated with one of the most accurate facilities for staff calibration at the Bundeswehr University Munich (UniBwM). A coded invar staff is mounted in a horizontal position and the edges of the code elements are automatically detected under control of a laser interferometer. The accuracy of the photoelectric edge detection is 0.7µm + L*0.4µm, with L being the position on the staff in meter. The determined scale value of the staff was 15.5±0.3ppm.

The system calibration was done with the new vertical comparator at the Graz University of Technology, also controlled by a laser interferometer. The internal precision of this vertical comparator is estimated better than ±4µm. For the system calibration the same staff and a brand-new Trimble DiNi12 digital level were used with the assumption that this new level has no scale value. The scale value of the system was determined with 15.0±0.3ppm. To prove the assumption (i.e. the DiNi12 has no scale value), further system calibration with two Zeiss DiNi11 and the same staff were carried out, yielding the same scale value as obtained with the DiNi12.

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

CONTACT

Helmut Woschitz and Fritz K. Brunner
Engineering Geodesy and Measurement Systems, Graz University of Technology
Steyrergasse 30
8010 Graz
AUSTRIA
Tel. + 43 316 873 6321
Fax + 43 316 873 6820
E-mail: {woschitz, brunner}@ivm.tu-graz.ac.at
Web site: http://www.cis.tugraz.at/ivm/

Hans Heister
Institute of Geodesy
Bundeswehr University Munich (UniBwM)
D-85577 Neubiberg
GERMANY
Tel. + 49 89 6004 3433
Fax + 49 89 6004 3904
E-mail: h.heister@unibw-muenchen.de

Scale Determination of Digital Levelling Systems Using a Vertical Comparator

Helmut WOSCHITZ and Prof. Fritz K. BRUNNER, Austria and Prof. Hans HEISTER, Germany

1. INTRODUCTION

Within 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 could be 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, and 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.

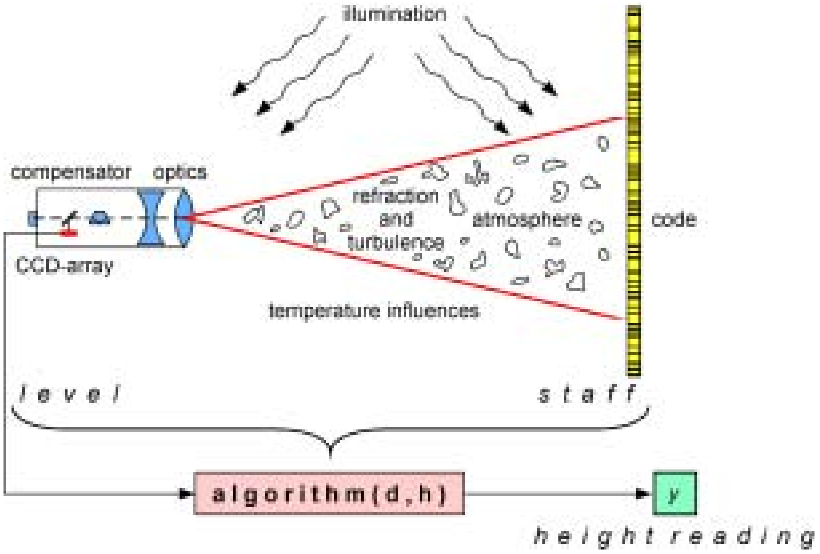

Figure 1: The digital level as a measuring system

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 from three manufacturers are used in high precision levelling. Commonly 3m 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 corrections for each graduation line. Subsequently, the readings were corrected with these values. A review of staff calibration is given by Rüeger and Brunner (2000).

1.3 System Calibration

In the measurement process with 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 with the true values of the motions, information about the behaviour of the levelling system can be derived (Brunner and Woschitz, 2001). Obviously it requires to have an adequate ‘machine’ to do the movements and to provide the true 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 a staff calibration was carried out with one of the most accurate facilities at the Bundeswehr University Munich (UniBwM). The system calibration was carried out at the Graz University of Technology (TUG) with 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. The analysis of the independently derived results is done 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 is 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 30m 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), resulting in a minimum change of length of the invar band. To adjust the staff into a position parallel 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 carriages move with the mounted staff beneath the microscope, which measures the edges of all code elements. The accuracy of automatic edge detection is 0.7µm + L*0.4µm, with L being the position on the staff in meter. Details about the construction and the achievable accuracy are discussed by Heister (1988).

Figure 2: The horizontal comparator for staff calibration at UniBwM

Figure 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. Being able to calibrate 3m long invar staffs, it was necessary to extend the laboratory with two shafts, to get enough space for the 6.5m high frame and the carriage on it. The carriage with the mounted staff is moved under the control of a laser interferometer (HP10889B). Abbe's comparator principle was strictly adhered to as shown in fig. 4. Since the level can be positioned on a concrete bench, the sighting distances can be chosen from 1.5m to 30m. In the GML the staff illumination is achieved by special light bulbs, radiating light in the range of the spectral response for any of the 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 this facility are given in fig. 5. We assess the internal precision of this vertical comparator with ±4µm.

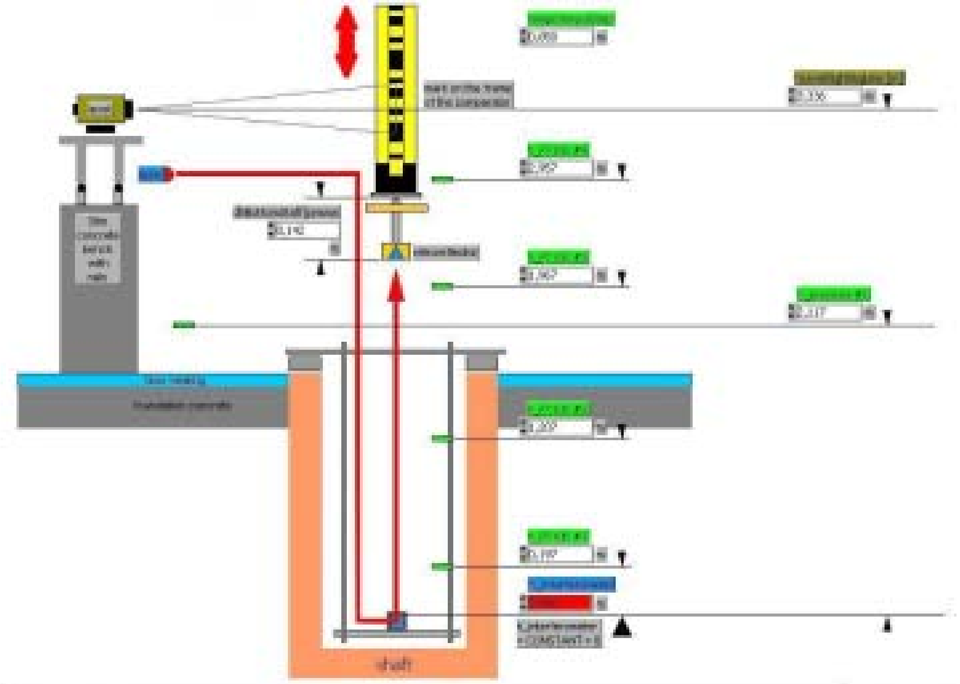

Figure 4: Scheme of the vertical comparator at the GML - TUG

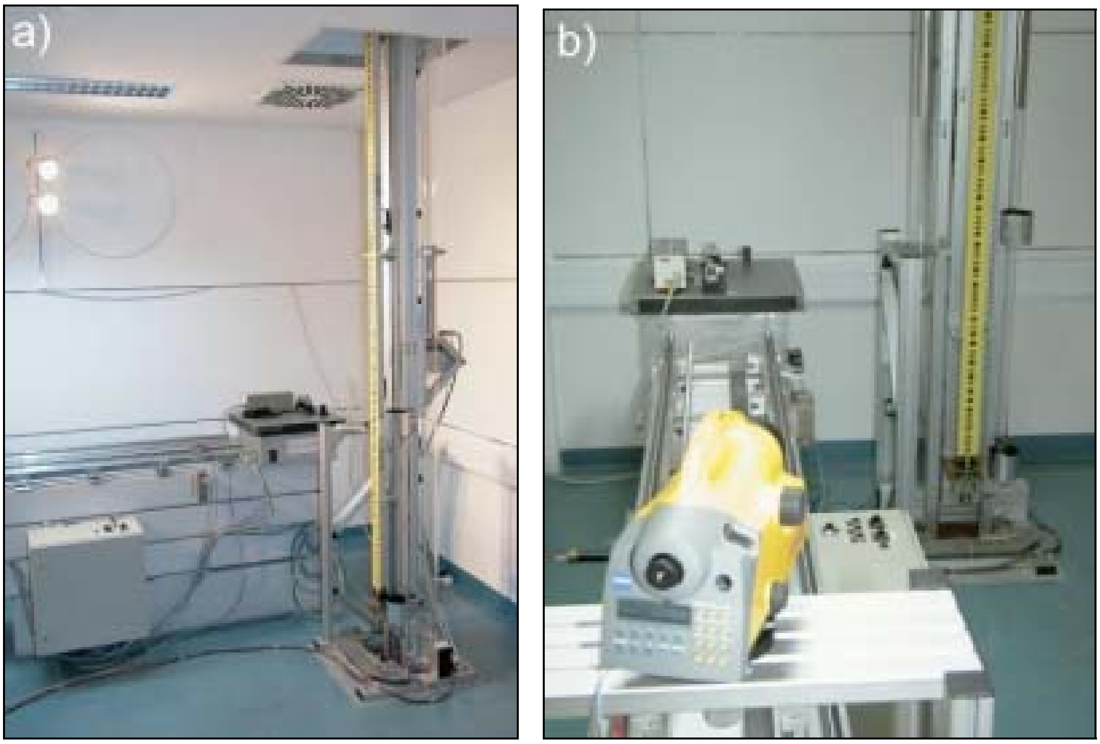

Figure 5: **The vertical comparator (a) with staff illumination and (b) as seen from the level's position**

3. TEST PROCEDURE AND RESULTS

In this section we will 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 of this paper, we used a Trimble DiNi12 digital level and one staff with the Zeiss code only.

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 from the staffs base plate to its upper end. After the first run, the staff is demounted, then mounted and positioned again for the second run.

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

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

for all measurements i=1,2,…,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 the 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 it termed e_i. The unknown regression coefficients are computed by the method of least squares. Tab. 1 shows the results of the staff calibration of the coded Zeiss staff (S.No. 15439).

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

measurement run	#1	#2
scale value [ppm]	5.2	5.9
s_{scale} [ppm]	0.3	0.3
s_y [µm]	3	3

The calculated scale value of the staff deviates by more than 15ppm 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 this 15ppm 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.

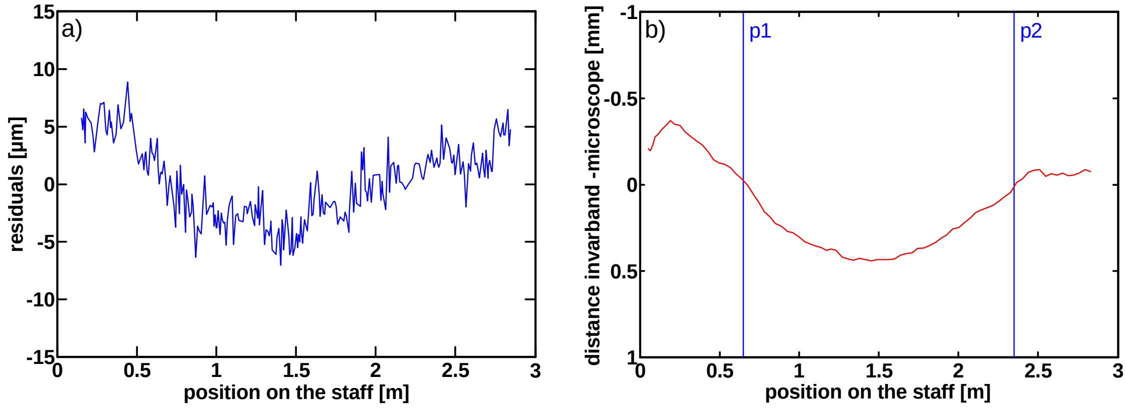

Figure 6: First measurement run at UniBwM: (a) residuals of the positions of the code elements; (b) height position of the invar band

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 deviations.

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

To avoid systematic errors of the level, which usually occur at the ends of a staff, the calibration was carried out between 0.15m and 2.85m. 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 of 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 3m. Note, that Rüeger and Brunner (2000) suggested to use *I/3*. In our case *I/12* equals 21.833mm. Both measurements, (a) and (b) together yielded 247 positions at the staff. Every position was calculated as the mean of three individual height readings. When the calibration of the staff was finished, the staff was removed and mounted again on the comparator, followed by the second calibration run.

Before estimating the scale value with the linear regression model, the measured heights have to be reduced to the reference temperature (20°C). For this purpose the thermal expansion coefficient of invar was assumed with +0.75ppm/°C (Maurer and Schnädelbach, 1995). 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.

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

	sighting dist.=3.3m		Sighting dist.=8.3m	
measurement run	#1	#2	#1	#2
scale value [ppm]	5.0	4.9	5.0	4.8
s_{scale} [ppm]	0.3	0.3	0.4	0.4
s_y [µm]	4	4	5	5

Exemplarily the residuals $\tilde{e}$ of the first calibration run at the 3.3m 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.

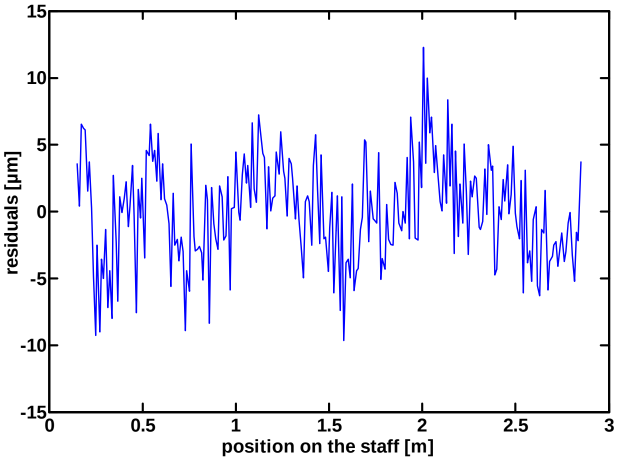

Figure 7: Residuals of the first measurement run at a sighting distance of 3.3m

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 0.9ppm smaller than for horizontal staff calibrations, but the range of the values is more than 10ppm.

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

	staff calibration		system calibration (DiNi12)			
			sighting dist.=3.3m		sighting dist.=8.3m	
measurement run	#1	#2	#1	#2	#1	#2
scale value [ppm]	5.2	5.9	5.0	4.9	5.0	4.8
s_{scale} [ppm]	0.3	0.3	0.3	0.3	0.4	0.4
s_y [µm]	3	3	4	4	5	5

The scale values obtained from the system calibration at the 3.3m and the 8.3m 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, get a stronger influence on the height readings with increasing sighting distance. As a result, the estimate of the scale value would become erroneous.

In section 3.2 we argued, that system calibration determines the composite value of the scales of the staff and the components of the level. Thus, the dependency of the scale value on the level used was investigated. We calibrated another three instruments from Zeiss (two DiNi11 and one DiNi10) with the same levelling staff (S.No. 15139). For all three instruments the same system calibration procedure, as described for the DiNi12, was used, but only at a sighting distance of 3.3m. All resulting scale values are listed in tab. 4 including the software version of the levels.

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 3.3m with the scale values derived by staff calibration

	staff calibration		system calibration							
instrument S.No. SW-Ver.	- - -		DiNi12 700376 3.31		DiNi11 #1 106755 3.31		DiNi11 #2 114766 3.31		DiNi10 212032 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
s_{scale} [ppm]	0.3	0.3	0.3	0.3	0.3	0.3	0.5	0.4	0.3	0.4
s_y [µm]	3	3	4	4	4	4	6	5	4	4

The scale values determined with both DiNi11 instruments are slightly smaller than those determined with 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 ±10µm which is an excellent result considering that the resolution of the staff reading is 0.01mm.

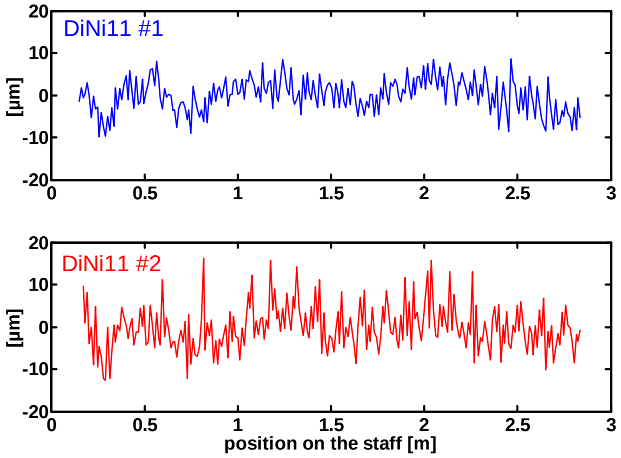

Figure 8: Residuals of the first measurement run of DiNi11 #1 and DiNi11 #2 at a sighting distance of 3.3m

The scale value associated with the DiNi10 is 2ppm 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 all calibrated 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.

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

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

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 determine the composite scale values of the whole levelling system with a standard uncertainty of about 1ppm.

REFERENCES

Brunner, F.K., Woschitz, H. (2001): Kalibrierung von Messsystemen: Grundlagen und Beispiele. In Heister H. and Staiger R., (ed.) Qualitätsmanagement in der Geodätischen Messtechnik. Konrad Wittwer Verlag, DVW Schriftenreihe 42: 70-90.

Fischer, T., Fischer, W. (1999): Manufacturing of High Precission Levelling Rods. In Lilje, M. (ed.) The importance of heights. FIG, Gävle, Sweden: 223-228.

Heister, H. (1988): Zur automatisierten Kalibrierung geodätischer Längenmessinstrumente. Universität der Bundeswehr München, Schriftenreihe 27, Neubiberg. 210 pages.

Heister, H. (1994): Zur Überprüfung von Präzisions-Nivellierlatten mit digitalem Code. Universität der Bundeswehr München, Schriftenreihe Nr. 46: 95-101.

Heister, H. and Staiger R. (2001): Qualitätsmanagement in der Geodätischen Messtechnik. Konrad Wittwer Verlag, DVW Schriftenreihe 42.

Ingensand, H. (1999): The evolution of digital levelling techniques - limitations and new solutions. In Lilje, M. (ed.) The importance of heights. FIG, Gävle, Sweden: 59-68.

Maurer, W., Schnädelbach, K. (1995): Laserinterferometry - Ten Years Experience in Calibrating Invar Levelling Staffs. Proc., First Int. Symp. Appl. Laser Techniques in Geodesy and Mine Surveying, Ljubljana, Sept. 1995, 9 p.

Rüeger, J.M., Brunner, F.K. (2000): On System Calibration and Type Testing of Digital Levels. Z. f. Vermessungswesen 125: 120–130.

Schlemmer, H. (1975): Laser-Interferenzkomparator zur Prüfung von Präzisionsnivellierlatten. Verlag der Bayrischen Akademie der Wissenschaften. DGK Reihe C, Bd. 210.

BIOGRAPHICAL NOTES

Helmut Woschitz received the degree Dipl.-Ing. from the Graz University of Technology in 1997 and is now a research assistant at the Graz University of Technology. His research concentrates on calibration and development of measurement systems.

Fritz K. Brunner received the degrees Dipl.-Ing. and Dr. techn. from the Technical University of Vienna in 1967 and 1972, respectively. During 1969-1974, he was an assistant at the TU Vienna. From 1974 to 1982, he was a lecturer at the University of New South Wales, Australia. During 1981, he was an A. v. Humboldt fellow at the Geodetic Institute, University of Stuttgart. From 1982 to 1986, he headed the Advanced Products Group at Wild Heerbrugg Ltd., Switzerland. In 1986 he was appointed Professor and Head, School of Surveying, University of New South Wales. In 1994 he received an A. v. Humboldt Research Award. Since October 1994 he is Professor of Engineering Geodesy, Graz University of Technology. From 1995 to 1999 he was President of Section I "Positioning" of IAG. In 2001, he was elected President of the Austrian Geodetic Commission.

Hans Heister received the degree Dipl.-Ing. at the University of Bonn in 1969. During 1970 – 1974 he was assistant at the Geodetic Institute of the TU Munich. 1974 he became director of the Geodetic Laboratory of the Bundeswehr University Munich (UniBwM), 1987 Dr.-Ing.habil., and since 1991 he is apl. Professor for Geodetic Metrology at the same University. Main activities: GPS, land navigation, kinematic survey, gyro-measurements, calibration of geodetic instruments, engineering and industrial surveying. Many professional activities abroad, numerous lectures at foreign universities and congresses. Member of FIG commission 5 "Positioning & Measurement".