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System Calibration of Digital Levels – Experimental Results of Systematic Effects

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Abstract

System calibration can be used to determine the scale value of a levelling system and to obtain information about its performance. System calibration uses height readings which are taken at different positions on the staff in comparison with their 'true values', which are obtained by a laser interferometer. For this purpose the staff should be in the vertical position. The vertical comparator of the Graz University of Technology (TUG) is briefly described. The results of a system calibration for the determination of the scale value are summarised. Examples investigate the performance of current digital levelling systems using the end sections of the staff and the effect of a damaged code element on the height results.

1 INTRODUCTION

In the measurement process of a digital level the whole system is involved, as shown in fig. 1.

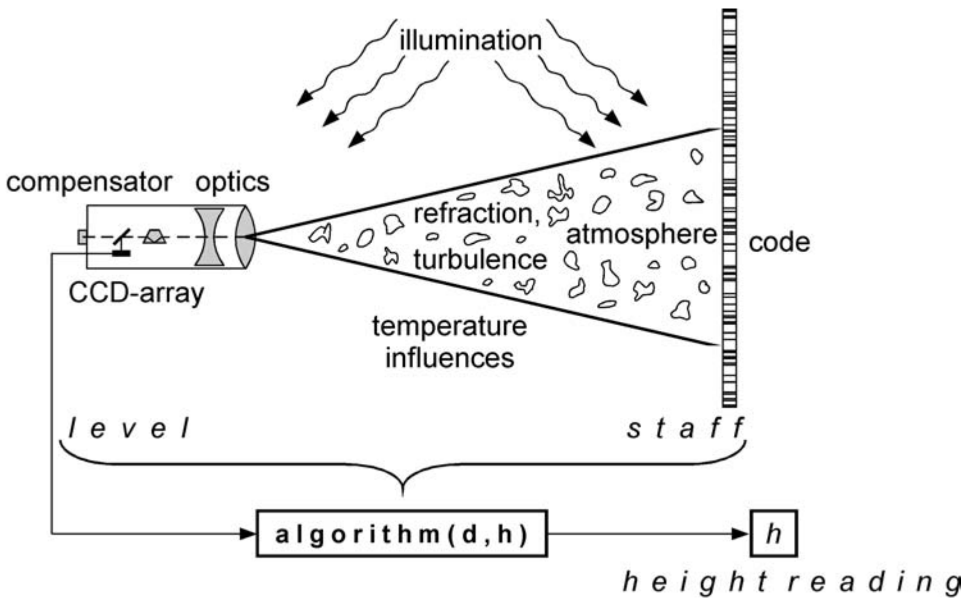

Figure 1: The digital level as a measuring system.

The staff reading is calculated using the image of the coded staff which is projected onto the imaging sensor (CCD). Different measurement techniques with the associated codes have been developed. Algorithms used for the calculation of the staff reading are correlation, geometric averaging and Fourier analysis. An overview of the different measurement techniques was given by Ingensand (1999). Currently, three different digital levels for precision levelling are available. These are the Leica, Topcon and Trimble (formerly Zeiss) digital levels, which are commonly used with invar staffs of e.g., 3m length.

As the whole system is involved in the measuring process, the most appropriate way to calibrate digital levelling systems is system calibration. The general idea of system calibration is briefly described in chapter 2. The system calibration facility of the Graz University of Technology is briefly presented in chapter 3.

To obtain accurate 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. Traditionally, the scale value was determined by staff calibration, which excludes the level from the calibration process. Experiments which are summarised in chapter 4, have shown that also the scale value can be determined by system calibration. The main advantage of system calibration is that additional information about the performance of the whole levelling system can be derived. Some examples are given in chapter 5.

2 SYSTEM CALIBRATION

Using a digital level, the whole system is involved in the measuring process. If any of the involved components (staff or level) are faulty, the measuring process is affected and as a consequence the height readings are erroneous. Such defects might be damaged code elements of the staff. Therefore system calibration has been considered the proper technique to calibrate the level and the staffs together (Heister, 1994).

The basic idea of system calibration 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. Information about the performance of the system can be derived from the differences of the heights readings of the level and the true values of the motion. However, to realise this simple idea, an adequate comparator is needed to perform the movements and to measure the true values of motion. Preferably, the staff should be mounted in the position of use i.e., vertically.

3 THE TUG VERTICAL COMPARATOR

At the Graz University of Technology the Geodetic Metrology Laboratory (GML) was established within the last decade. One of the calibration facilities in the GML is the vertical comparator, which allows to calibrate 3m long staffs in a vertical position. The staff is moved under control of a laser interferometer (HP10889B). The representative refractive index for the laser beam path is derived from measurements of four temperature sensors, one atmospheric pressure and one humidity sensor. One of the basic design principles was to strictly adhere to Abbe’s comparator principle, as shown in fig. 2a. The level can be positioned on a 30m long concrete bench, which allows to choose the sighting distance between 1.5m and 30m. A schematic overview of the calibration facility is shown in fig. 2a, a photograph of it is given in fig. 2b.

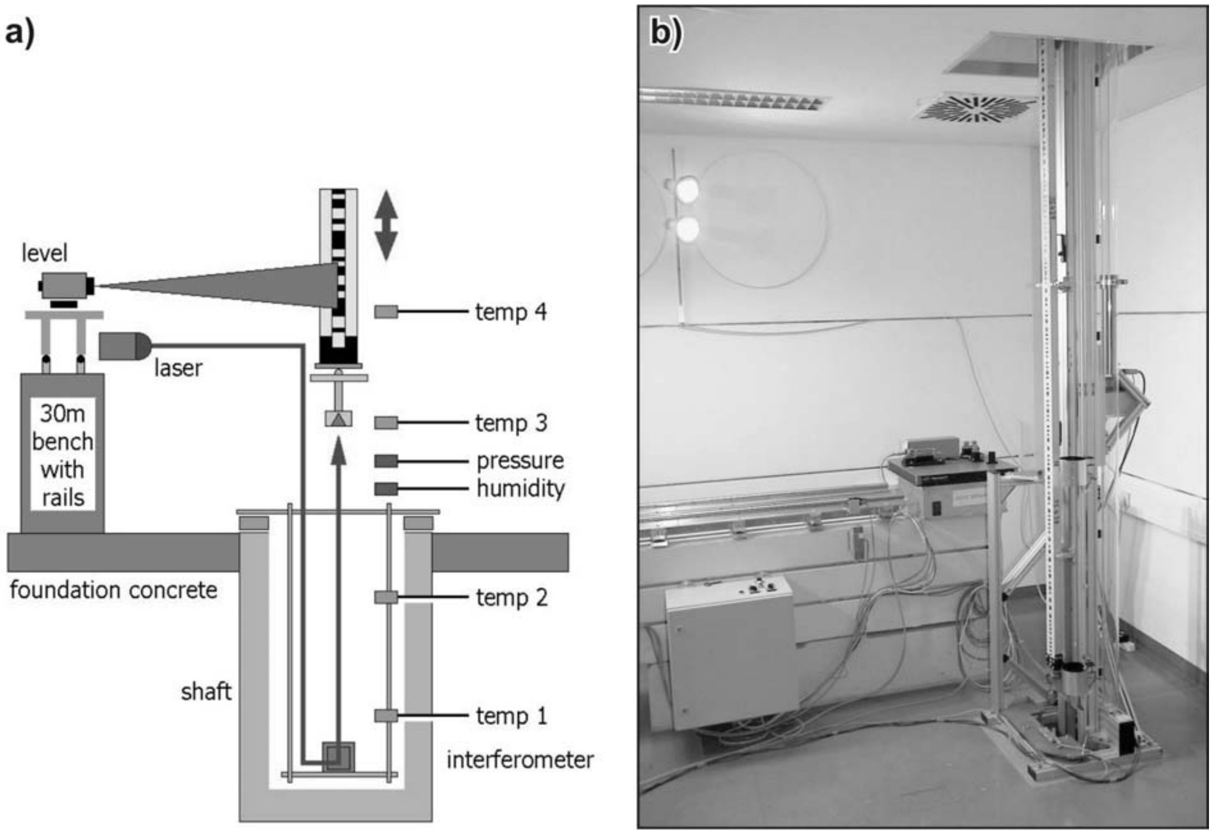

Figure 2: (a) Schematic overview and (b) an image of the TUG - GML vertical comparator.

The laboratory is climatically controlled with a temperature of 22.0°C ± 0.5°C and a humidity of 50% ± 10%. The staffs are illuminated by special light bulbs, which radiate light in the range of the spectral response for any of the current types of digital levels. We assess the internal precision of the vertical comparator with ±4µm. Further details about the comparator are given by Woschitz et al. (2002).

4 SCALE DETERMINATION

It would be an advantage to determine the scale value of the system as part of the system calibration. Critics of the system calibration have considered this impossible, mainly because the resolution of the current levelling systems is restricted to 0.01mm. However, Woschitz at al. (2002) proved experimentally that system calibration is capable to accurately determine the scale value. Thereby, a staff was calibrated with one of the most accurate facilities for staff calibration at the Bundeswehr University Munich (UniBwM), Heister (1988). There, the scale value of the horizontally positioned staff was determined by two independent calibration runs as 15.2±0.3ppm and 15.9±0.3ppm. The scale value of the staff is relatively large, which is most likely the result of tough field use.

The system calibration was carried out using the previously described TUG-GML vertical comparator. Thereby, the same staff was used as in the Munich runs, but in combination with a brandnew Trimble DiNi12. The procedure of the system calibration was carried out according to the proposal by Rüeger and Brunner (2000). At a short sighting distance (3.3m), two separate calibration runs were carried out, each of them consisting of a forward and a backward measurement, i.e. from the bottom to the top of the staff and vice versa. Between the two runs, the staff was demounted from the comparator, set up on a benchmark like it is done in field use, and mounted again on the comparator. The purpose of this procedure is to detect possible malfunctions of the staff. The scale value of the levelling system was calculated as the slope of a linear regression line using the combined data of the forward and backward measurements. The scale value was determined as 15.0±0.3ppm and 14.9±0.3ppm with the data of two calibration runs. Fig. 3 shows the residuals about the regression line of the first measurement run, and gives an impression of the high precision of this levelling system.

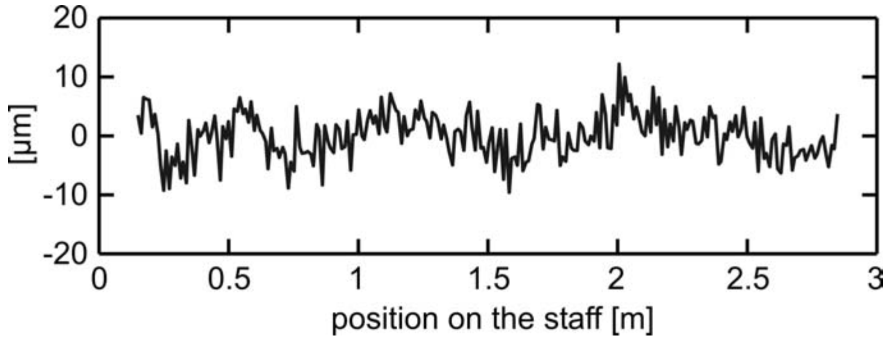

Figure 3: Residuals about the regression line.

The slight difference between the scale values determined by the independent calibration methods is not significant. However, Maurer and Schnädelbach (1995) using a vast amount of data obtained from staff calibration stated that scale values determined with staffs in the vertical position are on average about 0.9ppm smaller than those determined with horizontally positioned staffs.

5 PERFORMANCE OF LEVELLING SYSTEMS

System calibration provides also important information about the performance of the levelling system. Depending on the make of level, systematic height deviations may occur. Such system inherent deviations might be associated with special sections of the staff or with some specific sighting distances. The existence of the latter effect is well known for the Leica levels, e.g. Reithofer et al. (1996), where the effect mainly appears at multiples and fractions of 15m. At other distances, the periods of the height deviations are not noticeable.

Different levels of the same type might show a different behaviour, due to slight changes in the assembly of the level's components. User induced changes of the level's performance might be caused by tough use of the levelling system, especially of the staff. In the following, a few examples of system inherent and user induced height deviations of some levelling systems are shown.

5.1 HEIGHT DEVIATIONS IN THE END SECTIONS OF THE STAFF

When measuring at the lower or upper end of the staff, not only a part of the coded invar band is imaged by the CCD, but also part of the environment above or below the invar band. These disturbing regions on the CCD must be detected by the processing software of the level and excluded from further evaluation.

In these situations, the useable image of the code is asymmetric. As a consequence, the height readings are affected systematically, if the evaluation technique of the level is sensitive to an asymmetric pixel image. Let *L* be the size of the useable section of the staff i.e., in fig. 4a the distance from *DP1* to *DP2*. *L* changes with the size of $CCD^{proj.}$ which is the size of the CCD array projected to the staff (fig. 4b) or that section of the CCD array used for the height computation. $CCD^{proj.}$ can be calculated from the electronic viewing angle of the level which is 2° for the Leica instruments and 1°20' for the Topcon instruments. For the Trimble / Zeiss instruments $CCD^{proj.}$ is 30cm for all sighting distances, as these instruments use a maximum of 30cm of the code to calculate the height reading. The coded invar band is not fully visible at the end sections due to the mechanical construction of the staff, for which the distances *c1* and *c2* are introduced in fig. 4a.

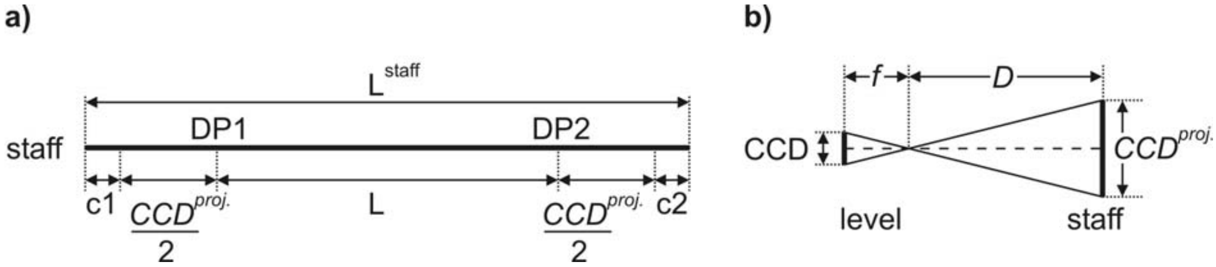

Figure 4: (a) Useable section of the staff. (b) Projection of the imaging sensor to the staff.

As an example, the invar band of a 3m staff is visible from 0.037m to 2.980m, and *L* is 2.943m-$CCD^{proj.}$. Thus measurements in the end regions of the staff may be defined as the height readings that are either smaller than *DP1* or larger than *DP2*. This definition means that always 100% of the CCD array are covered by the code.

Fig. 5 shows the performance of a Leica NA3003 (S.No. 282727, SW-Ver.4.3 and using extended system accuracy mode) in the end regions of the staff at a sighting distance of 10m and 30m. At these distances, $CCD^{proj.}$ is 0.346m (D=10m) and 1.038m (D=30m).

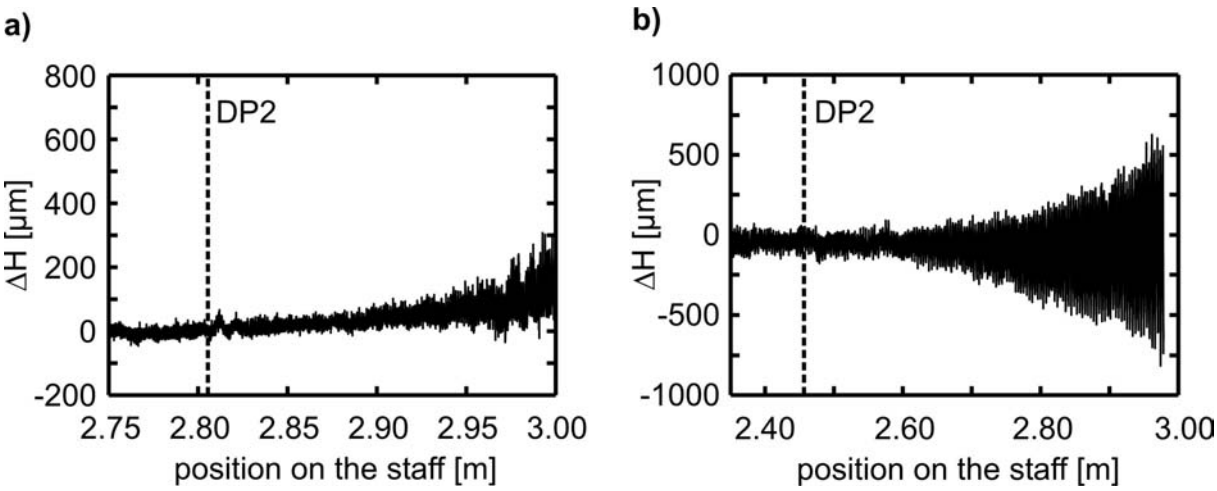

Figure 5: Height deviations at the upper end of the staff at (a) 10m and (b) 30m sighting distance measured with a Leica NA3003.

Fig. 5 shows, that the measurements beyond *DP2* are systematically affected and that the height readings might be wrong by more than 0.5mm in the extreme end regions. At a sighting distance of 30m, about 0.5m at the lower and upper end of the staff should not be used. However, the lower section is approximately as large as the section that should not be not used because of refraction effects. Furthermore, in fig. 5 the change of the performance of the height deviations with the sighting distance can be observed.

The different performance of three instruments of the same type at the upper end of a 3m invar staff is shown in fig. 6. The measurements were carried out using two Trimble/Zeiss DiNi11 (#1 S.No. 106755, #2 S.No. 114766) and one DiNi12 (S.No. 700376) at the same sighting distance of 10m, and the same software version was running on all three instruments (i.e., SW-Ver.: 3.31, which was the current one at the time of measurement).

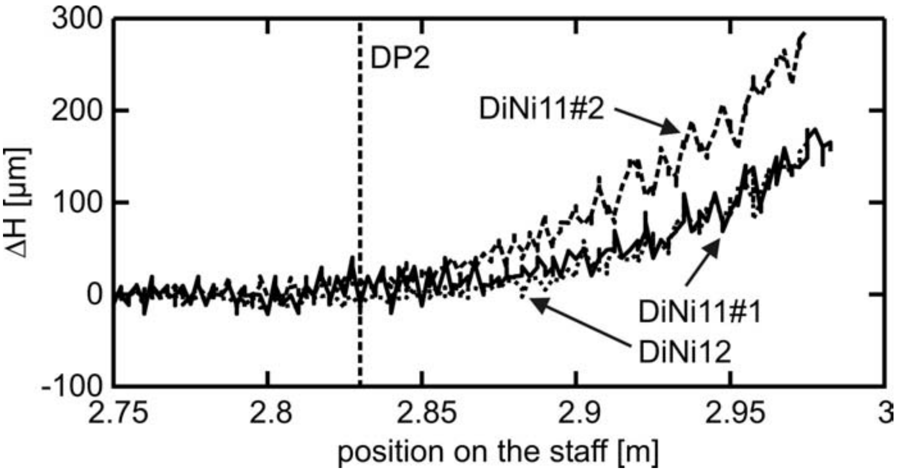

Figure 6: Height deviations at the upper end of the staff of two Trimble/Zeiss DiNi11 and one DiNi12 at 10.000m sighting distance.

The height values start to deviate at 2.80m and are wrong by 0.2mm to 0.3mm at the end of the staff. The DiNi11#2 has a different behaviour compared to the other levels. However, the reason for this difference is not known at the moment.

The Topcon level DL101C was also investigated with very similar results in comparison to the other level types. It can be concluded, that in precise levelling using digital levels of any make, measurements should be taken between *DP1* and *DP2* only, as defined by fig. 4a, thus safely avoiding the end sections.

5.2 DAMAGED CODE ELEMENTS

Maltreatment of the level and the staff will cause a change in the performance of the levelling system. In the following, the influence on the height readings by damaged code elements is shown.

There was only one damaged staff available (Leica code). The experiment was carried out with the same Leica NA3003 instrument as above, using the extended system accuracy mode. Fig. 7 shows the section of the staff with five damaged code elements.

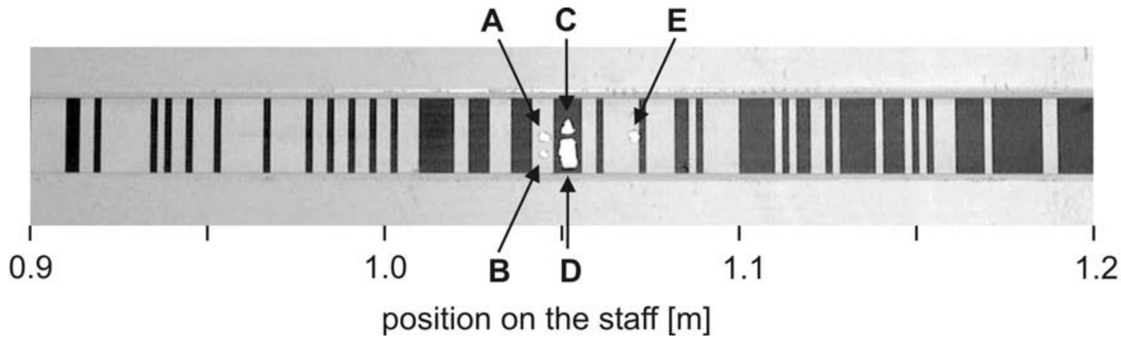

Figure 7: Picture of the damaged section of the Leica staff.

For the experiment, a sighting distance of 3m was chosen. At this distance, a 104mm long section of the code is seen by the imaging sensor. If there is a damaged code element in this section, then we expect the height reading to be erroneous. Therefore, the level was pointed to image the damages *A* and *E* in the first part of the experiment, see fig. 8. To get also unaffected height readings, the calibration was carried out for a 30cm long section of the staff, i.e. from 0.9m to 1.2m above the footplate. The sampling height interval was 1mm.

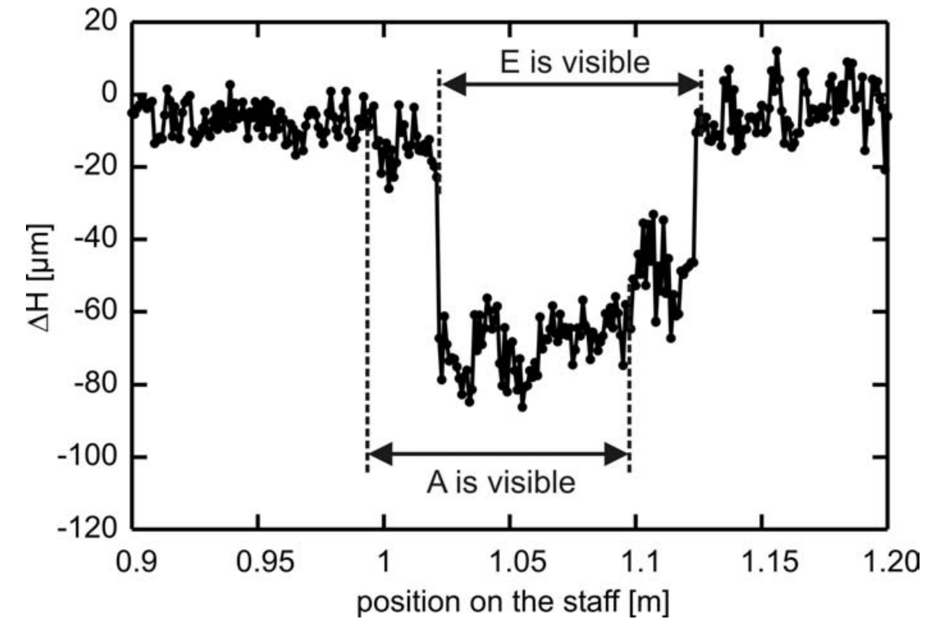

Figure 8: Height deviations caused a the damaged staff.

Considering the region $\pm\frac{1}{2}CCD^{proj.}$ about each damage, it becomes obvious, that damage *A* has a smaller influence on the height readings than damage *E*. In the region about *A*, where *E* is not seen by the imaging sensor, height deviations of only 0.01mm appear. Contrary to that, if damage *B* is projected to the imaging sensor, height deviations of up to 0.08mm are visible.

A reference measurement using the same staff, but pointing to the undamaged section, was the second part of the experiment. As expected, the height readings of the reference measurement did not show any deviations.

The example gives an impression about height deviations caused by damaged code elements. However, the magnitude of the effect depends on the evaluation method used by the level (i.e. correlation in the shown example) and might be much larger for other makes of levels. Also other shapes and sizes of the damages might enlarge the effect.

6 CONCLUSION

Although most examples were shown for the Leica NA3003, similar effects are observable with all three makes of precision digital levels. For achieving the highest accuracy, one must be aware of the systematic effects of the used levelling system and pay attention to not measuring at 'dangerous' distances. The usefulness of the vertical comparator at TUG-GML in system calibration was demonstrated by the experimental results shown.

Acknowledgement

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