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Calibration of Digital Levelling Systems

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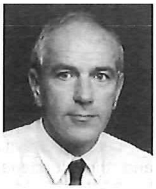

Calibration of Digital Levelling Systems

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Abstract

Since the introduction of the first digital level by Leica in 1990, this type of equipment is rapidly gaining acceptance in high precision levelling. A digital levelling system consists of the following main components: coded invar staff, illumination of staff, atmospheric propagation path, optics of the level, automatic compensator and electro-optical linear array. Therefore the complete system needs to be calibrated in order to assess its accuracy performance over a wide range of conditions.

A new vertical comparator has been developed for the calibration of digital levelling systems. The coded invar staff can be positioned vertically to better than 2 µm using a laser interferometer. The digital level can be positioned anywhere between 5 to 30 m from the staff. The true errors of the height differences can be determined as a function of distance from the difference between the vertical comparator and the digital level readings.

The performance of two digital levelling systems has been investigated in great detail. In the Leica NA 3000/3 results a clear periodic effect was discovered. The periods of this effect are distance dependent and range between 1 and 3 mm with amplitudes of up to 0.2 mm. The periodic nature of this effect raises the question of the correct choice of the sampling interval of the vertical comparator which is addressed. The specified RMS of double run levelling can be confirmed for the NA 3003, however, the accuracy of single height measurements is affected by the periodic effect. The results of the calibration of the Zeiss DiNi10 equipment do not exhibit any periodic effect. In conclusion, the calibration of digital levelling systems is recommended as part of the required quality control.

Zusammenfassung

Das Digitalnivellier und die dazugehörigen Invarcodelatten bilden jeweils das zu prüfende Meßsystem. Dazu wurde ein neuer Vertikalkomparator entwickelt, mit dem die lotrecht gestellten Codelatten um beliebige Intervalle mit Hilfe des Laserinterferometers automatisch positioniert werden können. Das Digitalnivellier ist meßgerecht in einer frei wählbaren Entfernung zwischen 5 m und 30 m aufgestellt. Die Beleuchtung der Latten wurde durch die Messung der Spektralverteilung optimiert.

Die Genauigkeiten der Digitalnivelliere LEICA NA3000/3 und ZEISS DiNi10 wurden unter Meßlaborbedingungen bei konstantem Klima untersucht. Bei den Typen NA3000/3 wurde eine Grundschwingung der Abweichungen von den Sollwerten, deren entfernungsabhängige Perioden zwischen 1 und 3 mm liegen, festgestellt. Die korrekte Wahl der Abtastung der Höhenablesung für die Kalibrierung bei Vorliegen eines periodischen Effektes wird geklärt. Bei einer Zielweite von 14,97 m tritt ein Maximum eines Überlagerungseffektes auf, der die Amplituden bis 0,5 mm vergrößert. An der Reduktion dieses Effektes wird bereits intensiv gearbeitet. Es sind bei Zielweiten zwischen 20 und 25 m maximale Amplituden von 0,2 mm der Abweichungen vorhanden, sodaß unter Berücksichtigung einer annähernden Gleichverteilung der mittlere Kilometerfehler eines Doppelnivellements – nach Herstellerangaben von 0,4 mm/km – eingehalten werden kann. Die Spezifikation des mittleren Fehlers einer Einzelmessung von ± 0.03 mm kann nicht bestätigt werden. Die ersten Untersuchungen des Digitalnivelliers Zeiss DiNi10 ergaben eine sehr hohe Genauigkeit unabhängig von der Distanz und es sind keinerlei periodische Effekte erkennbar. Diese Untersuchungen werden fortgeführt.

Schließlich wurde festgestellt, daß es zwischen den einzelnen Typen der Nivelliersysteme erhebliche Genauigkeitsunterschiede gibt, sodaß eine Kalibrierung jedes Meßsystems im Sinne einer Qualitätskontrolle der Meßmittel zu empfehlen ist.

1. Introduction

Since the introduction of the first digital level by Leica in 1990, [1], [2], this type of equipment is rapidly gaining acceptance in high precision levelling. A digital levelling system consists of a coded invar staff and an automatic level with an electronic eye piece in order to achieve an automatic horizontal height reading of the staff.

A new calibration facility has been developed for digital levelling systems using a vertical comparator in the measurement laboratory of the TU Graz. The performance of two digital levelling systems (Leica and Zeiss) has been investigated in great detail using this new vertical comparator. The results of these calibration tests are presented as functions of the sight length and the height reading on the staff.

2. Measurement System

The complete measurement system of a digital level consists of several basic elements (Fig.1). The first basic element is the staff with a known code of the sequence of black and white fields. Naturally, the staff has to be illuminated. Next, the coded information propagates through the atmosphere which causes refraction and scintillation of the staff image. Then the staff image passes through the optics and the automatic compensator of the level. A beam splitter directs the staff image on a linear CCD array. Finally the staff reading can be computed using the image and known code information. This process depends on the design of the levelling system. In the case of the Leica level the correlation between the staff image and the known staff code is calculated which will depend on the distance and on the height reading.

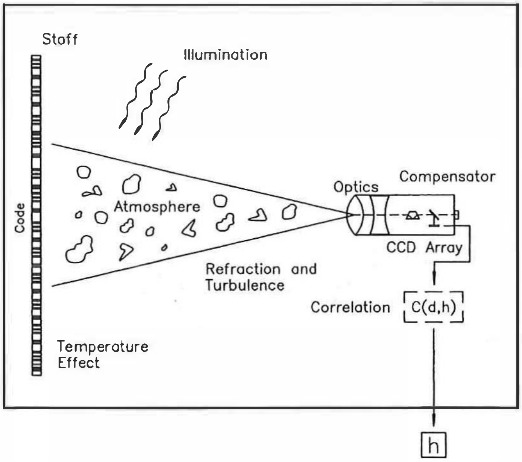

Fig. 1: Measurement system of a digital level

It would be a formidable task to calibrate each of these basic elements. Therefore it is of advantage to calibrate the measurement system as a whole, varying the height of the staff and the distance of the staff to the level. Since this calibration yields relative height information only, the standard level test continues to be mandatory for field work.

3. Vertical Comparator

The TU Graz is the owner of a temperature controlled (20°C ± 0,5°C) measurement laboratory [3] with a range of calibration facilities. During the past two years a vertical comparator for digital levelling systems has been developed (Fig. 2). A special shaft was built in order to move the staff up und down by ± 3 m using 3 m long standard invar staffs. The staff is attached to a vertical rail system on which the staff can be moved vertically. The motion is controlled by the laser interferometer. The vertical comparator design adheres to the Abbé principle (Fig. 3). Using a feed-back control system it is possible to position the staff with an accuracy of 2 μm.

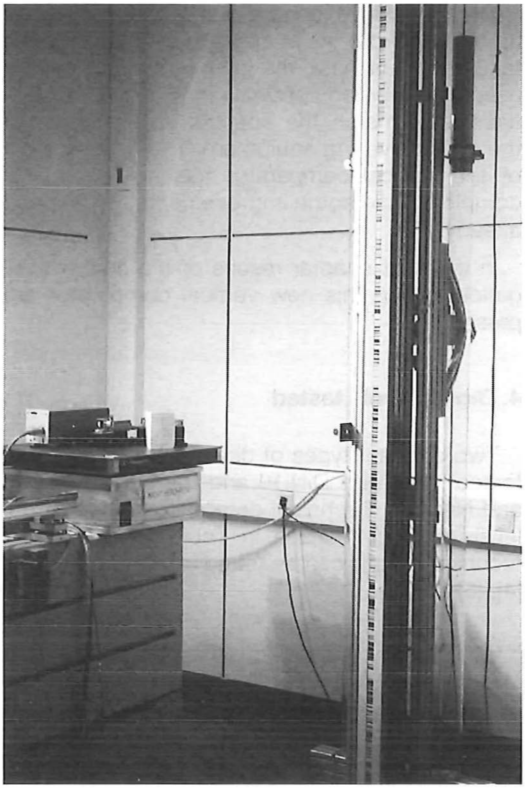

Fig. 2: Vertical comparator and laser interferometer

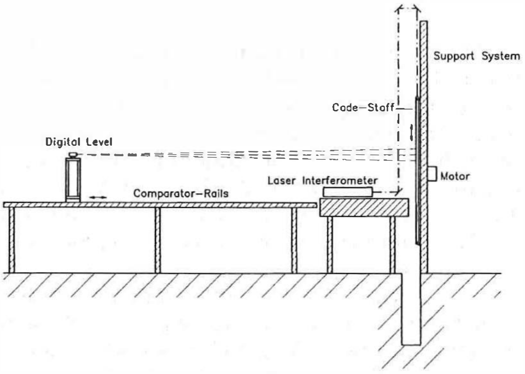

Fig. 3: System configuration of the vertical comparator

The digital level can be positioned in distance up to 30 m from the staff. Special care has been taken to illuminate the staff. Four lamps are used with a broad spectral range which was optimised to match the spectral requirements of the digital levelling equipment. The development of the vertical comparator has not been fully completed and some improvements are planned already.

In the next chapter results of the first investigations using this new vertical comparator are presented.

4. Digital levels tested

Two different types of digital levels have been tested: the Zeiss DiNi10 and the Leica NA3000 and NA3003. Technical details of the two digital levels are summarised in Table 1, and further technical details can be found in the publications [4], [5] and [6].

	ZEISS DiNi10	LEICA NA3003
Code field	0,3 m	2°
Measuring range	1,5 – 100 m	1,8 – 60 m
Setting accuracy of Compensator	0,2″	0,3″
RMS of 1 km double run levelling	0,3 mm	0,4 mm
RMS of single pointing, good atmospheric conditions		5 m : < 0,01 mm 10 m : 0,01 mm 20 m : 0,03 mm 30 m : 0,05 mm

Table 1: Specifications of the digital levels tested

There are several important differences between the two levelling systems which were tested. The code field measured by the Zeiss level is 30 cm independent of the distance, whilst the Leica level uses an angle of two degrees. For the fine measurements the Zeiss level uses 15 black and white intervals, however, the Leica level uses for this purpose a correlation function. This correlation function depends on two variables: the distance to determine the scale of the staff image and the staff reading for obtaining the required codeshift. Another important difference is that the basic interval of the Zeiss code is 20 mm, with some coded elements in it, whilst the basic chip length of the Leica code is 2.025 mm.

5. Results

The final result of a calibration test is the variation of height deviations which are calculated as the differences between the vertical comparator readings and the digital level results. These deviations can be considered true measurement errors of the digital levelling system.

The Zeiss DiNi10 was analysed with a 2 m staff, and distances between 10 and 25 m were used. Fig. 4 shows the true deviations of these test runs. The range of the true deviations is less than 0.1 mm with a very uniform pattern at all distances used. The staff readings were sampled with an interval of 10 cm. The RMS is calculated for each of the distances and the overall RMS is about 0.02 mm.

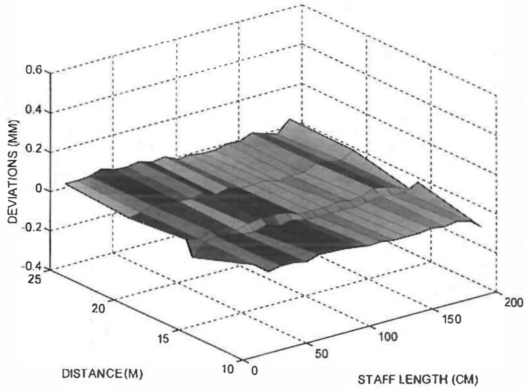

Fig. 4: Deviations of DiNi10 level readings

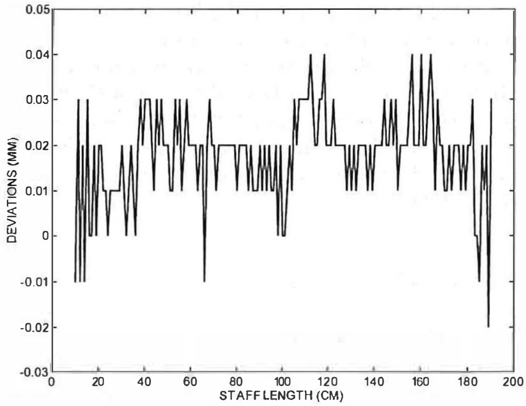

Fig. 5: Deviations of DiNi10 results at a distance of 20 m and sampling interval of 10 mm

It is of some concern that the staff readings were sampled at the rather arbitrary interval of 10 cm, and therefore larger but undetected deviations could still be hidden inside the 10 cm intervals. Thus the measurements were repeated with a 10 mm interval (Fig. 5). Additionally an interval of 0.5 mm was used which means that the staff is shifted after every measurement by 0.5 mm. This result shows a range of 0.06 mm for the true measurement errors and there is no pattern apparent in these results. In summary, the calibration tests fully confirmed the specification of the Zeiss DiNi10.

The Leica levels NA3000 and NA3003 were tested using a 3 m invar staff and again a distance range from 10 to 25 m at certain intervals. The results (Fig. 6) show a rather large deviation at a distance of 14.97 m. This effect was already discussed in a previous publication [7]. The reason for this effect is that at the distance of 15 m the picture of the code chip length of 2.025 mm is very close to the pixel length of 25 μm of the linear array. Therefore a problem occurs at that particular distance. The "sharpness" of this effect is of practical interest and therefore tests were carried out at several distances between 14.9 and 15.1 m. The effect disappears rather rapidly by moving away from the 14.97 m distance value. This is shown as the rather "flat area" before the "15 m effect" in Fig. 6. Larger deviations also occurred at a staff height of 2 m whose origin could not be clarified at the time of writing this paper.

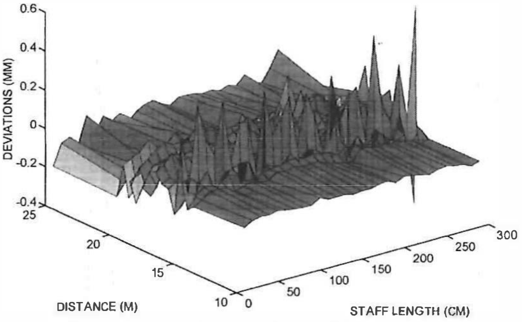

Fig. 6: Deviations of NA3000/3 readings

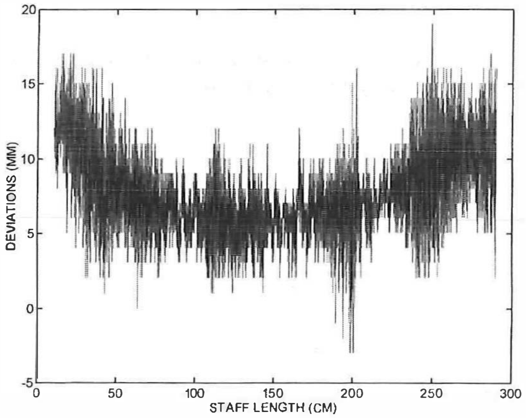

Fig. 7: Deviations of NA3000/3 results at a distance of 19 m and sampling interval of 2 mm

The results shown above were sampled using a 10 cm interval, which used to be the "standard sampling rate" at the time of these tests. However, as already mentioned above, it has been decided to sample at much shorter intervals because the 10 cm sampling interval may not reveal the full "picture". The fundamental Shannon's sampling theorem states that the full information of a signal can only be obtained if the signal is sampled faster than twice the highest frequency of the signal. Fig. 7 shows the result of the 2 mm sampling of the height deviations at the distance of 19 m. An enlargement of this figure revealed a clear periodic oscillation. Of course the sampling rate of 2 mm might still not be the correct value, because there could be an aliasing effect present. Therefore it was decided to sample at intervals of 0.7 mm and 0.25 mm. Fig. 8 shows the results of both measurements which demonstrate clearly that the results are independent of these two sampling rates. Therefore the smallest period of this periodic oscillation of the true deviations was found to be 2.5 mm with an amplitude of 0.15 mm. The power spectrum shows (Fig. 9) a definite peak for this particular measurement result.

Fig. 10 summarises the power spectra measured at different distances which show significant periods of 1 mm to 3 mm. The amplitudes

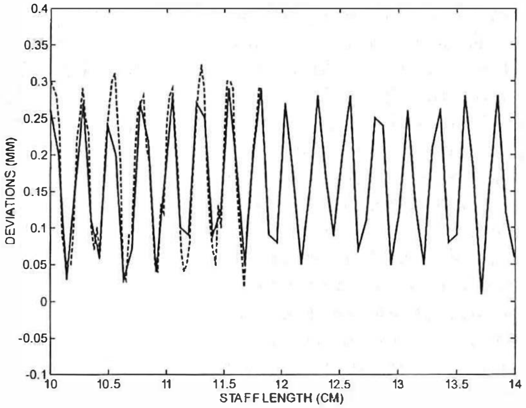

Fig. 8: Deviations of NA3000/3 results at a distance of 19 m and sampling interval of 0.7 mm and 0.25 mm

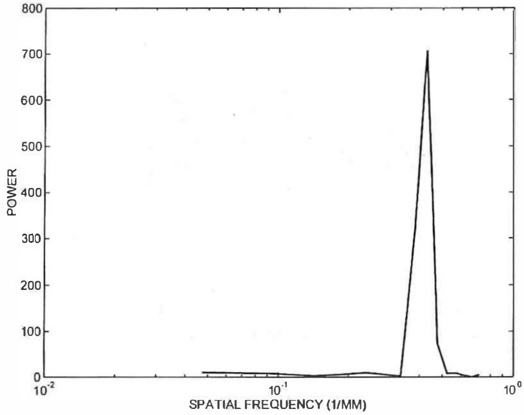

Fig. 9: Power spectrum of NA3000 results at a distance of 19 m and sampling interval of 0.7 mm

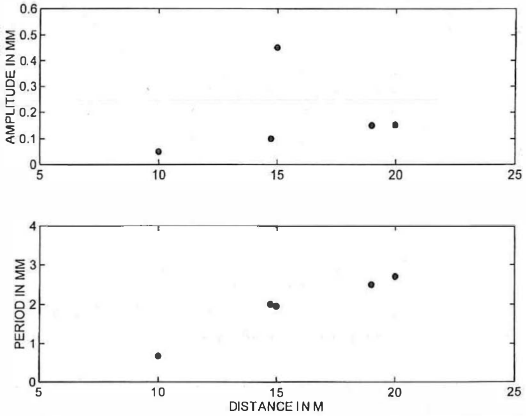

Fig. 10: Summary of power spectra for the NA3000/3 results

of these periodic oscillations are below 0.2 mm except at a distance of 15 m.

The important question is what causes such periodic oscillations in the results. There is a certain agreement of the 2.025 mm code chip length and the pixel size of the linear array. Therefore by forming the correlation function of the image and the code a new periodic function might be created. It has been suggested (H. Ingensand, personal communications) that by working in the open air this effect disappears because atmospheric turbulence randomises the effect. In order to test this explanation an experiment was carried out in the open air. The results of this experiment (Fig.11) show that the periodic pattern which was detected in the measurement laboratory also occurred using an open air propagation path.

6. Discussion

For the sight length of 20 m and a staff length of 2 m the calibration results under laboratory conditions yielded a RMS of ± 0.017 mm for the Zeiss DiNi10 levelling system and a RMS of ± 0.032 mm for the Leica NA3000 levelling system. These values are to be considered preliminary results as only one (Zeiss) and two (Leica) instruments have been tested so far.

A periodic oscillation of the true deviations of NA3000/3 levelling system was discovered. The amplitudes and periods of this periodic effect are distance dependent. Fig.10 shows maximum values of 0.2 mm for the amplitudes of this periodic effect if the values at the distance of 14.97 m are excluded. In view of this result, it appears necessary to explain the RMS of double run levellings as quoted in Table 1. Considering the periodic nature of the deviations, the RMS in a single staff reading, σ_i, needs to be calculated using an uniform probability density distribution. Using an amplitude of 0.2 mm, σ_i is calculated as $\sigma_i = 0.2/\sqrt{12} = 0.06$ mm. For an average sight length of 25 m, the RMS of 1 km double run levelling is calculated as $0.06\sqrt{20} = 0.27$ mm. This

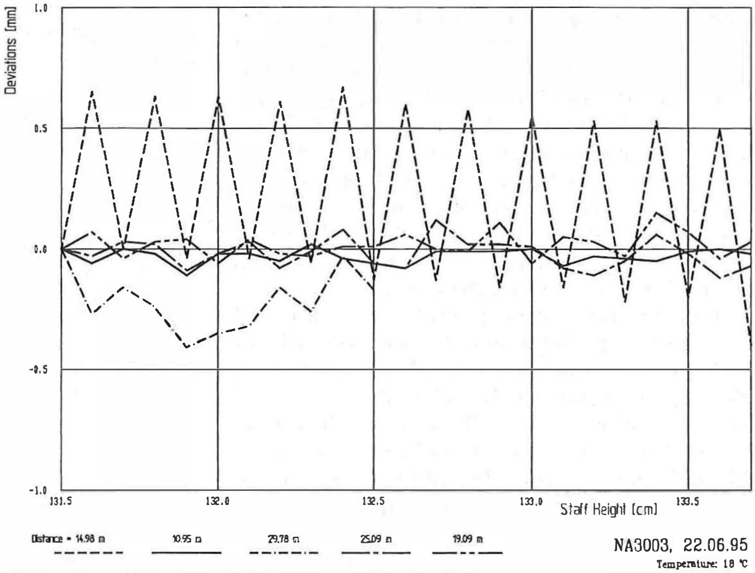

Fig. 11: Results with the NA3003 level in an open air environment

result is in agreement with the appropriate specification of line levelling as shown in Table 1 for the NA3003, which have been fully confirmed by all known practical measurements, e.g. [2]. However, the specifications for individual staff readings (Table 1) could not be confirmed by the calibration tests due to the periodic effect present in the true deviations of the NA3000/3 results. These results are summarised in Fig. 10. Therefore the accurate measurement of small height changes as frequently required in industrial applications would be affected by this periodic effect.

The periodic effect of the NA3000/3 equipment which was discovered by the present investigation raises also the fundamental question about the choice of the proper sampling interval for the calibration of a digital levelling system. Shannon's sampling theorem requires the sampling period to be shorter than half the shortest period of the signal which is represented by the true deviations of the height reading in the present case. Fig.10 also allows to determine the required sampling period using the appropriate periods of the periodic effect as a function of distance.

Acknowledgements

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Austrian Geoid 2000

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Abstract

By the impact of the relative GPS accuracy of 1 ppm to 0.1 ppm (for longer baselines), the Austrian geoid with its present mean accuracy of about 1 ppm is no longer considered to be sufficiently consistent. For this reason, a new computation of the Austrian geoid was initiated with the objective to obtain a relative accuracy of at least 0.5 ppm throughout the country. The project is denoted as Austrian Geoid 2000 to indicate that the resulting product is intended to survive the turn of the century.

The new computation of the Austrian geoid will be performed by three approaches, (1) the conventional least squares collocation method, (2) the fast collocation method which implies gridded input data and a symmetric block Toeplitz matrix for the covariance function, and (3) the gravimetric solution by the Fast Fourier Transform based on either a planar approximation or a spherical approach for the kernel functions.

As far as Austria is concerned, the data input consists of a 50 × 50 m digital terrain model, some 30.000 gravity data, about 700 deflections of the vertical, and GPS derived points. From the neighboring countries, gravity and height information is available in different quality and density.

1. Least squares collocation today

Slightly more than a quarter of a century ago, the estimation of linear functionals of the anomalous potential based on heterogeneous and noisy gravity data, one of the key problems in physical geodesy, was not yet solved. The mathematical solution of this problem was given by [6] and extensively elaborated by [8] and other scientists and is known as "least squares collocation" (LSC).