Development of a Vertical Comparator for System Calibration of Digital Levels

Helmut WOSCHITZ and Fritz K. BRUNNER

Abstract

Today, digital levels are commonly used in precise levelling. Every level at the market has its specific error pattern, and knowledge about this is essential to obtain precise height readings. To identify and investigate the error pattern of digital levels, a vertical comparator was developed at the Graz University of Technology. System calibration is used to calibrate the level and the staff together. This paper reports about the design of and experiences with the vertical comparator. The standard uncertainty of this comparator is ±3µm (computed in accordance with GUM, k=2). The vertical comparator can be used for both, the quality control of digital levels and the routine system calibration which also yields the scale value of the system.

Zusammenfassung

Heutzutage werden zur Übertragung von Höhen hauptsächlich Digitalnivelliere verwendet. Bei Präzisionsanwendungen ist die Kenntnis über das Verhalten des verwendeten Nivelliersystems notwendig, um unverfälschte Höhenwerte zu erhalten. Um das Verhalten von Digitalnivellieren bestimmen und untersuchen zu können, wurde an der TU Graz ein Vertikalkomparator entwickelt. Die Methode der Systemkalibrierung wird angewendet, bei der im Kalibrierprozess das Nivellier und die Latte gemeinsam verwendet werden. In der Arbeit wird über die Entwicklung des Komparators und die Erfahrungen mit diesem berichtet. Die Messunsicherheit des Komparators beträgt ±3µm (bestimmt nach GUM mit k=2). Mit dieser hohen Genauigkeit eignet sich der Komparator für die Qualitätskontrolle von Digitalnivellieren, aber auch für die Routinekalibrierung, in der auch der Maßstab des Systems ableitbar ist.

1 Introduction

Currently, there are three different makes of digital levels available for precise levelling. They are manufactured by Leica, Topcon and Trimble (formerly Zeiss). All three makes have a resolution of 0.01mm and are commonly used with invar staffs of e.g., 3m length. The digital code and the associated technique to evaluate the pixel image are brand dependent. Algorithms used for the calculation of the staff reading are correlation, geometric averaging and Fourier analysis. A survey of the different measurement techniques was given by [1] and a detailed description by [2].

Extensive tests are carried out by the manufacturer before the release of a new digital level. However, every level at the market has its specific error pattern. So, independent tests are essential to establish appropriate measurement procedures and to define the attainable accuracy. It is thus essential to establish and operate a few independent calibration laboratories [3]. Here, university departments have an important role to play. Their investigations have already shown weaknesses of instruments and lead to improvements.

Digital levels calculate the staff reading by processing the image of the coded staff which propagated through the atmosphere and the optical elements of the level. To assess the influence of defective system components (equipment, software) on the measurement result, [4] suggested to use system calibration. For levels, the basic idea is to carry out a height reading with the level, move the staff by a known amount, carry out another height reading, and so on. The performance of the whole system can be derived from the differences of the height readings by the level and the true height changes.

At the Graz University of Technology (TUG) a calibration facility for digital levelling systems has been developed. Its original design was described by [5]. An assessment of the required accuracy showed that the comparator must perform at the micrometer level. Thus a complete redesign of the calibration facility became necessary to achieve this high precision. Special features of the TUG comparator are the mounting of the staff in its position of use (thus called "vertical comparator") and the possibility to use sighting distances between 1.5m and 30m.

Using the vertical comparator at TUG, we have investigated the error pattern of the available digital levels [6]. In addition, we could show that system calibration is capable of determining the composite scale value of the staff and the level [7].

Currently, several institutions are considering to build a vertical comparator. Therefore here, we give a detailed report about the design of the vertical comparator at TUG. The hardware components are described in chapter 2, and the peripheral equipment for e.g., acquisition of meteorological data, in chapter 3. The vertical comparator system software is summarised in chapter 4 including a description of the calibration procedure. Finally, in chapter 5 the uncertainty of measurement using the comparator is estimated.

2 Design and Hardware

The performance of levelling systems depends on various factors, e.g., temperature, illumination, sighting distance. When testing an instrument, only one of these factors should be varied during the experiment to investigate the system's response. For system calibration, the height readings are varied by changing the staff's position. All other parameters should remain unchanged. This can be achieved in a laboratory.

At the TUG the Geodetic Metrology Laboratory (GML) was established during the last decade. The laboratory has a size of 33.2 x 6.3 x 3.5m^3 and is climatically controlled (temperature: 20.0°C ± 0.5°C, humidity: 50% ± 10%). The GML is situated on the ground floor of a building and its foundation is completely separated from the foundation of the building. Thus movements of the building induced by temperature, wind or traffic are reduced. Only artificial and therefore reproducible light is used in the GML.

The two photographs of the vertical comparator (fig. 1) provide an impression of the calibration facility.

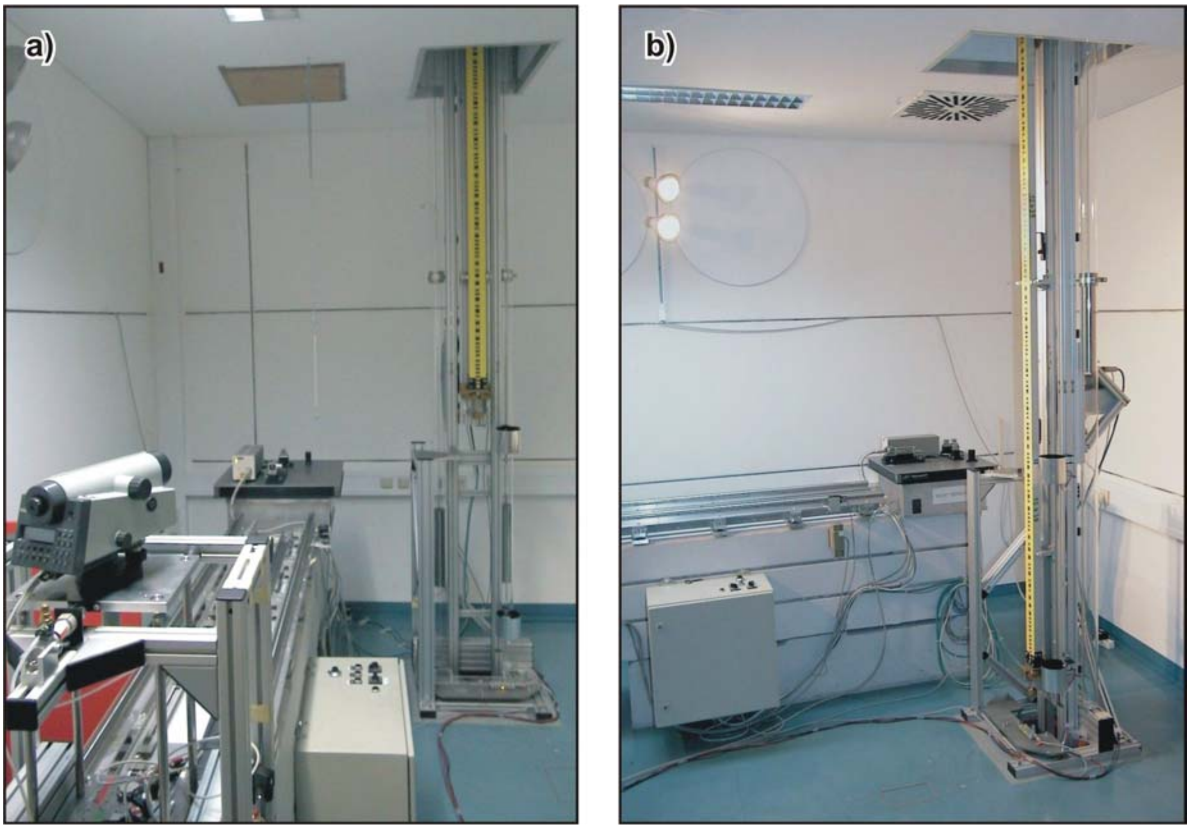


Figure 1: Overview of the vertical comparator showing (a) the level and (b) the staff illumination assembly.

The main parts of the comparator are: (1) a carriage for the level, (2) the frame of the comparator with a carriage moving the staff vertically, (3) the laser interferometer to measure the position of the staff, (4) the staff illumination assembly, and (5) the comparator system software, installed on a standard PC. Fig. 2 shows the vertical comparator schematically.

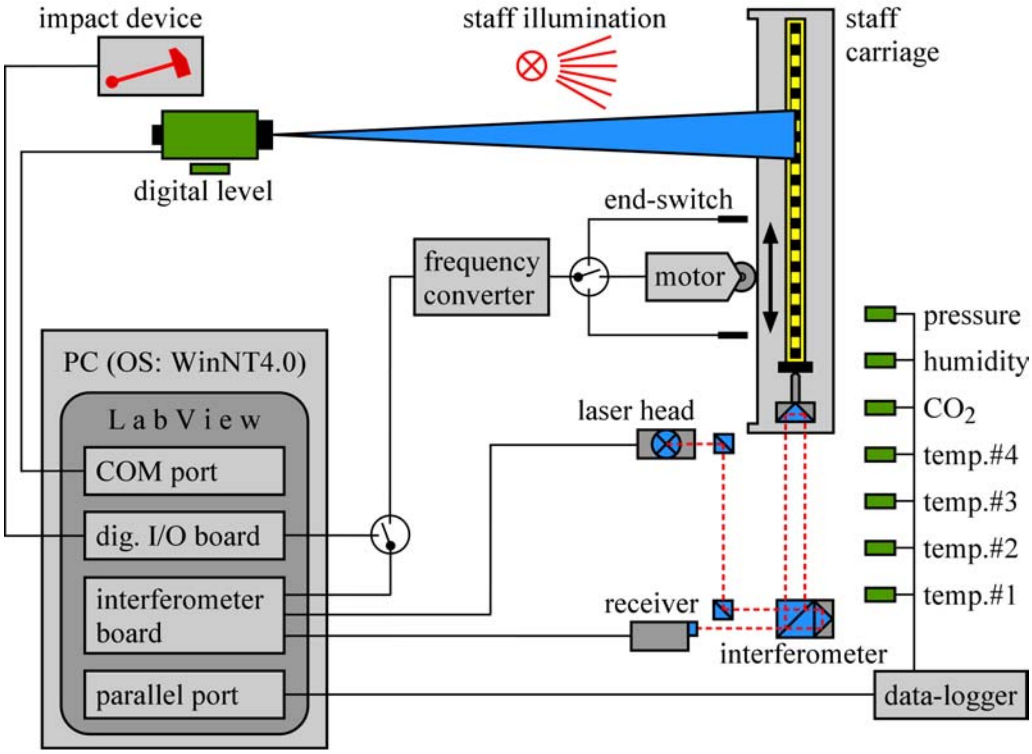


Figure 2: Components of the vertical comparator.

2.1 Carriage of the Level

The digital level is mounted onto a carriage in order to position the level along the concrete bench (see fig. 1a) at various distances from the staff. Sighting distances between 1.5m and 30m are possible for an unobstructed line-of-sight. This distance range is considered sufficient for calibrating digital precision levels.

The carriage consists of a wheel system and two separate frames (see fig. 3). Four invar rods are used for the inner frame on which the level is mounted. Invar is used to keep the level at a constant height independent of small temperature variations during the whole calibration process. The second frame, made of robust aluminium profiles, surrounds the invar frame, see fig. 3. It is used to mount additional equipment, as for example, a pneumatic impact device. This impact device is optionally used to activate the level's compensator before each measurement for the investigation of the compensator's behaviour.

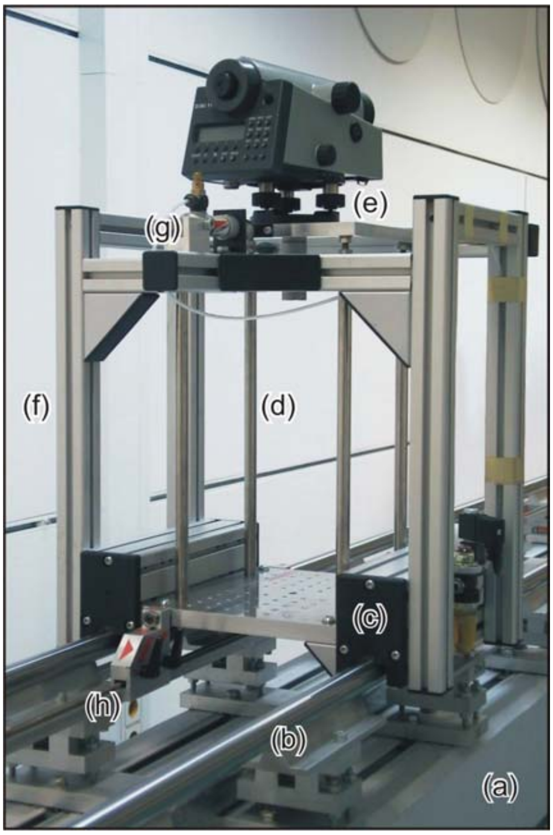


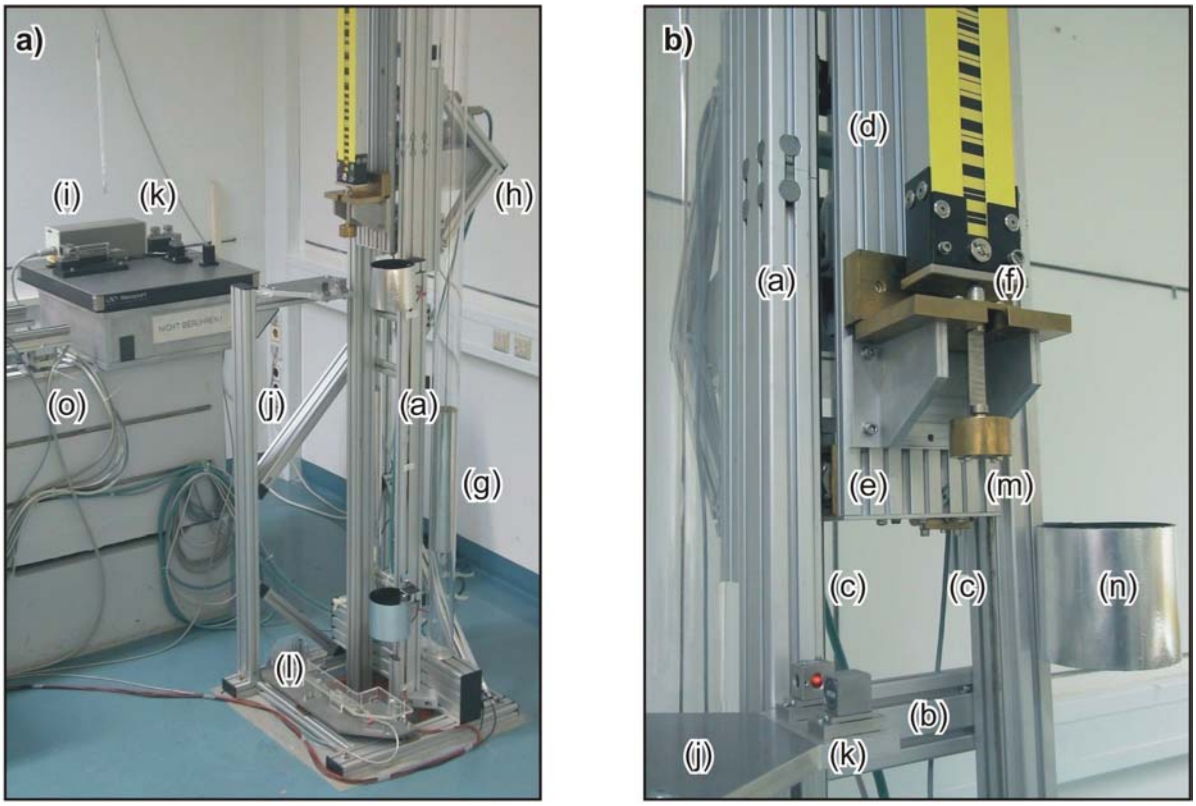
Figure 3: Level carriage: (a) 30m concrete bench, (b) rail system, (c) wheel system of carriage, (d) invar rods, (e) fastening plate of level, (f) aluminium frame, (g) impact device, (h) displacement protection.

2.2 Comparator Frame and Staff Carriage

For the calibration of 3m long invar staffs, a vertical frame of more than 6m in height is needed, reaching 3m above and below the level's line-of-sight. A shaft into the foundation (fig. 4a) and an insulated shaft through the ceiling of the GML had to be built in order to make room for the 6.5m tall assembly. The frame consists of aluminium profiles and is fixed to the foundation of the laboratory, see fig. 4a. As the comparator frame and the 30m concrete bench are on the same foundation, they cannot move differentially to each other. Consequently, the interferometer and the level's line-of-sight stay fixed in space which is a pre-requisite for the construction of a comparator. At the ceiling, the frame is guided only - not mounted - to keep it free of tensions. The guiding device at the ceiling is used to adjust the comparator to its vertical position.

The invar staff is mounted to a 3.4m long carriage. The carriage can be moved along two rails using a wheel assembly which is driven by an AC motor. The control signal for the motor is generated by a frequency converter coupled to the interferometer board.

The invar staff is set up on a bolt, see fig. 4b, and mounted to the carriage using two mounting brackets. These brackets allow the rotation of the staff by ±90° which can be used to direct the staff towards the level, when needed. The rotation axis coincides with the plane of the staff's invar band as well as the centre of the set-up bolt which is exactly below the invar band.



(a) comparator frame
(b) cross-beam of frame
(c) rails
(d) staff carriage
(e) wheel of staff carriage
(f) bolt for staff set-up
(g) counterweight
(h) motor mount
(i) laser head
(j) beam bender frame
(k) beam bender
(l) interferometer bearing unit
(m)retroreflector
(n) temperature sensor
(o) 30m concrete bench

Figure 4: Vertical comparator's (a) lower part, (b) staff carriage.

2.3 Interferometer Hardware

The staff carriage is monitored by a Hewlett-Packard interferometer consisting of a Zeemann stabilised laser head (HP5517B), a HP10702A linear interferometer, a remote receiver HP10780F with a fibre optic cable, an interferometer board (HP10889B PC Servo-Axis board), and additional optical accessories.

The resolution of the linear interferometer system is specified as $\lambda/128$, the nominal wavelength λ of the laser being 633nm (rounded) with a specified vacuum wavelength accuracy of ±0.02ppm. To avoid a scale error, a calibrated laser head is used with a relative error of the laser frequency of 6.6×10^{-9}. For further details about particular interferometer measurements, reference is made to [8, p.86-122].

2.4 Interferometer Set Up

To adhere to Abbe's comparator principle (see e.g., [8, p.32]), the light path of the interferometer is adjusted to be in the same axis as the staff's invar band. The retroreflector is mounted at the lower end of the set-up bolt (see fig. 4b) which is also made of invar.

The interferometer is placed near the lower end of the bottom shaft, in the same axis as the staff's invar band. Due to the small diameter of the shaft and its inaccessibility, the interferometer had to be mounted on a platform that can be lowered into the shaft from the laboratory level. The main components of this structure are three invar rods of 1.8m length. The use of invar was necessary, because the temperature in the bottom shaft can be up to 6K lower than the air temperature of the laboratory (see fig. 5b).

All optical parts of the laser interferometer need to be properly aligned. The special design of the interferometer bearing unit and the arrangement of the components simplify this procedure. For the alignment of the laser beam also the beam benders outside the shaft may be used. These are mounted on a frame which is completely separated from the comparator's frame (see fig. 4a) to avoid any influence of a possible deformation of the comparator frame on the laser beam.

3 Peripheral Equipment

3.1 Staff Illumination

The current digital levels use CCD arrays which are sensitive in different regions of the spectrum. For the calibration of all types of digital levels, the illumination of the staff must cover the appropriate ranges of the spectrum. Four light bulbs (Phillips PAR38-EC) were chosen for this purpose. Two of them can be seen in fig. 1b.

Currently, the alternative use of a neon lamp (1.5m long and vertically mounted) is being investigated. It might be useful for special investigations, where a more homogeneous illumination is necessary.

3.2 Meteorological Equipment

The wavelength of the interferometer depends on the ambient air's refractive index which can be calculated using meteorological data. In the laboratory, the main influential parameters are temperature, air pressure, humidity and the carbon dioxide content of air.

For a distance accuracy of 0.1ppm the required accuracies of the meteorological equipment are: 0.1K for temperature, 0.37hPa for air pressure and 12% for relative humidity. The CO_2 content should be known to 680ppm. Details about the chosen meteorological sensors are described by [2].

Due to variability of the air temperature along the laser beam path four glass-covered Pt100 temperature sensors are used in different positions, see fig. 5a. The sensors are mounted to the frame of the comparator in a thermally isolated manner and protected from heat radiation (caused by e.g., the staff illumination) by a plastic cover, see fig. 4b. The accuracy of the temperature sensor is about 0.05K.

The other three meteorological parameters are measured at one position only (fig. 5a). The sensors have the following accuracies: 0.3hPa for air pressure, 3.5% for relative humidity, and 25ppm for CO_2 content. The temperature sensors were calibrated at 0°C and approx. 22°C, using a precision glass thermometer with a resolution of 0.01K. A laboratory mercury barometer with a resolution of 0.1hPa was used to determine the offset of the pressure sensor. For the humidity and CO_2 sensors the factory calibrations were used.

3.3 Representative Meteorological Parameters

Fig. 5a shows a cross section of the vertical comparator, with the interferometer being placed near the bottom of the shaft. Though the laboratory is climatically controlled, the temperature in the shaft is different. Compared to the temperature in the laboratory it is lower by up to 6K depending on the ground temperature. Fig. 5b shows an example of the measured temperature distribution near the laser beam path.

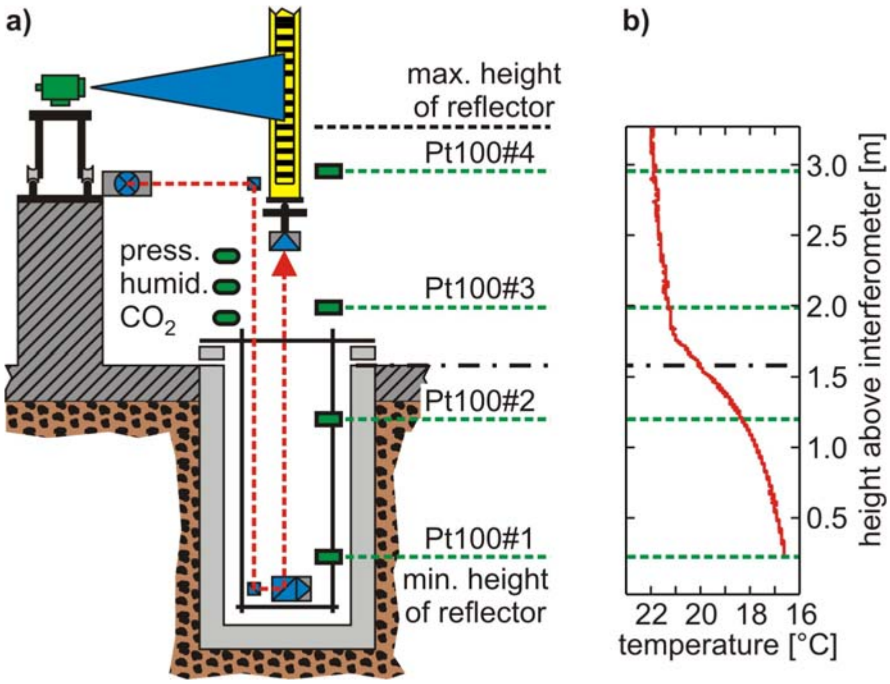


Figure 5: (a) Vertical comparator and distribution of sensors. (b) Measured temperature distribution.

The data of the four temperature sensors are used to approximate the vertical temperature distribution. Then, a single representative temperature value is computed for the actual laser beam path, depending on the position of the staff carriage. Similar to that, one representative value for the air pressure is computed, using the measured air pressure and the barometric height formula.

These values are used to calculate the refractive index of air and the proper atmospheric propagation correction for the laser path. The selection of the most accurate formula for the computation of the refractive index of air was investigated by [2]. Currently, the formula of [9] is used, however, it is planned to implement the resolution No.3 of IAG, 1999, see for example [10].

4 System Software

The vertical comparator system software (VCSS) is used for data acquisition and the control of the entire comparator. It was written using the graphical programming environment LabView5.0 and is installed on a standard PC running the Windows NT4.0 operating system. Drivers for the HP10889B interferometer board and for all current digital precision levels were developed. VCSS provides (a) an easy set up of a calibration run, (b) a fully automatic execution of the calibration, and (c) an output of a log-file which contains extensive information on the calibration run.

The initialisation of the system comprises also the input of the calibration parameters such as the type of level, the staff, and the positions of planned staff readings.

Before the calibration run can be started, a reference measurement with the level is needed to determine the distance between the interferometer and the staff at its initial position. Three modes are available for the reference measurement. Using the most accurate mode, the round-off error of the level is considered to yield a precision of the staff's position that is better than the resolution of the level.

Once the calibration run has been started, a PC window provides graphical information about the position of the staff, the positioning status, actual meteorological data and the level measurements, see fig. 6. The principal sequence of operation is as follows. Before the staff carriage is driven to a desired position, the refractive index of air is computed and the meteorological compensation factor of the HP10889B board is updated. Then the staff is moved to a specified position. Immediately afterwards, the HP10889B output signal is interrupted to ensure that the staff remains stable, whilst using the level. For the signal interruption a separate digital I/O board (National Instrument PCI6503) is used. The same board can be used to activate the impact device (see fig. 2). The program's execution is paused for half a second, before a position is read from the interferometer. This is done to avoid measurements possibly affected by an instability of the carriage due to oscillations. All the mechanical imperfections of the comparator's hardware cause a difference of 10 to 20µm between the carriage's settling position and the specified position. To obtain a positioning accuracy that is better than these values, several positioning trials are carried out until the positioning error is less than 2µm (i.e., current software setting), or a maximum number of trials is exceeded.

Whenever the level's impact device is activated, the program is paused to let the compensator settle down. Afterwards, the level measurement is started. An important quality control feature is the comparison of the interferometer readings before and after each measurement by the level.

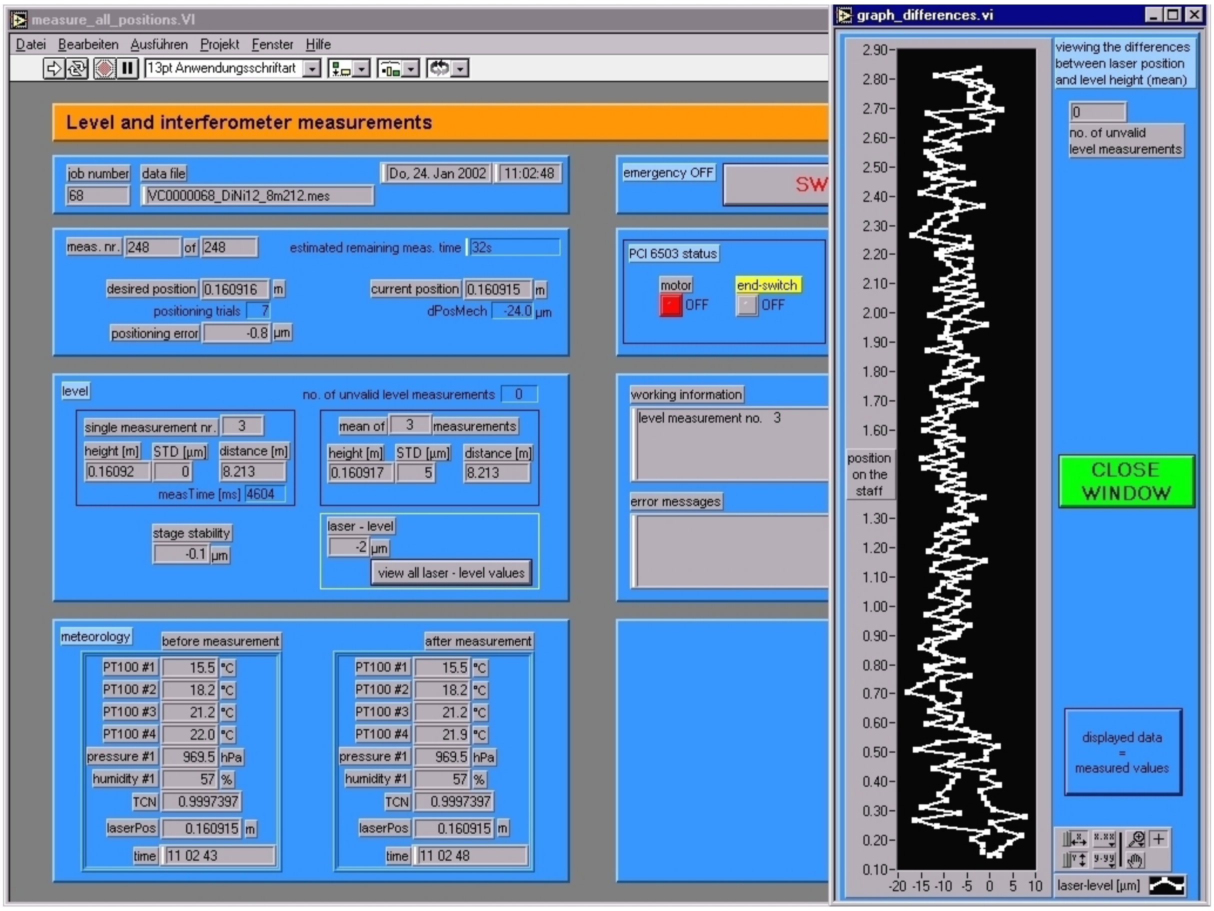


Figure 6: Snapshot of the vertical comparator system software's main window.

5 Standard Uncertainty of the Vertical Comparator

The fundamental measuring unit of the comparator is the laser interferometer with the frequency of the laser head defining the "metre". A basic assumption is that the relative position of the interferometer and the level remains constant during a calibration run. However, for example the thermal expansion of the interferometer bearing unit or of the level carriage, or a possible inclination of the laboratory's foundation might cause distortions which affect the measurements by the vertical comparator. The influence of some parameters may be eliminated by an adequate calibration procedure (e.g., [11]), however, a knowledge of the remaining influences is essential for quoting the comparator's uncertainty.

The ISO/BIPM "Guide to the Expression of Uncertainty in Measurement" [12] allows to estimate the uncertainty of the complex measurement system, taking into account also quantities that cannot be measured (e.g., [13]). First a model of the measuring process must be established. We start with the distance measurement *L* by the interferometer:

$$L = (C + \Delta C^{E} + \Delta C^{ON} + \Delta C^{OD}) \cdot \frac{\lambda}{R \cdot n} \cdot \cos a - \Delta L^{IS} + \frac{D}{\Delta n} \qquad (1)$$

Each term in eq. (1) is explained in tab. 1. To assess a vertical comparator measurement *H*, the external parameters of influence must be considered:

$$H = A - L - \Delta L^{S} + \Delta L^{LC} + \Delta L^{LOF} + \Delta L^{FC} \qquad (2)$$

Also the terms of eq. (2) are listed in tab. 1. Additionally, the estimates of the standard uncertainties of the terms are given in tab. 1. They were determined using the results of dedicated experiments. Where experimental values were not available, the values were assessed using experience or were obtained from literature. Some of the standard uncertainties listed in tab. 1 had to be estimated using the GUM procedure, e.g., the combined standard uncertainty of *n* which was determined using the uncertainties of the meteorological sensors, of the measurement and the formula used.

The "law of propagation of uncertainty" [12] was applied to eqs. (1) and (2) to determine the combined standard uncertainty $u_c(H)$ for an interferometer distance of 3m. In this paper, the partial derivatives of eqs. (1) and (2) are not explicitly stated. To determine the expanded standard uncertainty *U*(*H*) of a comparator measurement *H*, a coverage factor of *k*=2 was used, giving *U*(*H*)=±2.7µm. With this factor the level of confidence is approx. 95%.

Table 1: Description of terms and uncertainties.

Symbol	Description	Standard Uncertainty
C	number of counts measured by the interferometer	27.7counts
ΔC^{E}	interferometer electronic error	0.3counts
ΔC^{ON}	interferometer optics non-linearity	0.6counts
ΔC^{OD}	interferometer optics thermal drift	10.1counts
λ	wavelength of the laser head	0.01ppm
R	resolution of the interferometer	-
n	refractive index of air	0.13ppm
α	cosine error	1mm/3m
ΔL^{IS}	move of the interferometer due to thermal expansion of the interferometer bearing unit	0.8µm
D	deadpath distance	10mm
Δn	change of the refractive index during the calibration run	1.3ppm
A	comparator constant; vertical spacing between the interferometer and the level	-
ΔL^{S}	thermal expansion of the staff's invar band	0.6µm
ΔL^{LC}	thermal expansion of the level carriage due to temperature changes in the laboratory; causes a vertical move of the level	0.1µm
ΔL^{LOF}	change of the level's line-of-sight during a calibration run	0µm
ΔL^{FC}	inclination of the laboratories foundation concrete during a calibration run	0µm

The value 2.7µm determined by the GUM procedure is in excellent agreement with a prior assessment based on repetitive system calibration runs. So for example, using the data presented by [7], an overall accuracy of the TUG vertical comparator of better than 3µm was estimated.

6 Acknowledgements

We want to thank the Österreichische Nationalbank for partly funding the reconstruction of the vertical comparator, Leo Gruber for elaborating many constructive plans, and Robert Presl and Rudolf Lummerstorfer for their work to upgrade the vertical comparator.

References

[1] 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.

[2] Woschitz H (2003) System Calibration of Digital Levels: Calibration Facility, Procedures and Results. Shaker Verlag. In print.

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

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

[5] Reithofer A, Hochhauser B, Brunner FK (1996) Calibration of Digital Levelling Systems. Österr. Z. f. Vermessung und Geoinformation 74: 284-289.

[6] Woschitz H, Brunner FK (2002) System Calibration of Digital Levels - Experimental Results of Systematic Effects. In Kopáčik A and Kyrinovič P (eds.): Proc. INGEO2002 - 2nd Int. Conference of Engineering Surveying, Bratislava, November 2002: 165-172.

[7] Woschitz H, Brunner FK, Heister H (2003) Scale Determination of Digital Levelling Systems using a Vertical Comparator. Z. f. Geodäsie, Geoinformation und Landmanagement 128: 11-17.

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

[9] Bönsch G, Potulski E (1998) Measurement of the refractive index of air and comparison with modified Edlén's formulae. Metrologia 35: 133-139.

[10] Rüeger JM (2002) Report 1993-1999 of the Ad-Hoc working Party of the IAG Special Commission SC3 (on Fundamental Constants, SCFC) on Refractive Indices of Light, Infrared and Radio Waves in the Atmosphere. In Rüeger JM (2002): Refractive Indices

of Light, Infrared and Radio Waves in the Atmosphere. University of New South Wales, Unisurv Report S-68, 2002: 55-80.

[11] Rüeger JM, Brunner FK (2000) On System Calibration and Type Testing of Digital Levels. Z. f. Vermessungswesen 125: 120–130.

[12] ISO/BIPM (1995) Guide to the Expression of Uncertainty in Measurement. International Organisation of Standards, Switzerland.

[13] Heister H (2001) Zur Angabe der Messunsicherheit in der geodätischen Messtechnik. In Heister H und Staiger R (ed.): Qualitätsmanagement in der Geodätischen Messtechnik. Konrad Wittwer Verlag, DVW Schriftenreihe 42: 108-119.

Author's address

Dr. Helmut Woschitz, Univ.Prof. Dr. 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: helmut.woschitz@tugraz.at, fritz.brunner@tugraz.at
Web site: http://www.cis.tugraz.at/ivm