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**System Calibration
of
Digital Levels:
Calibration Facility, Procedures
and Results**

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Abstract

Since the first digital level was introduced to the market in 1990, digital levelling has become widely accepted for transferring heights, mainly because of the automated measuring process and higher productivity. Today three manufacturers offer digital precision levels.

A Level Simulator was developed to better understand the instruments' processing techniques and their dependencies on various influences and to derive the necessary information for their calibration. The processing techniques of the Leica, Topcon and Trimble/Zeiss levels are implemented. Measured pixel images may be processed as well as simulated images, where diffraction, distortion, vignetting, blur or pixel cross-talk are considered for example. Background knowledge achieved by developing the Level Simulator is used to describe the different height computation techniques.

Within the last years, calibration facilities were established to calibrate the level and the staff together by means of system calibration. The

existing vertical comparator at the Graz University of Technology was intensively investigated with the goal to make it more accurate. Rebuilding parts of the existing comparator improved its stability by a factor of about 30. A new comparator system software with a graphical user interface was developed to allow fully automated control of the whole calibration process.

The newest types of digital precision levels including the latest software versions were type tested using the vertical comparator. Their performance is shown for different sections of the staff in a distance range that is commonly used in precise levelling. The dependency on the individual level is shown as well as height errors caused by damaged staffs. All investigated systems show a variety of significant height deviations. Some effects were already known, others were discovered by this study. The application of the Level Simulator provides for the first time the insight about the cause of certain effects: processing technique or image acquisition device of the digital level.

So far, system calibration was not considered capable of determining the scale value of the system. One difficulty is the resolution of the height readings that are currently restricted to $10\mu\text{m}$. It was theoretically derived, how many measuring points are needed to compensate for this disadvantage. Another difficulty concerns the sampling of the height readings for the calibration process. The selection of the proper sampling interval is derived and verified by the analysis of simulated and calibration data. Finally, experiments prove that the scale value of the digital levelling systems can be determined with sufficient accuracy using system calibration.

Zusammenfassung

Seitdem 1990 Digitalnivelliere auf den Markt gebracht wurden, erlangte die digitale Nivelliertechnik weitgehende Akzeptanz bei der Übertragung von Höhen. Derzeit werden von drei Herstellern Präzisions-Digitalnivelliere angeboten.

Ein Nivellier-Simulator wurde entwickelt, um die von den Nivellieren verwendeten Auswertetechniken besser zu erfassen und Erkenntnisse für die Kalibrierung der Geräte abzuleiten. Die Auswertetechniken von Leica, Topcon und Trimble/Zeiss sind im Simulator implementiert. Es können sowohl gemessene als auch simulierte Pixelbilder ausgewertet werden. Bei der Simulation der Bilder werden verschiedene physikalische Effekte wie beispielsweise Beugungserscheinungen, Verzeichnung, Vignettierung, Unschärfe oder Pixelübersprechen modelliert. Basierend auf den bei der Erstellung des Simulators erworbenen Erkenntnissen, wurden die drei verschiedenen Auswertetechniken beschrieben.

Zur Systemkalibrierung von Digitalnivellieren wurden in den letzten

Jahren verschiedene Kalibrieranlagen entwickelt. Die an der TU Graz existierende Anlage wurde mit dem Ziel die Genauigkeit zu steigern untersucht. Durch umfangreiche Umbauarbeiten konnte eine Steigerung der Genauigkeit um den Faktor 30 erreicht werden. Zusätzlich wurde eine neue Komparator System Software entwickelt, die einen vollautomatischen Kalibrierungsablauf gewährleistet.

Mit dem Vertikalkomparator wurden die neuesten Digitalnivelliere mit der neuesten Systemsoftware getestet. Das Verhalten der Nivelliersysteme wurde für verschiedene Bereiche der codierten Latte in einem Distanzbereich von 1.5m bis 30m gezeigt, der bei Präzisionsmessungen nicht überschritten wird. Des weiteren wurden Verhaltensunterschiede einzelner Geräte desselben Typs entdeckt und alle drei Systeme mit zerkratzttem Lattencode untersucht. Bei den vielen Detailuntersuchungen wurden einige neue Effekte gefunden. Die Analyse mit dem Nivellier-Simulator erlaubt zum ersten Mal, Schlüsse über die Ursachen der Effekte zu ziehen. Manche können durch die verwendete Auswertetechnik der Nivelliere, andere durch die Unzulänglichkeiten des Abbildungssystems des Nivelliers erklärt werden.

Bisher wurde die Systemkalibrierung hauptsächlich zur Feststellung des Systemverhaltens, nicht aber zur Maßstabsbestimmung verwendet. Dies wurde bisher von Kritikern der Systemkalibrierung nicht für möglich gehalten. Gründe dafür liegen in der beschränkten Höhenauflösung der Nivelliere (derzeit $10\mu\text{m}$), die zu Quantisierungseffekten führt. Eine weitere Schwierigkeit tritt auf, wenn das Nivelliersystem kurzperiodische Höhenschwankungen aufweist, da bei der Kalibrierung im allgemeinen das Shannon'schen Sampling Theorem missachtet werden muss, um kurze Messzeiten realisieren zu können. Es werden Bedingungen für die Wahl des geeigneten Abtastintervalls abgeleitet, die eingehalten werden müssen, um eine geforderte Genauigkeit zu erreichen. Diese werden anhand von simulierten und gemessenen Daten verifiziert. Schließlich wurde mit einem Vergleichsexperiment zum ersten Mal bewiesen, dass der Maßstab mittels Systemkalibrierung mit einer Genauigkeit im 1ppm Bereich bestimmt werden kann.

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At this part of the thesis I want to thank all people, who assisted me in preparing the work and helped in its realisation.

Prof. Fritz K. Brunner, my advisor, acquired and provided always the financial resources to rebuild the vertical comparator. When investigating the existing comparator, we discussed many micrometer effects. Effects, that appear inconsiderable when measuring on a global scale, but are essential when calibrating digital levels with their 10 μ m resolution. His proposals were always a valuable enrichment in the design phase, later in the realisation and for writing the thesis.

Dr. Horst Hartinger proposed me to get a job at the university and therefore made it possible to do my research works at this institute with its excellent laboratory.

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My university colleagues Georg Gassner, Werner Lienhart, Dr. Andreas Wieser and Fritz Zobl exculpated me from teaching and project work within the last few months. So I could close the door of my room, keep dreaming of the microns and writing about them.

Our secretary Sandra Schmuck spent endless time in copying the literature I was interested in and was always friendly doing the jobs I asked her to do.

With Prof. Rüeger I had extensive discussions about the Topcon code and their instrument. Prof. Heister didn't get tired about philosophising with us about the micrometer-world. He helped us to prove the capability of system calibration for scale determination, provided me his DL101C to evaluate the discovered effects and always was willing to help me.

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