A new CCD-based Technique for the Calibration of Leveling Rods

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Key words: invar rod calibration, comparator, edge detection, interferometry, DIN18717, precise leveling

SUMMARY

At the Geodetic Laboratory at the Technical University Munich (TUM) there are the most advanced calibrators for precise leveling invar rods. They are equipped with a laser interferometer as a reference, and with an CCD array camera to detect the bars on the rod scales.
The technical setup, which was initially developed at the Chair of Geodesy at the TUM and is now state-of-the-art, is explained in this article. Further on, the concept of image acquisition and detection of graduation bar edges is shown.
Due to the wide field of view nearly the whole graduation width can be observed. The scale of the graduation therefore can be measured for different areas in only one working step, so differences or inhomogeneities of the scale due to manufacturing tracks can be identified very quickly and easily. The influence of rod scale variations with respect to other measurement influences is shown.
Furthermore, additional photographic information from the measurement system can be used e.g. to measure the graduation bar slopes or for documentation purposes.
The calibrators can not only be used for leveling rods, but also for various other objects like subtense bars.
In addition to the rod scale, also other parameters of the rods can be determined at the calibrators: the index correction of the rod and the thermal extension coefficient, which is measured in a climate chamber.

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1. INTRODUCTION

Even in the days of automatic measurement methods like GNSS, the method of geodetic precise leveling is still up-to-date. It is used to establish height reference systems (local or of first order, as will be done at the Deutsches Haupthöhennetz DHHN92 in the next years), for planarity measurements, for monitoring and evidence preservation purposes at construction sites.
Due to their high accuracy, the results of precise leveling often are of interest for actions with economic relevance both for the building promoter as for the surveyor.

As all other geodetic instruments, levels and leveling rods are high-precision tools which accordingly have to fulfill high standards.
The leveling rod as the carrier of the used scale is thereby of special interest, because precise height transportation only is possible with respect to its actual relation to the legal meter [Staiger 05].
The comparison of the rod scale with international standards in terms of the ISO 9000 has to be accomplished by periodical calibrations. According to the DIN 18717 it must be examined

- the rod scale: comparison of the legal meter and the graduation scale of the rod
- the thermal expansion coefficient: leads to a shortening or elongation of the rod and therefore to scale changes induced by a change of material temperatures
- the index correction: the difference between the set-up point and the origin of the scale
- the ground surface error: the difference of the standing area of the rod from the rectangularity to the graduation

The DIN 18717 regulates an invar tape with a thermal expansion coefficient α of less than $1 \cdot 10^{-6}\ K^{-1}$ for precise leveling rods. Additionally, for an arbitrary part of the scale, it must not differ more than $\Delta l = \pm\ 0.02\ mm + 2 \cdot l \cdot 10^{-5}$ (in [mm], where l is the rod length in [m]) from the real height difference, regardless if it's a digital barcode or analog rod.
Given a 3m-rod, this leads to a maximum deviation of 0.08 *mm*.
For the index correction the instruction shows a maximum deviation of 0.05 *mm* measured with respect to the first decimeter of the scale.

For the determination of the values mentioned in the DIN 18717 (respectively their international equivalents), since 1975 [Schlemmer 1975] comparators were developed at several institutes in the German-speaking countries, and also in Ljubljana (Slovenia), Delft (Netherlands, no longer used) and Stanford (USA).
They mostly work with a laser interferometer as a superior measurement standard, and since the beginnings with an optical microscope which either has to be focused on the graduation marks manually or with automation using a photoelectronic one.

These configurations are suited for the detection of narrow graduation tracks along the rod, additional information regarding the whole width of the graduation tape can be determined not at all or only by many discrete measurements.

In recent years the systems are increasingly altered to be used with CCD cameras; the first system with a line sensor is in use at the ETH in Zurich since 1995 [Schmid 95].
At about the same time [Friede 00] dealt theoretically with the new technique in Munich, the practical implementation started in the years 2001/2002, when also an increasing distortion of the microscope downgraded the results of the existing comparator visibly.
The modification was finished in 2004, together with a complete alteration of the hardware components and analysis algorithms.
Today the TU Munich has the two most advanced calibrators for leveling rods world-wide; the basic principles and applications are shown in this article.

2. THE CALIBRATORS AT THE GEODETIC LABORATORY AT TU MUNICH

2.1 The comparator design

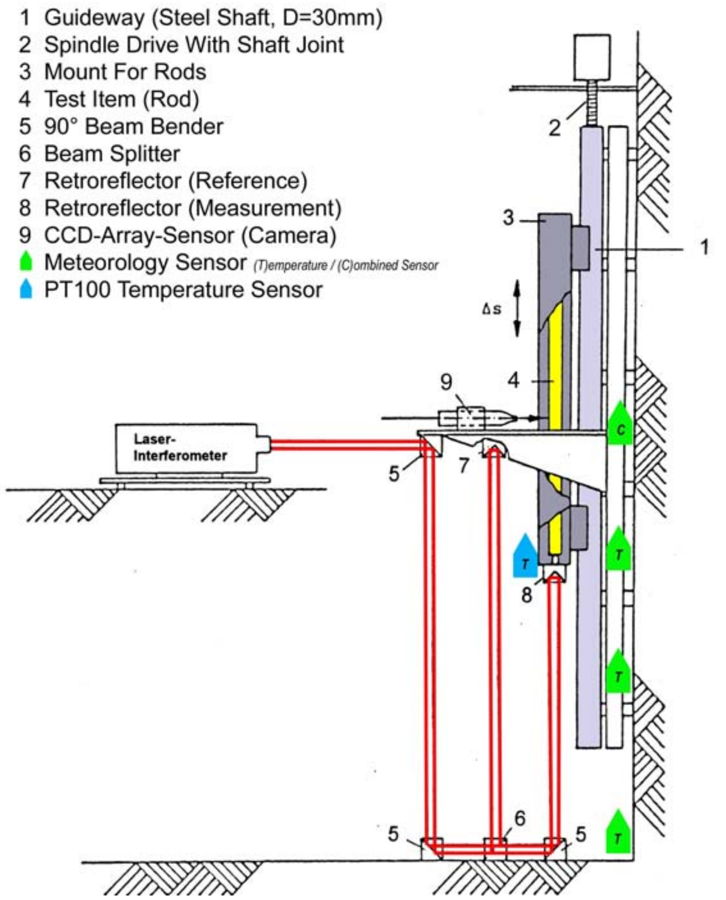

Fig.1 The design of the vertical calibrator at the Geodetic Laboratory at the TU Munich

The guideway for the rods was established in an former elevator shaft (Fig. 1). It is driven by a digital 3-phase servo motor with programm-able processor. Thus the control of various movements and downlocks is done on the hardware and without charging the controling computer.
The detection of the graduation bars is done with an object-sided telecentrical 2M-pixel CCD array camera, the recording of the related interferometer values is started via a high-speed real-time trigger together with the expo-sure.
To assure homogeneous illumi-nation on the whole graduation, a pulsed circle LED flashlight is used, whereas the pulse time of the flash at the same time is used as the exposure time of the camera (Fig. 2).
The reference retroreflector of the interferometer (accuracy 0.1 μm)

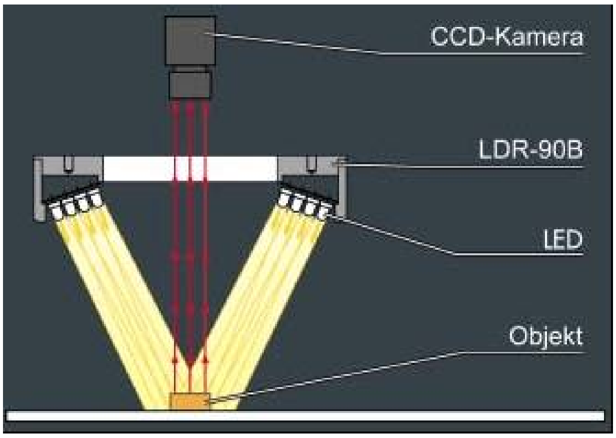

Fig. 2 Object illumination with an LED circle flaslight [Stemmer 06]

is mounted on the ground plate of the camera, so that possible movements of the whole measurement unit (e.g. due to day movement of the whole building) can be compensated automatically.

Four ventilated temperature sensors ($\pm 0.3°C$), one humidity sensor ($\pm 2\%$) and one air pressure sensor (± 0.8 *hPa*) along the guideway are used to control the meteorological conditions in the shaft, while a high precision temperature sensor ($\pm 0.03°C$) is fitted next to the measurement retroreflector directly at the moving rod mount.

The horizontal calibrator at the TU Munich has roughly the same design with moving the rod in horizontal position.

2.2 Image acquisition and evaluation

The CCD camera detects the edges of every single code bar elements (bright – dark respectively dark – bright transits).

While measuring, the rod passes the camera with a velocity of 3.5 *mm/sec*. Hence a sufficiently short enough exposure time is necessary to avoid blurring effects on the image. Exposure time is 2 *ms*, which correspond to 7 μm of movement and therefore less than 1 pixel. The arising blurring can be handled by the edge detector without any problem.

To make sure to have maximum one edge in the image at one time, for every image only a part of the CCD array with small height extent (but complete width) is used. Two consecutive edges have at least a distance of 1 *mm* (smallest bar width in all existing graduations). Hence the used image part is dependent on the pixel size und comes to ± 58 pixels from the array center at a size of 8.45 μm (see Fig. 3).

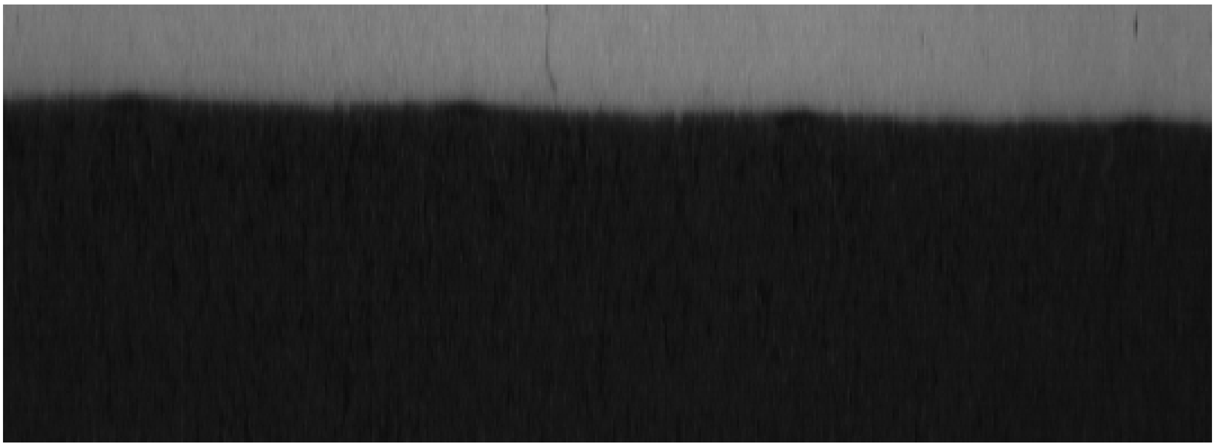

Fig. 3 Image of a barcode graduation edge, vertically stretched

In this area, possible radial lens distortion is minimized; however, for completeness the whole array was checked for distortion effects in a calibration process.
The small image height in reverse means for the edge detection algorithm, that a complete image has to be evaluated in less than 250 ms to ensure not to miss any edge.

For this reason a fast Deriche edge detector is used [MVTec 00]. To improve the result, the CCD chip is consciously tilted against the vertical movement direction of the rod by a well-calibrated amount to allow sub-pixel edge detection. As a result, the implemented operators enable a localisation of contours with an accuracy of 1/10 of a pixel, thus less than 1 μm (Fig. 4).

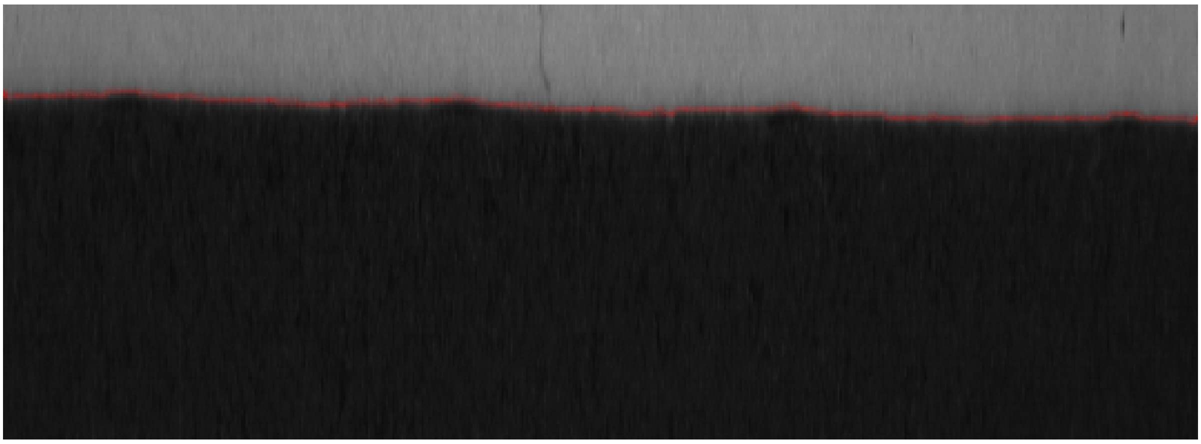

Fig. 4 Detected barcode graduation edge, vertically stretched

The detected edges pass through different plausibility checks, to eliminate dirt, scratches, colour defects and other artefacts (Fig. 5). If there are more than one edges with the same direction, it is tried to combine them to close gaps, non-horizontal edges in contrast are removed. By this method rounded bar borders, as commonly can be found on analog graduations, get reduced to their relevant horizontal boundaries (Fig. 6).

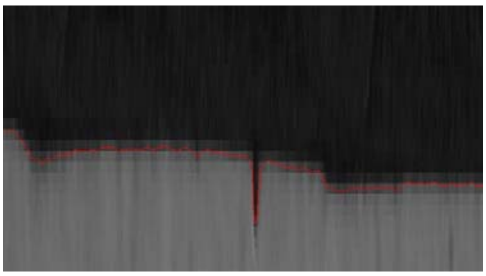

Fig. 5 Detected edge with a scratch

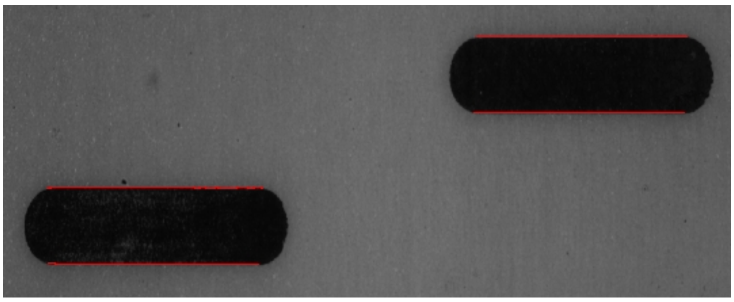

Fig. 6 Part of an analog two-scale rod and its detected edges

From the sub-pixel contours a regression line is calculated, which finally specifies the bar edge position. The deviations of the filtered contour from the regression line normally are less than 2 pixels (see Fig. 7).

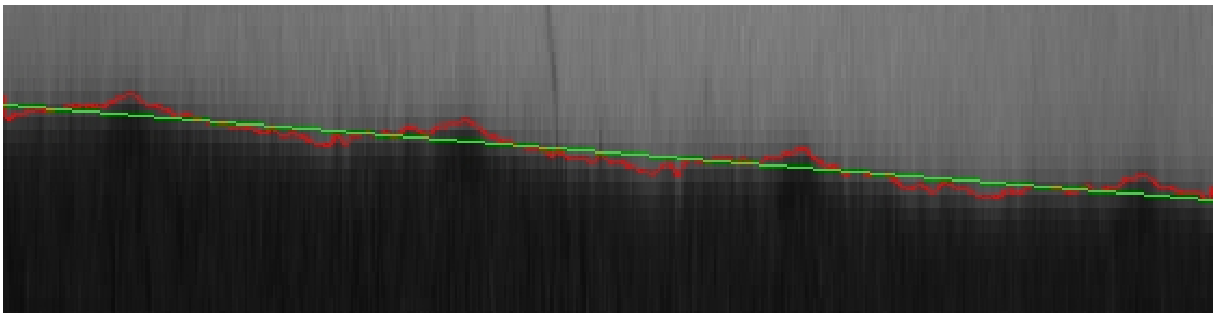

Fig. 7 Detected barcode graduation edge and regression line, vertically stretched

To express the edge position in the image in the metric scale of the interferometer, the rotation of the chip against the movement direction of the bar and the reproduction scale were calculated via a geometric calibration using a Reseau grid (coat thickness 3 μm). At present, this is done manually, but automatisation is under way.
After that the interferometer value becomes corrected by the distance of the detected edge towards an reference point in the image, and saved as raw data together with all meteorological input. For graduation documentation purposes also the images of the edges or of the whole rod can be saved in real time; this means very large data sizes, however.

The combination and analysis of the raw data is performed in a following process. Laser values become meteorologically corrected, and the detected edge positions are correlated with their known reference position (calculation basis for the levels). Thus for every bar on the rod a correction value is calculated from its two bounding edges, which then is the base for the derived rod calibration values.

3. ROD SCALE DETERMINATION

3.1 Definition of the rod scale

The gradient of the linear regression of this correction values leads to the rod scale m_0 (at a reference temperature of e.g. 20 °C).
Any rod, even a brand-new one, shows a scale in the range of ± 10 *ppm* – usually in consequence of various force effects in the tape. Especially with older rods, also the manufacturing process, storage, improper use effects etc. add up to a custom scale, so a scale factor calibration should be performed regularly.
Applying the rod scale to the height readings, the lion's share of the correction potential regarding the reference scale is considered. With analog rods, it is possible to give an additional graduation correction for each single bar, with barcode rods this is no longer useful due to the height information calculation out of a variable and interpolated section of the graduation [Heister 05].
A high-quality graduation is therefore not characterized by a small scale factor in absolute value, but by a small standard deviation of the correction values from the regression line and accordingly a homogeneous scale for any arbitrary graduation section. The deviation of a single bar correction value from the regression today is in the range of 1 – 5 μm.

3.2 Rod scale of different manufacturing tracks

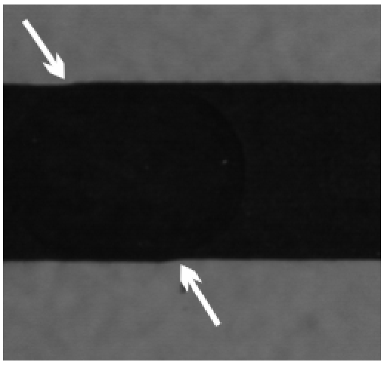

Fig. 8 Bar join fault in overlapping area

Due to the manufacturing method (a pulsed laser beam burns the varnish from the tape via a pattern) the edges of the graduation bars are not completely flat. The 25 mm wide bars are composed of five vertical manufacturing tracks with a segment width of about 6 mm each.
Hereby the single segments are partially slightly deformed, so that join faults can appear in the overlapping area (see Fig. 7 and 8).
In addition, shape and position of the segments can vary, leading to different positions of the bar edges when comparing different tracks.
The dimension of these variations is a few µm conditional to manufacturing. It has a stochastic part which has no significant effect on a single measurement, and as the case may be also a systematic one (e.g. different zero position or meteorological compensation when producing the tracks).
As this can result in a variation of the rod scale from track to track which can be detected significant by the calibrators' accuracy, its consideration has to be discussed.

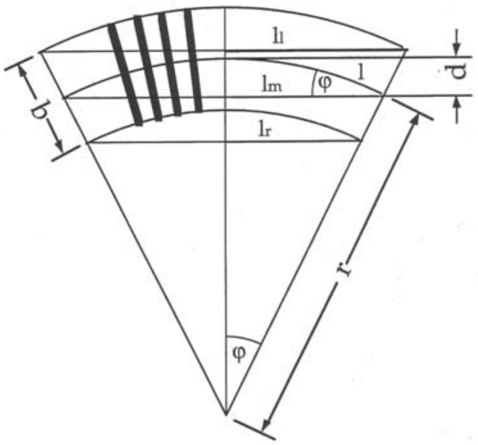

Fig. 9 Effect of the tape torsion on different reading tracks (from [Schmid 95])

Hitherto experiences have showed varying rod scales depending on the reading position on the graduation.
When developing a CCD line scan system, [Schmid 95] proved, that by the possible horizontal displacement of the tape in the guideway of about 1 *mm*, a scale difference between the two outer tracks of up to 4 *ppm* is possible. This is a result of the tape torsion with the bar edges having different slopes towards the longitudinal axle of the rod (Fig. 9).
Because of the fixed mounting of the tape at the rod foot and the spring tension at the top, the lateral torsion curvature and therefore the deformation is reproducible in the position of use (rod standing upright). In horizontal position intead, the sidesteps of the tape are largely accidental due to sag and friction. Hence a rod scale calibration in the position of use is to be preferred.

Furtheron it was known, that the graduations of analog two-scale rods also have different scales. Besides the discussed torsion effect, the consecutive manufacturing process mentioned above has an impact here.
These influences can also be found at the tracks of barcode rods.

To improve the results' comparability of the different institutes working with slightly unequal methods, [Schauerte 05] determined the manufacturing track scales of various rods at the authors' suggestion during the last interlaboratory test. The graduations consistently showed track scale variations of several *ppm*, in single cases more than 10 *ppm*. This fact was validated by measurements at the TU Munich and in other laboratories.
One part of this variation can be traced back on the manufacturing process, another one on the condition of the (used) rod and its spring tension. Tapes not free to move in the guideway (kinks, crustification etc.) lead to strongly varying scales with non-linear behaviour, which furthermore can change erratically from now to then.

It's problematic, that in practice a level reading along one single track can not be assured. In fact the used graduation width by the levels of all makers is theoretically small enough to stay in one 4 *mm* wide track at a distance of 30 *m* (1.45 – 2.27 *mm*, see [Sparta 06]). But in reality this is nearly impossible because of the tape torsion, the slight dithering when holding the rod and last but not least when working with the leveller's principle "accurate, but efficient".
Furtheron no calibration of single tracks is considering the effects of overlapping areas.
Hence for practical usage a mean scale not only from one single track, but from a preferably wide graduation span should be derived, particularly as the influence of the track scale variations is much less significant than the influence of the bubble level's accuracy [Fischer 06].
However, for the verification of the scale homogeneity along the rod the variation of the single track measurements should be used.

3.3 The advantage of acquisition width

The advantage of the new system at the TU Munich now lies in its acquisition width. While common comparators equipped with microscopes or line scan CCDs only evaluate discrete sections or track lines respectively, the vertical comparator at the TU acquires more than three complete tracks at once at a field of view width of 16.2 mm (in Fig. 7 the three tracks can be seen as "sinks" between the joins).
Moreover, the implemented image capture and processing algorithms allow the real-time evaluation of up to three additional image parts separate and independent of the whole scenery. The results of one curtly 30 minute measurement with the TU system are therefore both the scales of all three practice relevant single manufacturing tracks 2 – 4 and their variation, as also a mean scale of nearly the whole graduation width approximating the edge shapes best possible.
When the variations of measurement targeting are considered to be randomly distributed around the middle track, this mean scale is the best correction value one can get.

Also when calibrating analog rods, a wide calibration span is beneficial. Using the TU Munich system, both scales together with the scale offset constant can be determined in only one pass (see Fig. 6). The results refer to identical environment conditions then and are comparable best possible.
This very efficient method generates all necessary calibration results quick and reliable.

Furthermore the detection of edge positions in a wide image scenery is very robust against disturbances like scratches, dust, blotches or similar. While a line scanning system can't react on these effects, or at most by dropping the adequate edge, with an array camera one can try to repair the defect by suitable algorithms.
This leads to a more homogeneous detection of the scale factor with fewer gaps and less variation; the effects of a defect graduation part on a level's height reading however, can only be determined when using system calibration [Woschitz 05]. This would also be possible at the TU Munich, but is only performed for exercise purposes.

With the calibrators at the TU Munich the rod scale of a 3*m*-invar rod can be determined with a standard deviation of approx. 1 *ppm*, including the uncertainty of the edge detector and meteorology by the law of error propagation.

4. INDEX CORRECTION

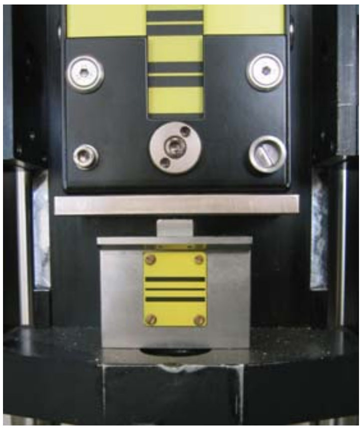

Fig. 10 Attachment block for index correction

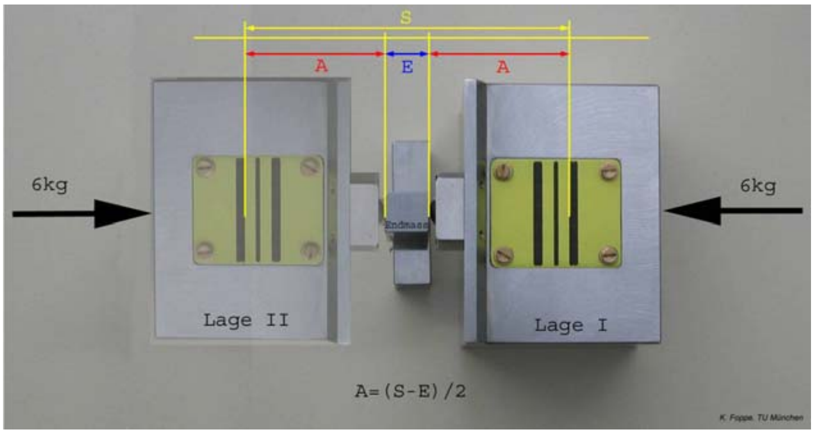

Fig. 11 Calibration of the attachment block by a calliper measurement in two faces

For the determination of the index correction an attachment block with reference bars and a setup-ball on top is used to support the rod right under the graduation tape (Fig. 10).
The position of the reference bar edges relative to the ball is determined with high precision by a two-face measurement with a calliper in the middle (Fig. 11). Therewith the nominal distance of every single graduation bar from the reference bars at the attachment block can be calculated; the deviations are used to specify the index correction.

Taking into account that for the determination of the index correction as defined in the DIN 18717 exactly one single edge of the graduation is referred, one can see that it must be precisely deduced by only a few measurement values.
The acquisition of the attachment block edges over the whole graduation width increases the reliability of the index correction value compared to a line scan, because the input information density is higher and the measurement more robust.

Having a damaged index correction reference edge on the rod, with common methods often no determination is possible at all. Using the whole image width, such problems can often be avoided.

The standard deviation for the determined index correction, following the law of error propagation, is about 6 *µm* with the comparators in Munich.

5. THERMAL EXPANSION COEFFICIENT

The thermal expansion coefficient of the invar tape is determined on a horizontal comparator in a climate chamber controllable from -10 °C to + 50 °C [Maurer 00]. After proper acclimatisation the rods become calibrated at the temperature cycle of 30 °C → 0 °C → 20 °C → 40 °C → 10 °C, and a linear regression calculated from the results.
This method now is in use for over 20 years in Munich, and also was upgraded to the CCD technique in the year 2003 following the principles described above.
The pixel size with 12.4 *µm* and the field of view with 12.7 *mm* are slightly inferior than at the vertical comparator, but no disadvantages show up when determining the expansion coefficient.

Dependent on the used invar material charge, the thermal expansion coefficient of new rods is in between 0.4 and 0.7 *ppm/°C* und therewith clearly accomplishes the specification of the DIN 18717. A periodical re-calibration of the expansion coefficient without any special reasons (e.g. after damages) is therefore not necessary [Foppe et al. 05].

The determination of the thermal expansion coefficient is done with a standard deviation of approx. 0.05 *ppm*.

6. ADDITIONAL USAGE OF THE NEW COMPARATOR

6.1 Bar edge slopes

The additional information which can be gathered when using a CCD array camera, can be used beyond the traditional calibration results.
One example is the determination of the bar edge slopes along the whole graduation. This information can be used to calculate the sidestep torsion of the tape; furthermore it is a criteria to detect tape guidance differences between two calibration dates (e.g. when a sudden scale factor change appears, this might be because of tape adherence to the guideway).
At analog two-scale rods with strongly different scale factors on the two graduations, also a clearly differing slope figure can be seen. This comes from a non-parallel adjustment of the two graduation scales.

Tests with various rods have showed the bar edge slopes to be largely constant along the graduation width. Visible variations are correlated with the tape curvature in the rod guideway. Any significant correlation with the single bar corrections or the deviations of the bars from the scale factor regression line cannot be observed (see Fig. 12).

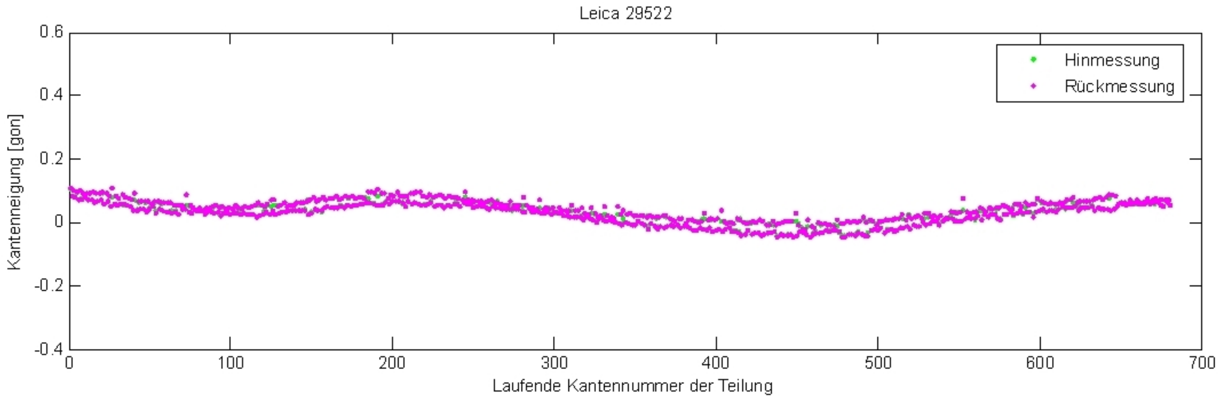

Fig. 12 Edge slopes of a barcode graduation – its variation is correlated with the curve of the tape in the guideway, the gap between the two data lines is due to the shape form of the code elements resulting in different slopes at the upper and lower boundary

6.2 Documentation

CCD camera equipped comparators take photos of the whole graduation with very high resolution. Hence these images are very well suited for documentation of the actual state of the tape and graduation.
Figure 13 shows a part of a Topcon rod with a scratch across several bars and a small varnish blistering. This figure is an automatically generated composition of 100 calibration images and is exact to the pixel in uncompressed state. Even in this image detail measurements with the same accuracy than while the calibration process are possible.

Single defects, regardless if they do affect the scale determination or have been fixed by image analysis algorithms, can be detected in the documentation image by means of semiautomatic extraction.

More extended fault areas can be recognized and marked, whereby a well directed search for specific damage symptoms like the blurred bars in Fig. 14 (induced by the rod-holder's sweat) is possible using image analysis operators.

6.3 Calibration of arbitrary objects

Besides the standard conception for calibrating invar rods, the comparators at the TU Munich are suitable to measure any object, as long as it fits in the rod mount and can be supported in the focus plane of the camera.
An example is the calibration of subtense bars (Fig. 15). Both a manual feature extraction and measurement and an image analysis operator supported extraction are possible.
Alas, completely automated measurement processes cannot be realised without great effort and only as special solution and therefore are not efficient in practice.

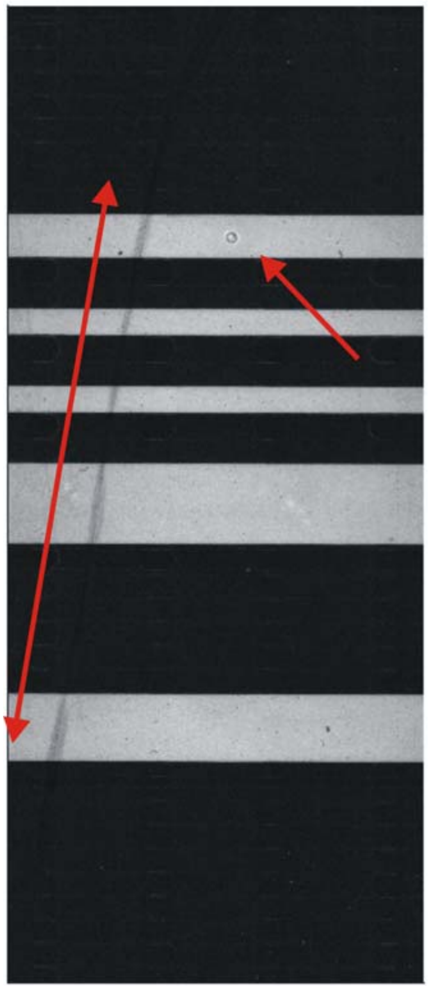

Fig. 13 CCD image for documentation

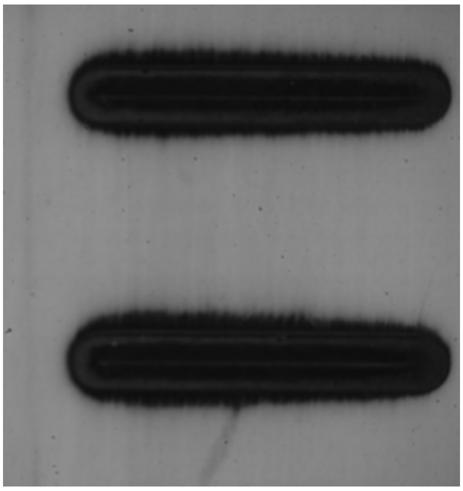

Fig. 14 Blurred graduation bars on an analog rod

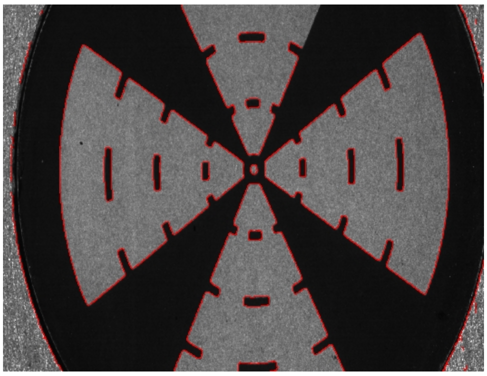

Fig. 15 Target of a subtense bar with automatically extracted edges

6.4 Quality Assurance

To preserve the permanent high quality of the calibration results, the single sensor components of the calibration systems at the TU Munich are periodically compared with international and national standards in terms of the ISO 9000 instruction.
The calibration of the interferometer laser heads is performed once a year, likewise the meteorology sensors. This is done by the particular distributor.
Recalibrations of the camera parameters take place in irregular cycles, but at least twice a year or after a re-mount of the camera. The results up to now show, that an unmoved camera does not change its parameters significantly over the years.

7. CONCLUSION

The comparators at the Geodetic Laboratory at the TU Munich hold a high standard concerning hardware components and data analysis algorithms.
Compared to the predecessor microscope system, an explicit reduction of the measurement variation combined with a yet unequalled resolution and accuracy have been reached. The evaluation of the largest part of the graduation in only on working passage today are the most reliable and efficient way of precise invar rod calibration.

REFERENCES

Fischer 06	Fischer, T 2006, Auswirkungen einer Lattenverkippung und Brennspureinfluss, internal note
Foppe 05	Foppe, K., Wasmeier, P. and Wunderlich, T. 2005, Erfahrungen aus nahezu 25 Jahren Nivellierlattenprüfung an der TUM, Allgemeine Vermessungsnachrichten 6/2005, p.213-220,Wichmann, Heidelberg
Friede 00	Friede, O. 2000, Ein hybrides Messsystem zur Kalibrierung von Strichteilungen, DGK, Reihe C, Heft 521, München
Heister 05	Heister, H. ,Woschitz, H. and Brunner, F.K. 2005, Präzisionsnivellierlatten, Komponenten- oder Systemkalibrierung?. Allgemeine Vermessungsnachrichten 6/2005, p.233-238,Wichmann, Heidelberg
Maurer 00	Maurer, W. 2000, Kalibrierung von Nivellierlatten. presentation slides Ingenieurvermessung 2000, München
MVTec 00	MVTec Software GmbH 2000, Halcon C++ Manual, München
Schauerte 05	Schauerte,W. and Heister, H 2005, Der Ringversuch 2003/2004 zur Kalibrierung von Präzisionsnivellierlatten, Allgemeine Vermessungsnachrichten 6/2005, p.221-228,Wichmann, Heidelberg
Schlemmer 75	Schlemmer, H. 1975, Laserinterferenzkomparator zur Prüfung von Präzisionsnivellierlatten. DGK, Reihe C, Heft 210, München
Schmid 95	Schmid, C. and Ingensand, H. 1995, Automatisierte Nivellierlattenkalibrierung für Strich- und Codeteilungen. Schriftenreihe „Berichte des Instituts für Geodäsie und Photogrammetrie“, Bericht 244, Zürich
Sparta 06	Sparta, M. 2006, Anlage 7 zur Feldanweisung für die Präzisionsnivellements zur Erneuerung des DHHN92, AdV, Bonn
Staiger 05	Staiger, R. and Witte, B. 2005, Zur Bedeutung der Prüfung von Präzisionsnivellierlatten für die Praxis. Allgemeine Vermessungsnachrichten 6/2005, p.200-203,Wichmann, Heidelberg
Stemmer 06	Stemmer Imaging 2006, LED-Ringleuchten der LDR2/SQR-Serie, data sheet, Puchheim
Woschitz 05	Woschitz H. 2005, Systemkalibrierung: Effekte von digitalen Nivelliersystemen, Allgemeine Vermessungsnachrichten 6/2005, p.239-244,Wichmann, Heidelberg

BIOGRAPHICAL NOTES

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