Improved quality of levelling staffs in the Netherlands

An overview and analysis of 12 years calibration of precise invar levelling staffs

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Mit dem im Geodäsiegebäude der TU Delft aufgebauten Komparator wurden seit 1992 Präzisionsinvellierlatten kalibriert. Die Ergebnisse der Kalibrierung werden vorgestellt. Es zeigt sich, dass fast alle Latten, die seit dem Jahr 2000 kalibriert wurden, eine sehr hohe Qualität besitzen. Es konnte keine signifikante Verschlechterung in der Qualiät der Präzisionsnivellierlatten im Laufe der Zeit festgestellt werden, wenn diese sorgfältig behandelt wurden.

1 Introduction

In the Netherlands, lying mainly below sea level, it is of vital importance to have accurate, detailed and up to date information about the altitude. For this purpose a large dense network of benchmarks (more than 50 000) in buildings, bridges and other objects with good stability, has been realized. To keep the height information of these benchmarks up to date every year on average 3000 kilometres are levelled.
In the eighties, the Survey Department of the Ministry of Transport, Public Works and Water Management, now Geo-Information and ICT Department (AGI/RWS), the government agency responsible for the primary network of benchmarks, suspected systematic errors in the line graduations of levelling staffs. At that time it was not yet possible in the Netherlands to calibrate levelling staffs and this was regarded as a serious shortcoming.
In 1986, in collaboration with the Department of Geodetic Engineering in Delft, a case study was done to build an instrument for automated calibration of levelling staffs. Also a study was done on a new sensor for automated detection of line graduations. In 1988 a start was made in developing and constructing a horizontal comparator in the temperature-controlled verification room of the Department of Geodetic Engineering. Since January 1992 the comparator (see figures 1a and 1b) for calibration of levelling staffs has been operational [1].
Because of problems with the sensor for automated detection of line graduations the first calibrations had to be done manually with an optical microscope, a time consuming and tiresome method. In March 1994 a new sensor (see figures 2a and 2b) for automated line detection became operational. This surprisingly simple but accurate sensor is based on edge detection which also has the advantage that graduation lines with different width (for instance used on modern levelling staffs with barcode) can be measured easily [2]. The unintended differences in line width (up to 100 micron) of staffs with centimeter graduation was one of the main problems with the old detector, which was based on symmetry detection. Since 1992 a total of 652 levelling staffs have been calibrated with an accuracy of a few micron (0.001 mm).
At the end of 2003 the Geodesy building, including the comparator, was sold to the Dutch Metrology Institute (NMI) and the geometry related groups of Geodesy were integrated in the faculty of Aerospace Engineering. In January 2004 the NMI started to renovate the building (see figure 3) and therefore the comparator had to be, temporarily, dismounted.
This article is organized as follows. First the accuracy of the comparator is demonstrated. This is followed by a general overview of the results of all 652 calibrations. Then a general analysis is made of levelling staffs which demonstrated errors larger than 50 micron followed by a more detailed analysis of all levelling staffs since 2000 which showed errors larger than 25 micron. Also a few peculiar results are described. This article ends with an outlook on how to continue with calibration of levelling staffs in the Netherlands.

Fig. 3: Renovation activities at the former Geodesy building

Set-up horizontal comparator

Figure 1a shows a schematic overview of the horizontal comparator. The levelling staff is put on top of a horizontal 3 m length carriage. As reference a Heidenhain-incremental measuring system LS107 of 3 m length is installed at the side of the carriage. This measuring system contains a glass scale with very fine graduation which is counted by a photo-electric scanning unit (mounted on the measuring bridge) with a resolution of 0.5 micron. The carriage can be moved automatically with the aid of a motor (speed is about 30 cm/minute). The reference scale is triggered every time an edge of a graduation line from the invar levelling staff passes below the sensor for automated line detection (see figures 2a and 2b).

Figure 1b shows a close-up of the set-up.

1. Base profile, length about 9 meter.
2. Rail, length about 6 meter, mounted on a edge profile which is tightly fixed on the base profile.
3. Carriage fit for different types of levelling staffs, length about 3 meter.
4. Reference scale, length about 3 meter, fixed at the side of the carriage.
5. Steel tape towards motor for automated movement.
6. Temperature sensor (accuracy 0.1°C).
7. Levelling staff.

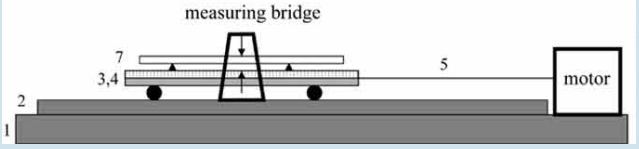

Fig. 1a: Set-up horizontal comparator

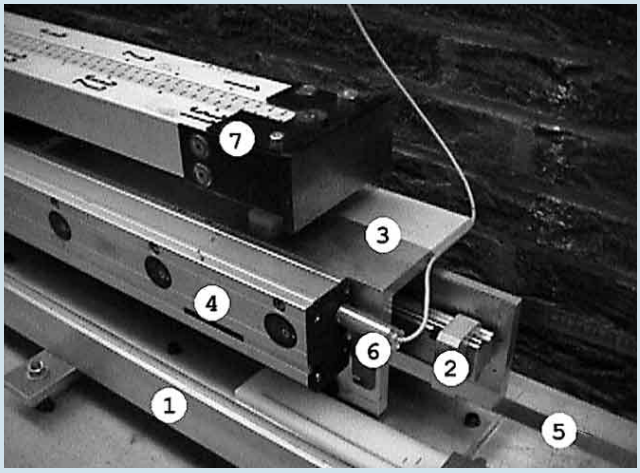

Fig. 1b: Close-up comparator

2 Regularly checks with reference staff

A specially constructed reference staff of 3 m length has been used regularly for control purposes. This staff is provided with a 1 cm invar scale under constant tension of 30 N. In order to relate the reference staff to the international meter standard it was calibrated on October 16th, 1994 by the Dutch Metrology Institute (NMI). The standard deviation of the calibration was 1,4 micron ± 0,1 micron/meter. The differences between the measurements from the NMI and the comparator have always been at the level of a few microns so there has been no need for extra (and expensive) calibrations of the reference staff.
In January 2004, after the last customer and just before the start of the renovation activities in the calibration room, the reference staff was measured for the last time. The differences from this measurement with the results from the NMI from 1994 are presented in figure 4. The figure shows that the differences are random at the level of a few microns with a maximum difference of only 4,3 micron. This confirms the stable and good quality of the comparator and demonstrates that there has been no significant degradation of the invar reference staff.

3 General overview of all calibrations since 1992

Since the start of calibrations with the comparator in 1992 a total of 652 invar levelling staffs have been calibrated. Most of these calibrations were done for AGI/RWS and for engineering companies which had projects for AGI/RWS. Other customers included municipalities and engineering companies which needed certified instruments for special projects such as monitoring deformations.
In table 1 a general overview is given of the quality of the line graduations of all calibrated levelling staffs since 1992. The number of levelling staffs for which the graduation errors are within a certain range, which varies from 0–25, 25–50, 50–100 and more than 100 micron, are presented for each indicated period of time.
It is remarkable that since 2000 only a very few levelling staffs have been detected with errors larger than 25 micron. It seems that the demands for certified instruments, by AGI/RWS and others, have resulted in the use of better levelling staffs. This was badly needed because during the first few years of calibration the quality of some staffs were very poor: invar strips which were heavily damaged, missing graduation lines were sometimes even ‘repaired’

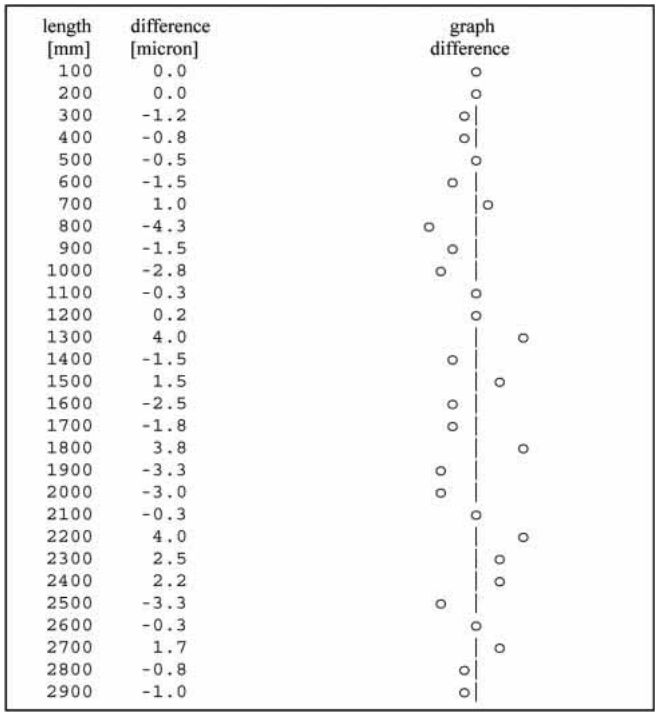

Fig. 4: Differences of two calibration results from reference staff. First calibration by NMI in 1994 and last calibration with comparator in 2004

with a black pen, invar strips were fixed with tape on the staff housing (intention was masking left graduation) and finally some staffs had very rusty feet. It is strange that requests were made to calibrate these staffs for new projects as a previously visual inspection would have made it clear that these staffs were not suited for the most accurate work.

It is noted that the quality of a levelling staff is not only defined by the graduation lines but also by the non-skewness of the foot of the levelling staff and the zero offset (and stability) of the graduation. These items have also been measured during calibration and it seems that these errors are even larger than the graduation errors. This will not be analysed in this article.

4 Analysis results

A total of 652 levelling staffs were calibrated and many peculiar results showed up. In order to limit the size of this section only the most remarkable results will be presented. First the large errors, larger than 50 micron, which frequently occurred in the first few years since calibration started, are analysed in general. Then a detailed analysis is made of all errors larger than 25 micron since the year 2000. Finally a few other peculiar results are highlighted.

4.1 General analysis errors larger than 50 micron

From table 1 we can see that between 1992 and 1999 a total of 77 levelling staffs demonstrated an error of more than 50 micron, with a maximum error of 425 micron. For accurate deformation measurements and for first and second order levelling this error is too large. There are several causes for these large errors. In 31 occurrences the large errors appeared to be related to wooden levelling staffs. Wooden staffs are nowadays not used anymore. The reason that so many wooden levelling staffs have been calibrated is that AGI/RWS wanted to know what the quality was of old levelling staffs which they had used in the years before, and among them were many wooden staffs. Another cause for the large errors is the experiment which AGI/RWS performed with in-house made staff housings. The scale factor of the graduation was for these staffs regarded as not so important and therefore the (scale) errors were sometimes very large. As a final general cause it is worth mentioning that during the first few years of calibration there was not yet much awareness of the quality of levelling staffs, so mainly existing levelling staffs, including inferior ones, were offered for calibration. This changed in 1996, when the large fifth national levelling campaign, organized by AGI/RWS, started. For this campaign mainly new levelling staffs were used. Table 1 shows that since 2000 only very few outliers in the line graduations have been detected so all old levelling staffs seem to have been deselected for accurate levelling work.

4.2 Detailed analysis errors larger than 25 micron since 2000

If the graduation errors of a levelling staff are smaller than about 25 micron the staff is in general fit for the most ac-

Tab. 1. General overview of the quality of the line graduations of all calibrated levelling staffs since 1992

range corrections	number of calibrated staffs in 1992–1999	number of calibrated staffs in 2000	number of calibrated staffs in 2001	number of calibrated staffs in 2002	number of calibrated staffs in 2003
0–25 micron	273	42	41	38	65
25–50 micron	111	1	1	2	0
50–100 micron	51	0	0	0	0
> 100 micron	26	0	0	1	0
total	461	43	42	41	65

Schematic overview of the sensor for automated edge detection

Figure 2a shows a schematic overview of the sensor for automated edge detection. A horizontal laser beam passes a cylindrical lens and changes the shape of the beam from a circular shape into a very small bar shape. It is noted that the only function of the laser is to transmit a stable light beam. The beam passes through a pentagonal prism and is projected on the levelling staff. A photodiode transforms the reflected light into a voltage. On a black surface (graduation line) little light is reflected and the voltage output by the photodiode is low and on a yellow or white surface the voltage is higher. The mean voltage from the black and yellow (or white) surface is regarded as the reference value and is measured for each type of levelling staff in advance. When, during calibration, the voltage is equal to the reference value a trigger pulse is given to read the Heidenhain reference scale. In this way all edges of graduation lines are measured. The speed is about 30 cm per minute. Figure 2b shows the set-up of the edge detector.

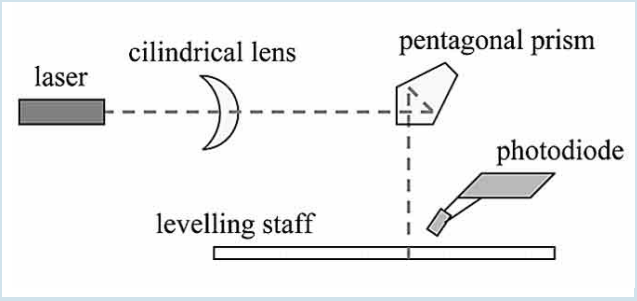

Fig. 2a: Schematic overview of sensor for automated edge detection

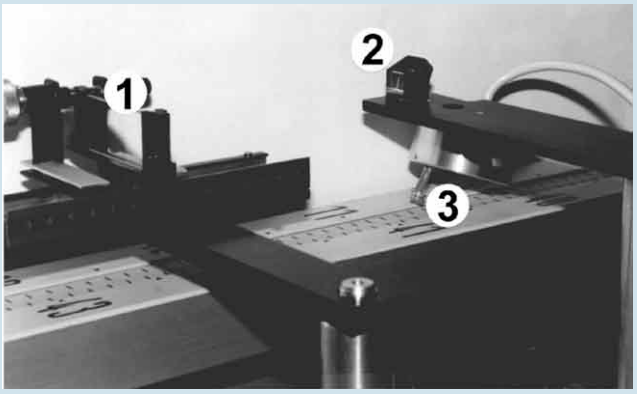

Fig. 2b: Set-up sensor for automated edge detection: 1. cylindrical lens; 2. pentagonal prism; 3. photodiode

Polynomial for error correction

Calibrating levelling staffs results in corrections for the nominal values. A polynomial can be computed to describe the corrections (see e.g. figure 9). The polynomial is used for easy comparing results between different calibrations and can be used for rod-corrections. The general formula for a polynomial is given below:

$$Y = C_0 + C_1X + C_2X^2 + C_3X^3 + \ldots$$

With the parameters C_0, C_1, C_2, C_3 etc., the correction Y (in micron) for each nominal reading X (in meter) can be computed.

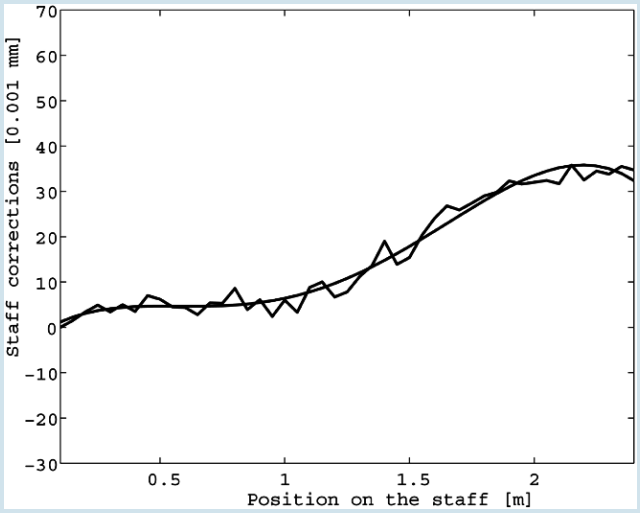

Fig. 9: Polynomial fitted through estimated corrections using least squares adjustment. The irregular line presents the estimated corrections for each graduation line of the levelling staff

The parameters of the polynomial are estimated with a least squares adjustment method. The number of significant parameters is defined by a statistical test. If the quotient of an estimated parameter and the estimated standard deviation of this parameter (signal to noise ratio) is larger than 2, the parameter is regarded as significant. The estimation of the polynomial starts with 2 parameters and is extended until the next parameter is not significant.

curate levelling projects. In order to get more insight into the causes for the occurrence of errors larger than 25 microns for modern levelling rods all detected errors since the year 2000 larger than 25 micron are analysed here. Table 1 shows that in the year 2000 there was only one staff with an error between 25 and 50 micron. This was a 3 meter long staff which had a maximum error just slightly larger than 25 micron, namely 31 micron. Among all calibrated levelling staffs there are only very few staffs longer than 2.5 meter. In Holland, which is a very flat country, these staffs are seldom needed. It is also not very convenient to transport these long staffs in ordinary

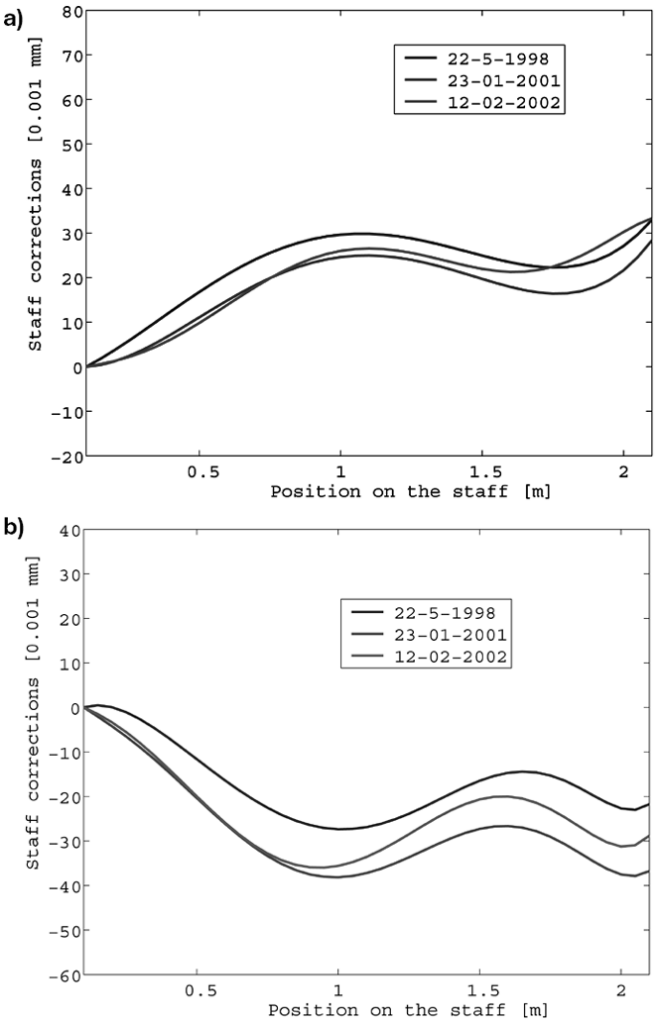

Fig. 5: Example maximum graduation errors between 25 and 50 micron. The figure on top presents three calibrations of a centimeter graduation and the figure at bottom presents three calibrations of a millimeter graduation from the same levelling staff

cars; a large van is in that case needed for careful transport.
Also in 2001 only one staff had an error between 25 and 50 micron but this was a very special staff. It was a staff specially made for AGI/RWS by NEDO and used for hydrostatic measurements with the vessel 'NIVEAU'. This staff has two line graduations, one with a separation of one centimeter and one with a separation of only one millimeter. In figure 5 the polynomials of the graduation errors are presented. The figure on top presents the centimeter graduation and the figure at bottom presents the millimeter graduation. This staff has been calibrated three times, namely for the first time, when it was brand new, in May 1998 and for the second time in January 2001 and for the last time in February 2002. From the figure it appears that over a period of almost four years, between the first and last calibration, the graduation errors have changed only about 10 micron. It is remarkable that the polynomial on top and at bottom have a different pattern which also indicates that this problem already existed when the staff was brand new.

In 2002 three staffs had an error larger than 25 micron. One is related to the same staff mentioned just before in the overview of the previous year. Another one demonstrated a graduation scale error with a maximum of 104 micron. It appeared that this staff had been used in salt water and that had caused the invar strip to get stuck to the staff housing which caused a large scale error.
The third staff, with an error of maximum 29 micron, was clearly damaged. It showed two dents in the staff housing. Also two screws from the foot of the levelling staff were missing. This seems an example of lacking careful maintenance.
In 2003 extra calibrations were performed because it was clear that the comparator would be out of service in 2004 because of renovation activities of the building by the new owner NMI. All calibrated staffs in 2003 demonstrated only small errors, smaller than 25 micron, in the line graduations. In order to get over the outage period of the comparator, AGI/RWS has prolonged (temporarily) the validity of calibration certificates from 1.5 year to 3 years, under the condition that the levelling staff has no serious visual damage.

4.3 A few peculiar results

Many peculiar results have shown up in calibrating levelling staffs. Three most remarkable items will be described here. The first item is related to levelling staffs which have been calibrated most frequently (three staffs were calibrated five times each). This gives more insight in the behaviour of the invar strip during aging. The second peculiar item shows that sometimes the graduation lines contain small manufacturing errors. And the last item presents that sometimes batches of levelling staffs have the same graduation scale errors.

4.3.1 Example of repeated calibrations over several years

Many staffs have been calibrated repeatedly: 120 staffs 2 times, 43 staffs 3 times 11 staffs 4 times and 3 staffs even 5 times. The results of the three staffs which have been calibrated five times are presented in figure 6. All three staffs are from the same engineering company and have a length of 2.5 meter. They all were calibrated five times, each time in the same week. The first calibration was done in January 1993 and the last one in February 1998.
These staffs have not been calibrated any more after 1998 because from then onwards levelling was done with digital levelling instruments which use code levelling staffs. From figure 6 follows that for all three staffs the graduation errors are within a range of about 10 micron, which indicates a stable behaviour of the invar strips under working conditions, except for one calibration! For all three staffs the third calibration, from August 1995, shows a different pattern. The maximum deviation from the third calibration compared with the others is about 30 micron. After the third calibration the results became normal again. The most likely explanation for this behaviour is

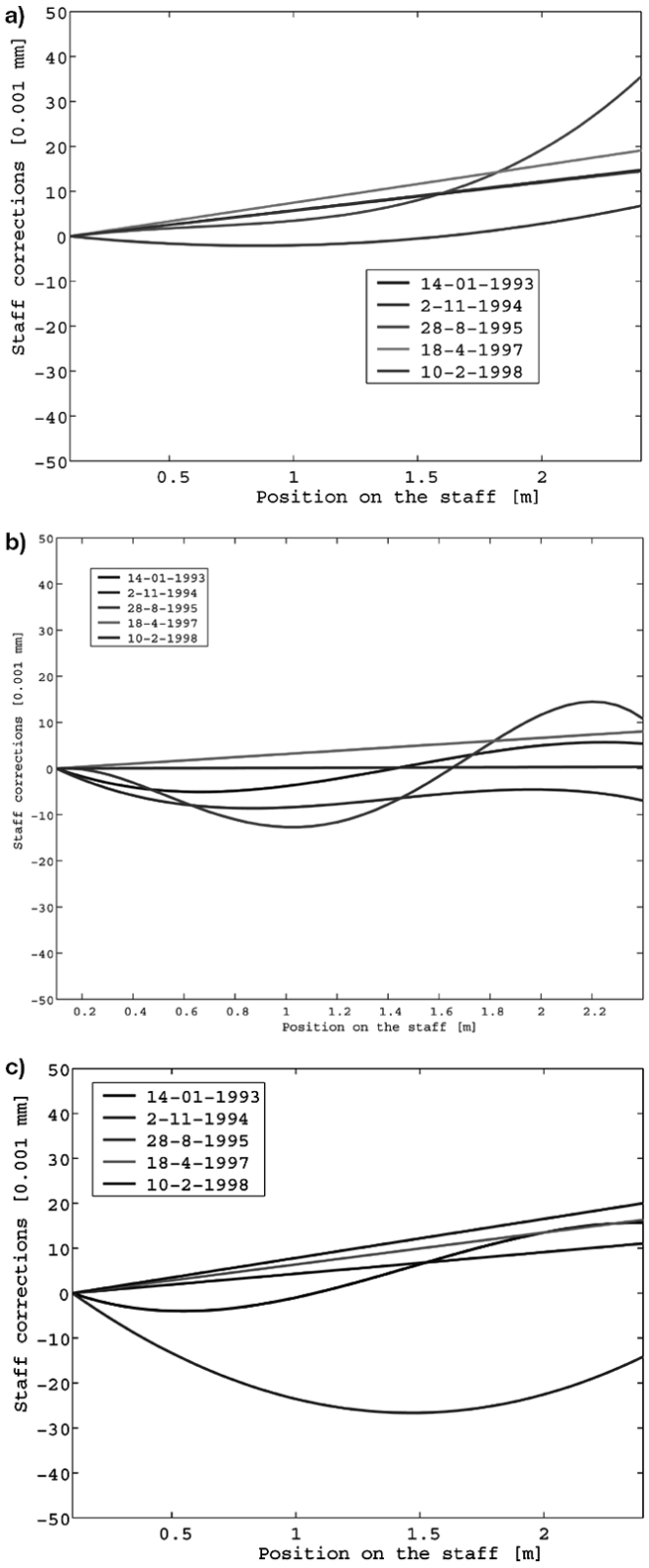

Fig. 6: Example graduation errors for three staffs which have been calibrated five times each. For every staff the third calibration demonstrates an outlier

that the length of the invar strip had changed temporarily because of rough transportation or use in the field, e.g. no transportation boxes had been used. This effect has also occasionally been seen at other staffs.

4.3.2 Examples of manufacturing errors

In the beginning period of calibration with the comparator there were sometimes doubts about the quality of the comparator, especially when the results demonstrated a peculiar effect. But checking the comparator with the reference staff and repeated calibration of the staff with the peculiar effect over several days made it clear that the peculiar results were 'typical' results, caused by manufacturing or by aging.

In figure 7 four examples of (small) manufacturing errors are presented.

The first one demonstrates a shift of several tens of microns every 50 centimeter. It seems clearly that this graduation was made with a stencil of 50 centimeter length. This pattern has been observed several times with wooden staffs. This method of manufacturing is nowadays not used anymore.

The second example demonstrates a saw tooth pattern of about 10 micron. All corrections are clearly within a small range of 20 micron, which is good, but the typical pattern indicates that there was a small problem during manufacturing. This pattern has been observed with 2 levelling staffs made by NEDO.

The third example is related to old wooden staffs made by WILD. The plot presents the results of three different levelling staffs. In all three cases the graph presents a little 'hill' of only about 20 micron, between 50 and 70 centimeter. This phenomenon was observed at 10 staffs with different length of 1-meter, 2-meter and 3-meter.

The last example is related to a new levelling staff of 3-meter length, made by NEDO, with a 0.5 centimeter graduation. The graph presents a peak of about 30 micron which is a little too large. This is the only new levelling staff which has demonstrated a jump larger than 20 micron.

4.3.3 Examples of scale 'errors'

Some new levelling staffs demonstrated clearly a significant scale effect. It was observed that the serial numbers of the related staffs were close to each other. In figure 8 two examples of this phenomenon are presented. In the figure on top the results are plotted for four staffs, with serial number 6209, 6210, 6213 and 6217. The last staff demonstrated a maximum error of about 50 micron. It seems that the graduation errors were related to the serial number. This is most likely related to a manufacturing problem. It would be interesting to see at which serial number this phenomenon started and stopped. It is noted that this phenomenon was observed in 1996 and that it was related to staffs which had been kept in stock by the dealer for several years so the scale errors could also be caused by aging, perhaps even under unfavourable conditions. In the figure at bottom a similar phenomenon is presented for four NEDO code staffs with serial numbers 23312, 23319, 23409 and 23411. The order of the lines is the same as the order in the serial numbers. The most extreme error is with serial number 23411, about – 20 micron. It seems very likely that this, very small, scale error occurred for at least all manufactured staffs with serial numbers between 23312 and 23411.

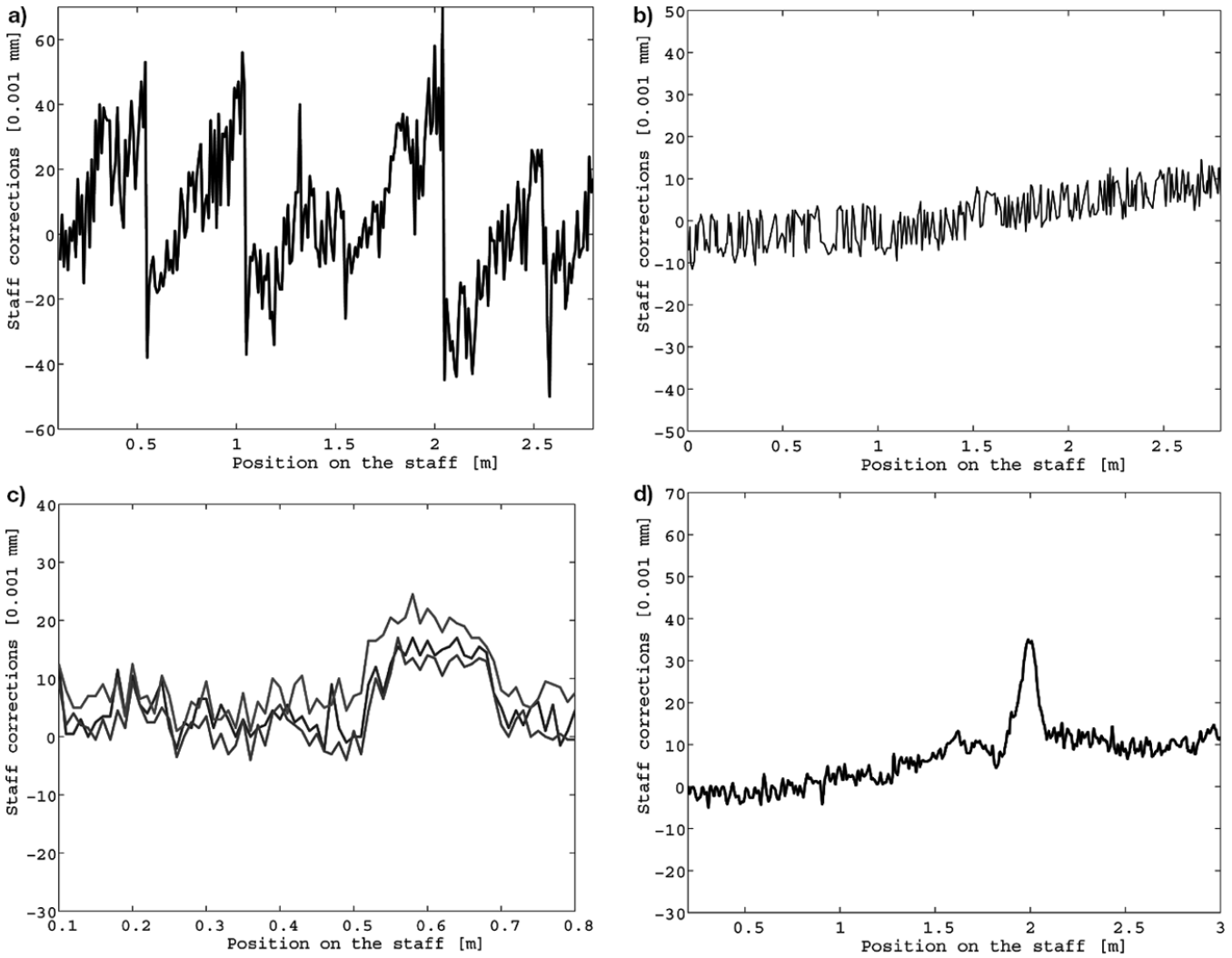

Fig. 7: Four examples of (small) manufacturing errors

5 Outlook continuity of calibration in the Netherlands

Calibrations since 1992 demonstrated clearly that the quality of the invar levelling staffs was poor at the beginning. Since the start of the fifth national levelling campaign in 1996, organized by AGI/RWS, the calibration results have become much better, mainly because many new levelling staffs were used. And since 2000 only very few outliers in the line graduations have been detected so it seems that all old and inferior staffs have been deselected for levelling. It is remarkable that most outliers could also have been detected even without calibration, by only visual inspection of the levelling staffs. Most outliers since 2000 were caused by either missing screws in the staff foot, the influence of salt water on the invar strip (gets stuck), or obvious damage (probably caused by careless use in the field or by rough transport). So it seems that it is not really necessary to calibrate the graduation lines very frequently and that it becomes more important to perform regular official visual inspections of the levelling staffs to check for damage.

Another aspect which is important for the quality of levelling staffs is the non-skewness of the foot of the levelling staff. From calibrations it appears that these errors can easily be as large as 0.1 mm, which is much larger than graduation errors, and are not so constant over time as the graduation errors. Unfortunately the non-skewness could only be measured with a limited accuracy of about 0.02 mm.

The move of Geodesy to the Faculty of Aerospace Engineering has resulted in abandoning the activity of calibration of levelling staffs. Fortunately the former Geodesy building was bought by the Dutch Metrology Institute (NMI) whose core business is to calibrate length, weight, volume, time and other measuring instruments. They have committed themselves to take over the activity of calibration of levelling staffs. Because of renovating activities – they are also improving the temperature controlled calibration room in order to meet the highest standards – the comparator has been dismounted for the period of about one year. The comparator is planned to be operational again in summer 2005.

There will be a few major advantages when calibrations of levelling staffs are done by the NMI. The NMI is able to

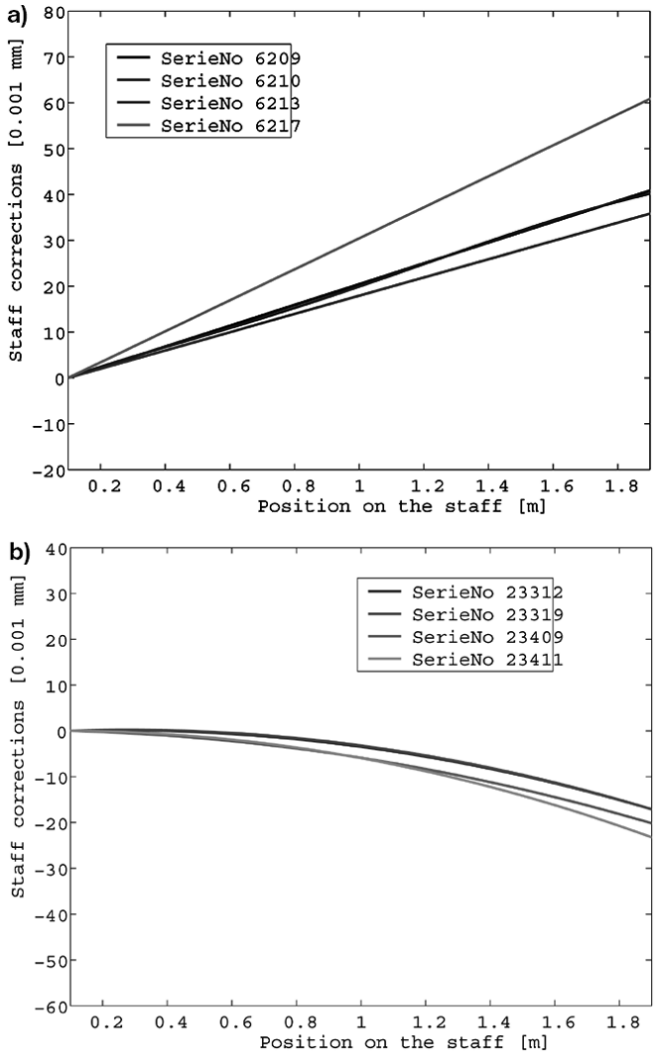

Fig. 8: Two examples of scale errors for four levelling staffs each with serial numbers close to each other

measure the non-skewness of the staff foot, which is nowadays becoming a more important error source, at the few micron level, which is much more accurate than with the old system (accuracy about 20 micron). This measurement could easily be combined with an official visual inspection, which is cheaper than a complete calibration, of the levelling staff.

Finally it will be clear that continuity of calibration of levelling staffs at NMI is much better guaranteed than at the Faculty of Aerospace Engineering. The future for calibration of levelling staffs in the Netherlands looks very positive.

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Summary

In the former Geodesy building at Delft University of Technology, a comparator for dynamic calibration of levelling rods had been operational since 1992. In 2004 the comparator was dismounted by the new owner of the building, the Dutch Metrology Institute (NMI), because of reconstruction activities. The comparator is planned to be operational again in September 2005.

Discussed are the results of calibration since January 1992. It appears that almost all rods that have been calibrated since 2000 are of very good quality and that there is no significant degradation if the levelling staffs are treated carefully.

Zusammenfassung

Im ehemaligen Geodäsiegebäude der Technischen Universität Delft war ein Komperator für die dynamische Kalibrierung von Nivellierlatten seit 1992 im Betrieb. The Komperator wurde 2004 durch den neuen Eigentümer des Gebäudes, das Niederländische Mess-Institut (NMI), im Zuge von Renovierungsarbeiten abgebaut. Ab September 2005 soll der Komperator wieder an der selben Stelle im Einsatz stehen.

Die Resultate der Kalibrierungen seit Januar 1992 werden in diesem Artikel besprochen. Es zeigt sich, dass beinahe alle Latten, die seit dem Jahr 2000 kalibriert worden sind, sehr hoher Qualität besitzen, und dass es keine signifikante Verschlechterung in der Qualität der Messlatten gibt, wenn diese sorgfältig behandelt werden.