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Development of a System Calibration Comparator for Digital Levels in Finland

Mikko Takalo and Paavo Rouhiainen
Finnish Geodetic Institute, Department of Geodesy and Geodynamics
Geodeetinrinne 2, FIN-02430 MASALA, Finland
mikko.takalo@fgi.fi, paavo.rouhiainen@fgi.fi

Abstract: *A high precision digital levelling system uses invar bar code rods and a linear CCD camera technique. The scale of the bar code is a function of temperature. The scale and a constant are determined by the rod calibration. When carrying out digital levelling, the scale of the whole system, in fact the scale given by the instrument, is expected to be equal with the scale of the rod.*

However, with time, the scale of an instrument and also a rod can change. To check the behavior of the whole system, i.e. rod and instrument together, we have to use the "system calibration" procedure, where the height readings are taken from different sectors on the bar code rod and compared with their true values obtained by a laser interferometer.

In the Finnish Geodetic Institute (FGI) automated rod calibrations have been carried out since 1996 using the FGI vertical laser rod comparator and system calibrations since 2002. The FGI system calibration comparator applies elements of the existing FGI rod comparator. Some results of the calibration for the Zeiss DiNi12 systems are given.

1 Importance of system calibration

The system calibration (Rüeger and Brunner 2000) is used to determine the scale of digital levelling systems, to study their measuring behavior, and to estimate the standard uncertainty of the digital levelling.

During the last decades geodetic instruments have become more automatic, converted into measuring systems being externally fine constructed and well operating. Software has replaced most of the observer's tasks. Also, the levelling itself has gradually experienced a similar development: The discovery of digital levelling in the beginning of the 1990's led levelling into a new era - levelling became almost totally automated.

Previously, when the conventional levelling technique was applied, instruments were simply constructed, but also manufactured with great care applying precision mechanics. Users knew and understood the function of the levelling instruments better and had better possibilities to locate functional faults and even correct small imperfections.

Nowadays, it looks like manufacturers have reduced the use of precision mechanics in production, mostly, due to economic reasons. The instruments and the measuring systems are calibrated by the manufacturers themselves and when finding imperfections, corrections are added to the measuring software. All that is kept secret by appealing into commercial reasons (Woschitz *et al.* 2002). The user, unaware of that, pushes an operation button and gets readings without any possibilities to control them and in the worst case does not even care about the correctness of readings. This is one reason why, e.g., the system calibration of digital levelling systems is so important.

In this report, we give a review of the digital levelling technique in Chapter 2, a description of the FGI laboratory in chapter 3 and of the system calibration in Chapter 4. In Chapter 5 we estimate the uncertainty of system calibration and in Chapter 6 some examples of results obtained using the FGI system calibration comparator are given.

2 Digital levelling system

The first almost totally automated levelling system Wild NA2000 was launched in the beginning of the 1990's (Ingensand 1990). Currently, the following four makes of digital levelling systems are on the market: Leica, Trimble (former Zeiss), Sokkia and Topcon. A measuring system consists of a level, comprised of optics and a compensator, and a bar code scale, mostly on an invar band fixed into a rod frame. In addition, there is a CCD linear camera and software controlling all operations, procedures and processes of the digital level (Ingensand 1999).

When we operate with a digital levelling system, the CCD camera observes a certain sector of the bar code scale above and below the horizontal level as illustrated in Figure 1. The bar code image is then evaluated using the whole scale pattern stored in the memory of the instrument. Each manufacturer has its own method to process the final height reading (Ingensand 1999).

There are some differences between the digital levelling system and conventional levelling:

- In a digital level the height readings are automatically processed applying electro-optical technique, while in conventional levelling readings are manually created by the observer using the optical tools of the instrument, e.g. line of sight, cross hair, ocular, micrometer, line of level, etc.
- In the digital levelling a CCD camera replaces the human eye.
- By processing a height reading the digital level employs more than just one code line. For instance, the Zeiss DiNi12 system uses a 30 cm sector of bar code scale (Feist *et al.* 1995; Figure 1) whereas in conventional levelling the height reading is based on the observation of one graduation line.
- In conventional levelling the scale, i.e., realization of the length unit, e.g., meter, is based on the length of the rod, while in digital levelling we can consider two scales: Scale given by the instrument and scale by the rod. In fact the scale of the level is expected to be equal with the scale of the rod, but with time the scale of the level can change e.g. due to aging of the CCD sensor. The height reading of the digital level can be sensitive for influence of scratches of code elements or shadows on the invar band etc. (Woschitz and Brunner 2002; Takalo *et al.* 2001).

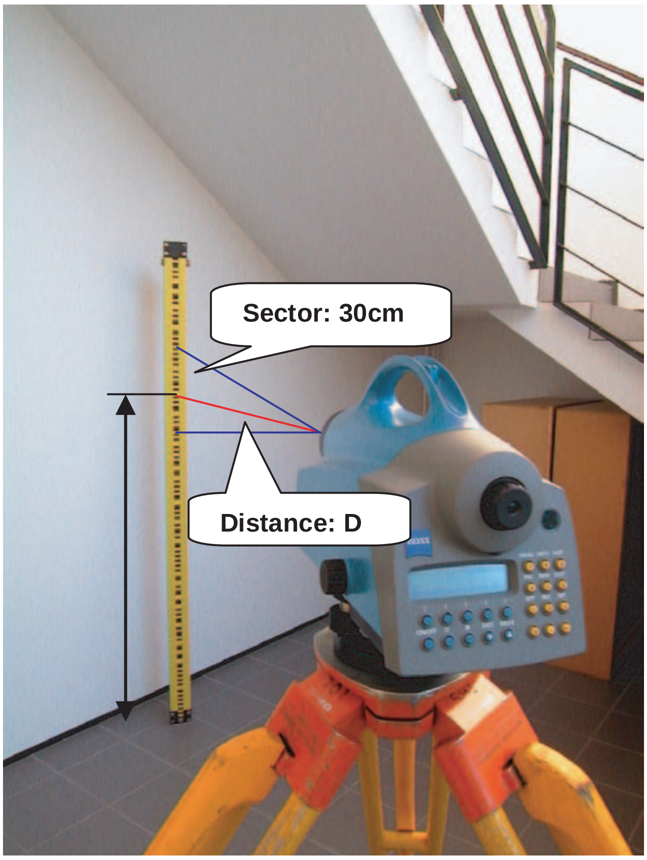

Figure 1. *The digital levelling system Zeiss DiNi12. The DiNi12 uses about 30 cm constant sector length from the rod scale independently from the distance. The sighting distance can be varied from 1.5 m to 100 m.*

3 Laboratory

The Finnish Geodetic Institute (FGI) acts as the National Standards Laboratory for Free Fall of Acceleration and Length. When the FGI moved to Masala in 1995, a laboratory for rod calibration purposes was designed in the main building of the FGI. The size of the laboratory room is partly 8.7 m in height for the vertical comparator and 5.2 m for the horizontal comparator, 2.7 m in width and 10 m in length (Figures 2 and 3). There are three floors: the first one for horizontal operations, the second one at the height of 2.8 m for vertical and system calibrations and the third one at the height of 6.4 m for maintenance of the vertical comparator (Figure 2). The measuring room is air-conditioned and we can change the temperature from 5°C to 35°C and the relative humidity from 5% to 95%.

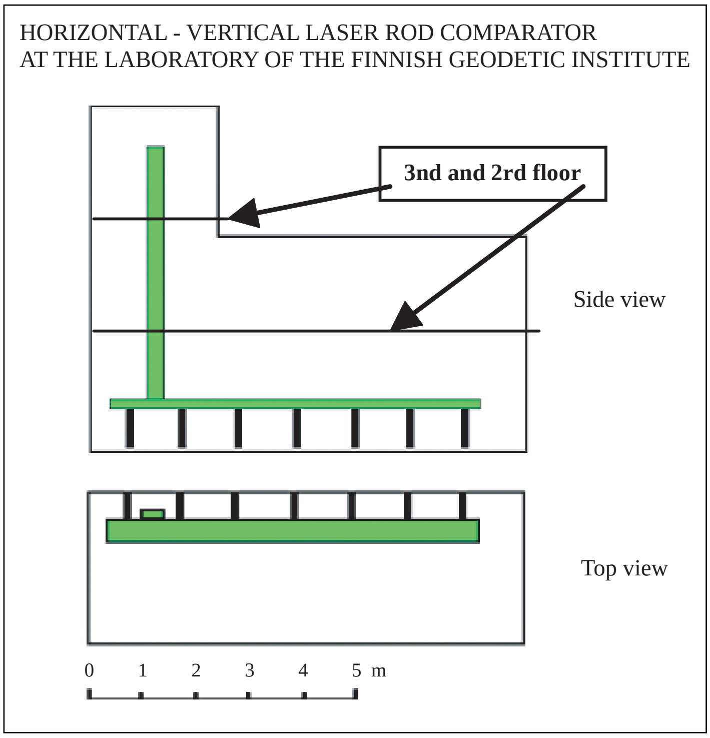

Figure 2. *Horizontal-vertical rod comparator at the FGI laboratory, originally designed for rod calibration*

Figure 3. *Interior of the laboratory, the second floor of the measuring room*

4 System Calibration

Principle:
In the system calibration the rod is set on the conveyor of the vertical comparator and the digital level on top of the observation pillar at a certain distance from the rod as illustrated in Figure 4, right. The rod is controlled by a laser interferometer and moved step by step in vertical direction. The height and the laser interferometer readings are observed during the stops of the rod on the conveyor. Thus, the height readings are taken from different sectors of the bar code rod and then compared with true values obtained by the laser interferometer (Rüeger and Brunner 2000). This procedure is called the system calibration of digital level.

Figure 4. *The system calibration in the FGI laboratory*

Comparator:
The FGI system calibration comparator was designed for calibration of Zeiss DiNi digital levelling systems (Figure 4). But, we can also calibrate other digital levelling systems on the market (Takalo *et al.* 2001). Designing the FGI comparator was initiated at the end of 2000 and it was operational in spring 2002.

The comparator consists of two 4 m high concrete pillars for the levelling instruments and a vertical conveyor system to move the rod. The comparator employs some components of the existing FGI vertical laser rod comparator (Takalo 1997), e.g., the lift system with stepping motor, the automatic weather station, the laser interferometer, the data computer, etc. Two pillars at a distance of 3.0 m and 7.6 m are used (Figure 5), because the Zeiss DiNi digital level changes its calculation mode at the distance of 6 m. There is one temperature sensor at the height of 1.5 m relative to the beam splitter and near to the path of laser beam. The vertical temperature gradient along the path of laser beam is less than +0.1°C/m (Takalo 1999).

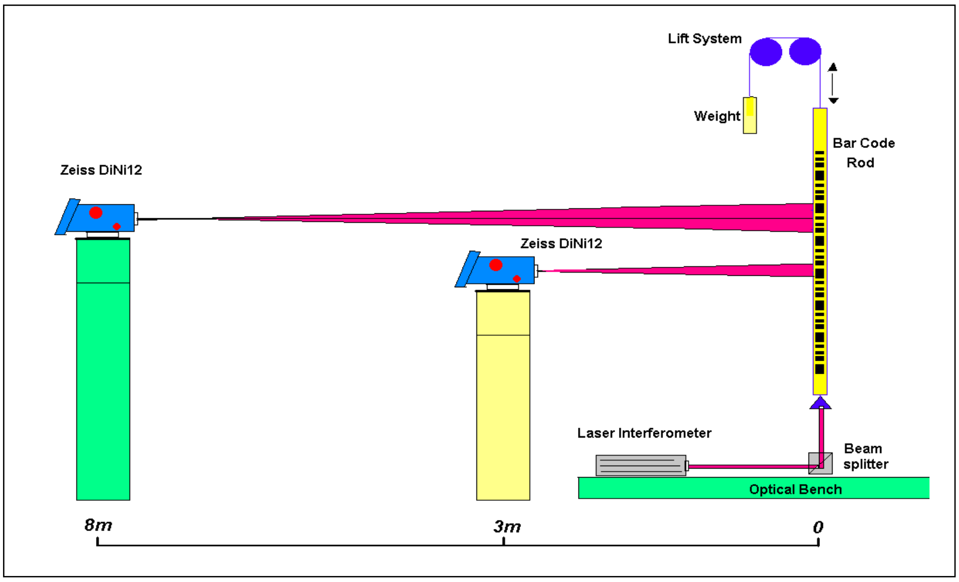

Figure 5. *The system calibration comparator, that is especially designed for the Zeiss DiNi12 digital levelling system with two observation pillars*

FGI-Procedure:

The FGI system calibration procedure consists of forward (A) measurements from the lower to the upper end of the rod and backward (B) measurements from the upper to the lower end of the rod. In order to get better covering over the whole rod scale, rod is measured three times down to up and back, thus including 6 one side measurements and we change the starting point of calibration with app. 8 mm after the first and the second reverse measurement (Figure 6). When moving the rod, the length of step is 25 mm, which is optimal for 3 meter rods (Rüeger and Brunner 2000). The sighting distance from the instrument to the rod is 7.6 m or 3.0 m. The height reading is an average of three successive readings taken during the stop of the rod.

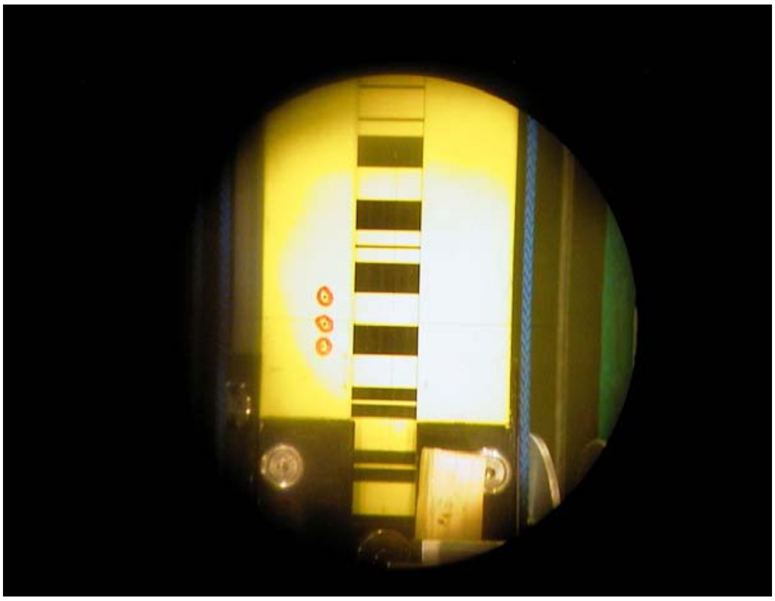

Figure 6. *Starting points of the system calibration are marked as three spots on the left side of the rod. The distance between the points is approximately 8 mm.*

5 Standard uncertainty of system calibration of the FGI

In order to estimate the uncertainty of the system calibration measurement, we model the measuring process using the FGI system calibration comparator and the Zeiss DiNi12 system as object. The correction for the height reading is

$$\delta H = \Delta H - \Delta L = (H_i - H_0) - (L_i - L_0), \qquad (1)$$

where

H_i = height reading when the rod is in position i
H_0 = initial height reading of calibration (Figure 6)
L_i = laser reading when the rod is in position i
L_0 = laser reading when the rod is in initial position

When applying the law of error propagation of uncertainty (ISO 1993) to the equation (1) we get

$$u(\delta H)^2 = 2u(H)^2 + 2u(L)^2 = 2\{\mathrm{u}(H_R)^2 + u(\mathrm{H}_C)^2 + u(L_L)^2 + u(L_C)^2\}, \qquad (2)$$

where

$u(\delta H)^2$ = variance of correction for height reading
$u(H)^2$ = variance of height reading
$u(L)^2$ = variance of length measurement
$u(H_R)^2$ = variance of height reading resolution
$\mathrm{u}(H_C)^2$ = variance of compensator

$u(L_L)^2$ = variance of laser interferometer
$u(L_C)^2$ = variance of conveyor.

The reading resolution of the Zeiss DiNi12 digital level is

$$H_R = 10\ \mu\text{m}.$$

Hence we get the standard uncertainty due to the reading resolution

$$u(H_R) = 10 / (2\surd 3) = \pm 2.89\ \mu\text{m}.$$

Due to the construction of the pillar, the horizontal vibration of the pillar was observed. This effect causes a swinging of the compensator and this in turn affects the uncertainty of the height reading of the digital level as follows:

The random tilt of the compensator is estimated to be 1/3 of its setting accuracy, 0.2”, and this causes an error of ±2.67 µm when the sight distance is 8 m. Hence we can estimate the standard uncertainty due to the level compensator

$$u(H_C) = 2.67 / (2\surd 3) = \pm 0.77\ \mu\text{m}.$$

The combined standard uncertainty of the height reading, including three repeats, is

$$\text{u(H)} = \surd(2.892 + 0.772)/3 = \pm 1.73\ \mu\text{m}. \qquad (3)$$

The length measurements (3 m) with the laser interferometer involve the following sources of errors, which Takalo (1999) has derived using original calibration values from certificates given by the manufacturers and tests made by the authors:

Dead path	2x10-9 (Takalo 1999)
Edlen equation	25x10-9 (Edlen 1966 in Birch *et al.* 1993)
Frequency of laser	3x10-9 (Calibrated by the Centre for Metrology and Accreditation (MIKES)
Pressure of air sensor	28x10-9 (Takalo 1999)
Humidity sensor	19x10-9 (Takalo 1999)
Temperature sensor	48x10-9 (Takalo 1999)
Abbe error	70x10-9 (Takalo 1999)
Alignment of laser	54x10-9 (Takalo 1999)
Installation of rod	2x10-9 (Takalo 1999)
Thermal expansion: Rod	74x10-9 (Takalo 1999)
Thermal expansion: Humicap**	35x10-9 (Takalo 1999)

**Humicap is the trade mark of the temperature and humidity sensor manufactured by Oy Vaisala Ltd.

Hence we get the standard uncertainty of laser interferometer measurements

$$u(L_L) = \pm 0.14\ \mu m.$$

During the observation time with the Zeiss DiNi12, 4-6 seconds, the rod can slide in the vertical comparator as much as 2 µm due to the imbalance of the lift system (see Figure 5). Hence we can estimate the standard uncertainty due to sliding of the rod to be

$$u(L_C) = 2/(2\sqrt{3}) = \pm 0.58\ \mu m.$$

Thus, the combined uncertainty of the length measurement is

$$u(L) = \sqrt{(0.14^2 + 0.58^2)} = \pm 0.60\ \mu m. \qquad (4)$$

By substituting values (3) and (4) into equation (2) we get the standard uncertainty of one system calibration measurement

$$u(\delta H) = \sqrt{2}\ \{u(H)^2 + u(L)^2\} = \sqrt{2}\ (1.73^2 + 0.60^2) = \pm 2.59\ \mu m \qquad (5)$$

and hence we get the expanded standard uncertainty by using the coverage factor of k = 2, i.e., with the 95% level of confidence

$$U(\delta H) = \pm 5.18\ \mu m.$$

Because the system calibration with the FGI comparator consists of 6 one side measurements, we can achieve an uncertainty of the correction for the height reading better than ±2.11 µm. This agrees well with results obtained from practical system calibrations in the FGI since 2002 (Results are unpublished).

According to the FGI unpublished tests a small error in focusing of the Zeiss DiNi12 has not any influence to the height reading.

6 Results

According to a separate rod calibration of the Nedo LD13 rod No. 15814 with the FGI vertical laser rod comparator (Takalo 1999) the obtained scale, –6.8±1.7 ppm (Figure 7), is close to that obtained from the system calibration, –5.8±1.3 ppm, using the same rod and the digital level Zeiss DiNi12 No. 700960 (Figure 8).

The system calibration is an excellent tool to detect possible errors in digital levels as we can see in Figure 9 In this case the readings taken from the upper and lower end of the bar code rod deviate from the main trend because only a part of the barcode scale is visible and imaged by the CCD. Hence, we can conclude that height readings between 0.25 m and 2.80 m are correct and the values from the restricted area we can use to determine the scale as shown in Figure 8.

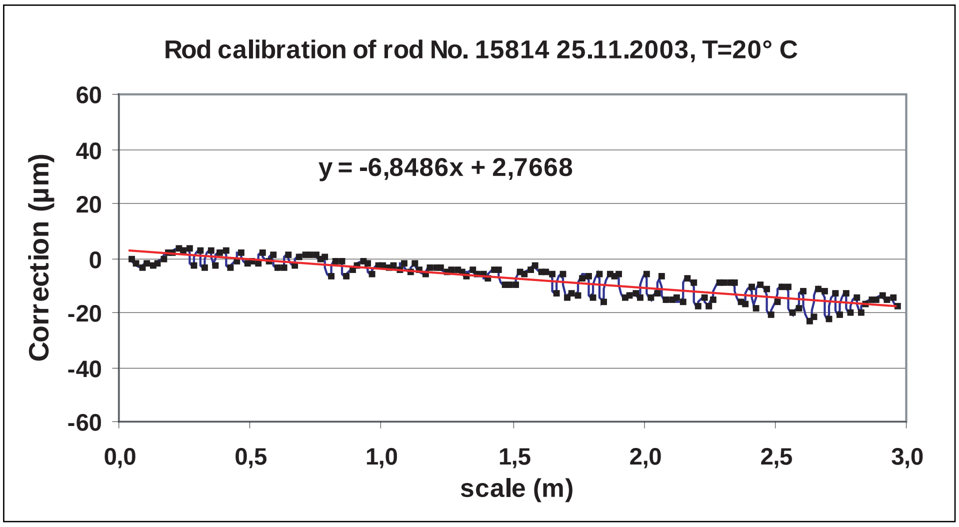

Figure 7. An example of rod calibration and linear regression to determine the scale of a rod

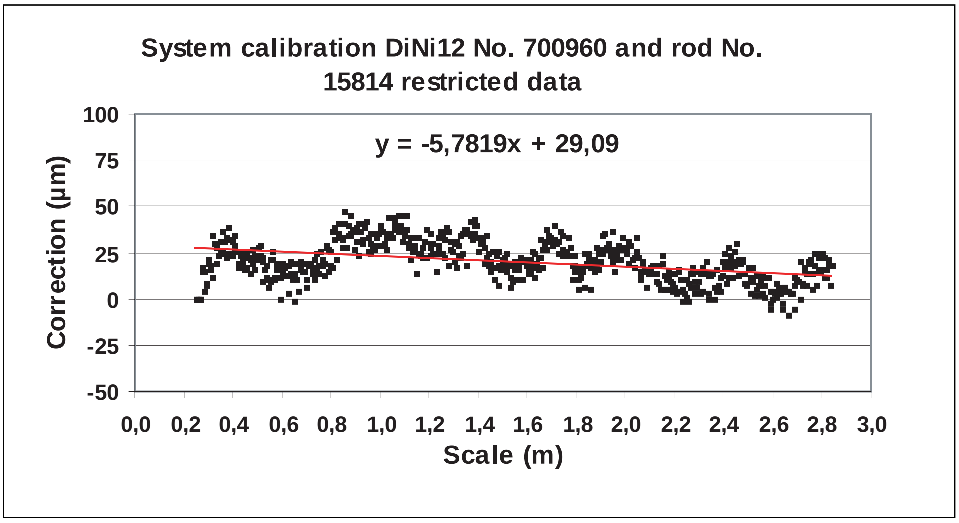

***Figure 8.** An example of system calibration: Restricted data 0.25 – 2.80 m*

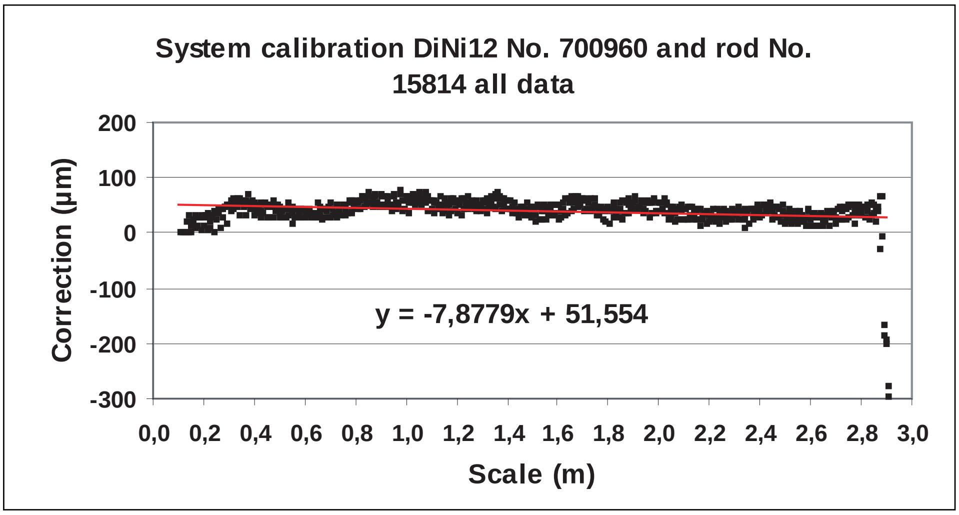

Figure 9. *An example of system calibration: It is better to avoid the lower and upper end of the bar code rod.*

7 Summary and Future Works

The FGI system calibration comparator is an efficient tool

- to determine the scale of a digital levelling system, which is the final output to correct levelling data,
- to control the variation of the scale, which can indicate changes in a rod or in the CCD sensor and
- to examine behavior of the digital levelling system, for example in different ambient temperatures.

One of our objectives today is to carry out simultaneously the system calibration and the rod calibration using the rod and the system calibration facilities. To realize the planned task some constructional changes of the comparator are still required, e.g., to strengthen the observation pillars to make them more rigid and stable etc.

We will develop the hardware and software to versatile activities of the comparator for studying the digital levelling technique.

An inter-comparison with the corresponding comparator in Graz, Austria, will be plant for the coming year.

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