The SLAC Comparator for the Calibration of Digital Leveling Equipment

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At SLAC digital levels are used for precise leveling, both for setting out and monitoring. A very high precision of 30 µm is required, which can only be achieved by regularly calibrating the leveling equipment. The calibration facility is also used for detailed investigations to refine the SLAC leveling procedure. In this paper the setup of the SLAC vertical comparator is described. In order to also perform traditional staff calibration a CCD camera was integrated into the SLAC comparator. Finally an overview of further investigations of our leveling equipment is presented.

1. INTRODUCTION

Digital levels being used more and more due to their highly accurate and fast measurements in an automated measuring process. A shortcoming is that they give less accurate measurements in some cases. When it is not possible to avoid a critical set-up with the digital leveling system, we use the Wild N3 analog level.

There are several sources which are known to have a systematic effect on the height reading and therefore have to be investigated for our digital leveling equipment. One source is the scale factor which has to be determined on a regular basis. Other sources for inaccurate height readings are measurements at critical distances and at the end sections of the rod, a defocused set-up and artificial illumination. Using different rods in a single set-up also makes it necessary to determine the offsets of the rods. With the findings of the experiments investigating the aforementioned error sources, rules for our fieldwork were established.

As mentioned sometimes we use analog levels, therefore the analog rods also have to be calibrated. The calibration is performed with a CCD Camera which automatically detects the edges in the image and compares them with the interferometer readings.

2. DESIGN AND HARDWARE

2.1. The Metrology Laboratory

The laboratory is situated in an old access tunnel to the linear accelerator. Its size is about 30 m × 5 m × 3 m. The walls are made of concrete with a thickness of about 1 m. The whole laboratory, except the portal, is about 5 m beneath the earth surface, therefore the laboratory provides excellent thermal stability. It is air conditioned to achieve a constant temperature of 20°C, which is the reference temperature for instrument calibration.

The vertical comparator was built during the year 2003. The calibration facility is designed to calibrate up to 3 m long invar rods.

2.2. The System Calibration Facility

The procedure of system calibration of digital levels is described in detail in [1]. The principle is to use both the level and the rod in the calibration process. The level is kept at a constant height and the rod is mounted vertically on a rail system where it can be moved up and down. The level's output is compared to "true values". The "true values" are

acquired by reading the position of the rod with a laser interferometer (Agilent N1231A, resolution: 0.6 nm). The meteorological reduction of the interferometer distances is done using the refractive index formula of Ciddor [2] as recommended by IAG [3]. The mean temperature along the laser beam path is computed by modeling the vertical temperature profile that is measured by six temperature sensors (Sensor Scientific WM222C). Further sensors are an air pressure sensor (Vaisala PTB 100A) and a humidity sensor (Vaisala HMP45A). The values of all sensors are measured by an Agilent 34970A data logger and A/D converter. All sensors are calibrated once a year.

The basic setup of the comparator is schematically shown in Figure 1. The section denoted by "CCD section" will be explained in chapter 2.3. The conceptual design of the vertical comparator system was inspired by the TUG design [4] and realized in cooperation with the TUG.
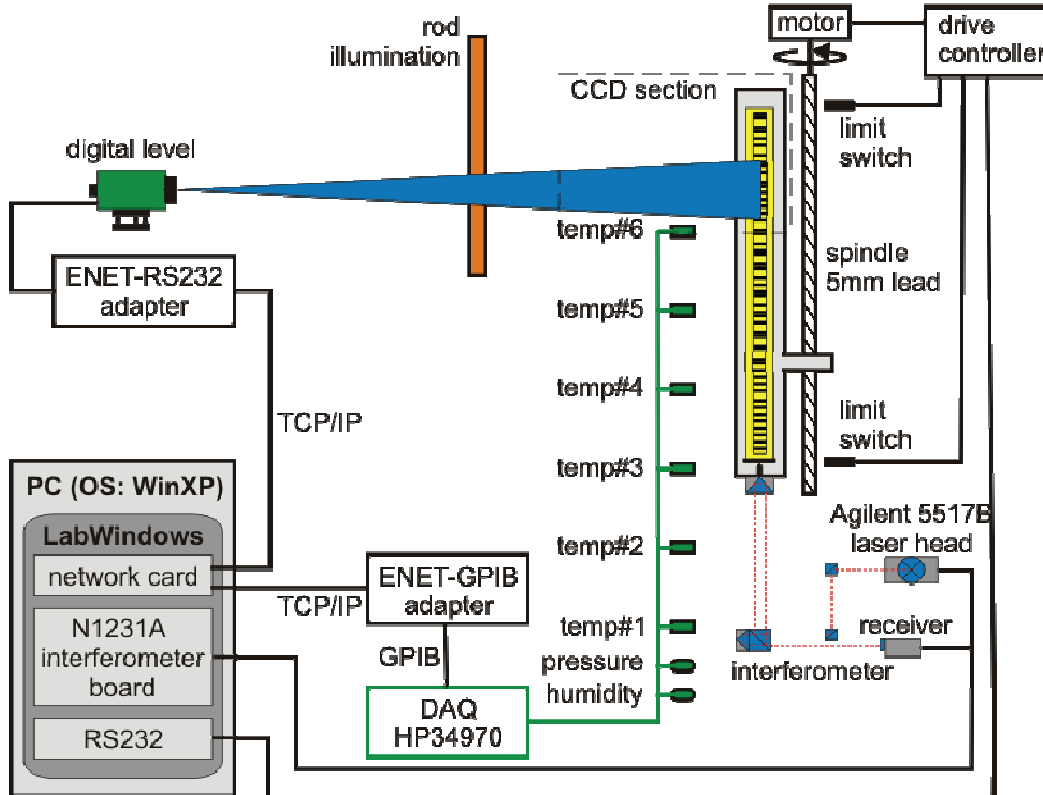

Figure 1: Schematic of the vertical comparator.

The whole comparator is controlled by a standard PC with Windows XP as the operating system. As the comparator system software, the TUG software [4] is used, which was converted to National Instruments "LabWindows" and adopted for the actual hardware components.

The level is mounted on a carriage that can be moved horizontally on a rail system which is attached to the ceiling, see Figure 2. Any sighting distance between 1.65 m and 30 m (this is the distance that should not be exceeded in the case of precise leveling) can be realized. The carriage was manufactured using invar and aluminum in order to form a temperature insensitive support system. Hence, the level remains at a constant height, even if there might be small temperature changes in the laboratory. It is most important that the level and the interferometer do not move with respect to each other during a calibration. The duration of a calibration mainly depends on the number of repetitive measurements by the level (e.g. about 2 hours for a 3 m rod).

Figure 2: Overview of the vertical comparator.

The interferometer is mounted at the bottom of a shaft that is 0.7 m deep and has a diameter of 0.62 m. It was necessary to drill this shaft in the floor (and another one in the ceiling) in order to facilitate the calibration of 3 m long rods. The rod is mounted on a carriage that can be moved 3 m up and 3 m down with respect to the level's line of sight on a 6 m high frame. A precision lead screw (diameter: 32 mm, lead: 5 mm per revolution) is used to perform the motion in combination with an index stepping motor device. A 1.25 m long fluorescent tube emitting a broadband spectrum is used to illuminate the rod.

2.3. The Rod Calibration Facility

Rod calibration has been performed since the beginning of leveling. As the level is not part of the calibration procedure, this technique is not adequate for the calibration of digital leveling systems [5]. However for the continuing use of analog levels (e.g. Wild N3), line-scaled rods need to be calibrated and checked too.

To implement rod calibration on the SLAC vertical comparator, only minor modifications were necessary. A CCD camera (Sony XCD SX900, 1280×960 pixel, 4.65 µm $\times$ 4.65 µm per pixel) is used in combination with a telephoto lens (Schneider Kreuznach, macro iris Componon S 5.6/100, macro extension 75 mm and macro tele 29.4 mm with f=128 mm and a magnification of 3.3) to detect the graduation lines on the rod. The camera is mounted to the ceiling at a distance of 420 mm from the rod. A section of 15.2 µm by 15.2 µm is projected onto each pixel. Hence, at the rod the image area is 19.4 mm by 14.6 mm in size. The illumination of the scale is realized by a flashing light that consists of

12 white LED's. It is mounted at a distance of 160 mm from the rod. Figure 3 shows the setup and Figure 4 shows a schematic of its operation.
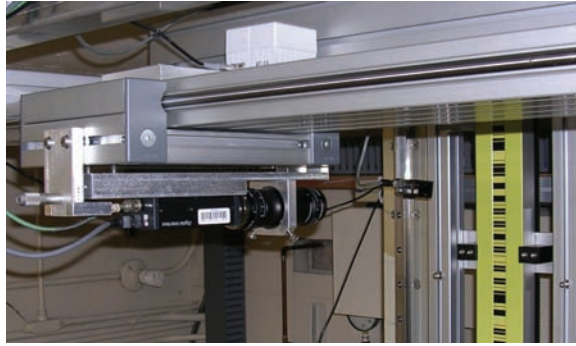

Figure 3: CCD camera set up.

It is important that the line of sight of the camera is stable with respect to the interferometer during the whole calibration. Hence, a second interferometer and an inclinometer (Leica Nivel20) are used to monitor the stability of the camera, see Figure 4. The rod readings are corrected for slight changes in a post processing step.
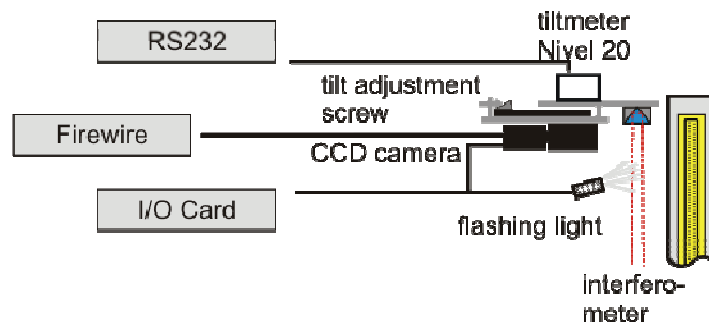

Figure 4: Schematic overview of the CCD camera part of the SLAC vertical comparator.

During a rod calibration, the images are taken with the CCD camera while the rod is moving. The constant velocity of the rod is 1 mm/s. Therefore the camera is set to a short exposure time (1 ms). Imaging the moving rod at this velocity still causes an additional blur of 1 µm length (aside diffraction effects). Because of the short exposure time, bright illumination is needed. The illumination device is switched on for only 10 ms, during which time the LEDs emit a bright flash. The CCD camera, the LEDs and the interferometer that monitors the rod's position are electronically triggered by a digital I/O card (National Instruments NI6601) that generates the trigger impulses with an accuracy of 1 µs. The interferometer is triggered at the mid-time of the CCD camera exposure.

The images taken with the CCD camera are immediately analyzed to detect edges, see Figure 5. The commercially available "Halcon Library" for digital image processing is used for the detection of the edges of the graduation lines. The positions of the edges in the image coordinate system are stored in a file. As every edge appears in multiple images, they are analyzed in a post processing step together. Combined with the interferometer reading at the time the images were taken the edge position can be referred to an interferometer reading in an adjustment step. As nuisance parameters the scale factor of the image and the rotation of the image are estimated.
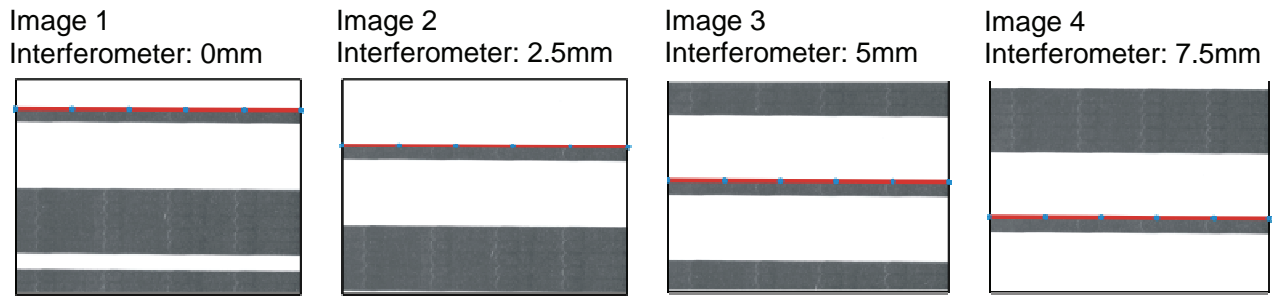
Image 1
Interferometer: 0mm

Image 2
Interferometer: 2.5mm

Image 3
Interferometer: 5mm

Image 4
Interferometer: 7.5mm

Figure 5: CCD Image sequence of one edge.

3. EXPERIMENTAL RESULTS

3.1. Scale Determination

To achieve the highest accuracy with a level in combination with a rod, the determination of the scale factor is necessary. As the scale value may change with time and to check the equipment, scale determination needs to be repeated regularly. In Figure 6b the results of a scale determination are given. The graph shows the dependency of the height deviations from the position on the staff where the measurements were taken. Results obtained with the CCD camera calibration for the same rod are given in Figure 6a. The difference between the two methods is most likely an artifact of the measurement process of the level and its software.
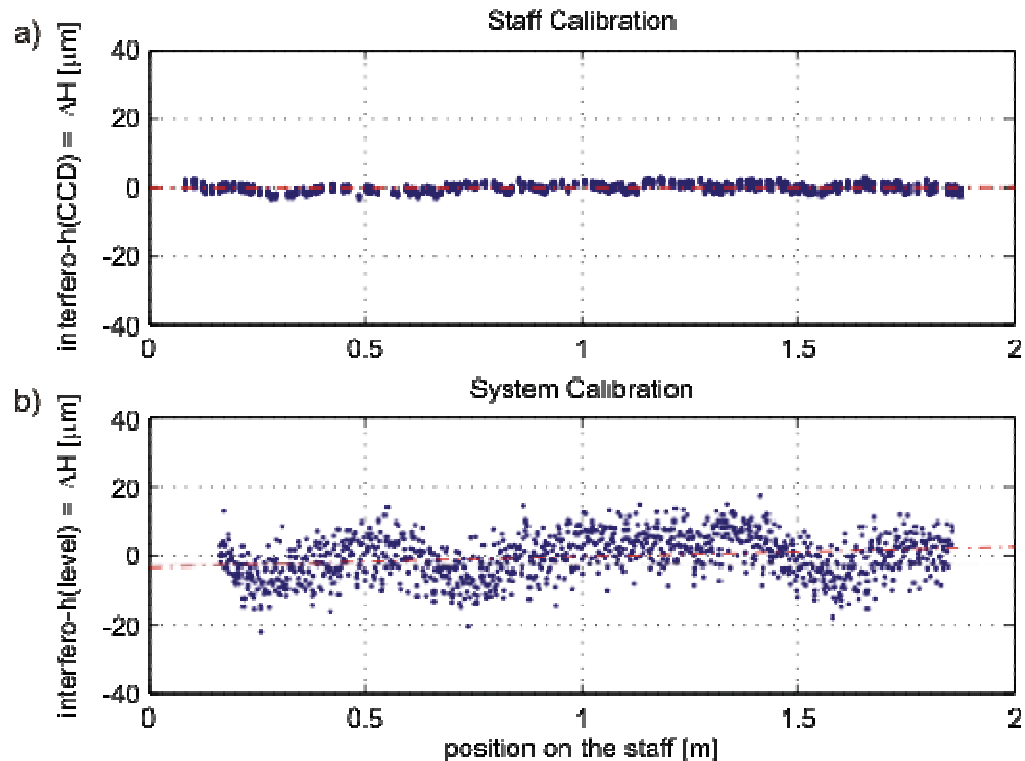

Figure 6: Calibration results for Trimble rod 13702 determined (a) by rod calibration and (b) by system calibration in combination with a Trimble DiNi12.

3.2. Critical Distances

It is well known in the metrology community that digital levels give inaccurate results at certain distances. The Leica NA3000 for example has a critical distance at about 15 m where deviations of up to 0.7 mm could occur, [6]. Woschitz [7] has investigated this effect in detail for the Zeiss/Trimble DiNi 12 and the Leica NA3003 instruments and found that it occurs when the size of code lines, projected onto the CCD array, have exactly the size of one pixel. If a multiple of code lines is mapped to a whole number of pixels a deviation also occurs. Taking these findings, we tested our instruments at their critical distances.

For the DNA03 one code element of size 2.025 mm is projected onto the CCD array with the size of one pixel at a distance of 26.7 m. We are only interested in sighting distances of up to 15 m due to the tight tunnel set-ups. So we carried out experiments around a sighting distance of 13.35 m where one code element is projected onto two pixels and around 8.9 m where one code element is projected onto three pixels. The results for the 8.9 m distance are given as an example in Figure 7. A sinusoidal pattern is recognizable in the results but its magnitude is rather small with a range less than 50 μm.

A similar situation is observable with the DiNi 12 where the code elements have a width of 20 mm. For example at a distance of 10.98 m one code element is projected onto the CCD array with the same size as 38 pixels [7], results of this experiment are given in Figure 8.
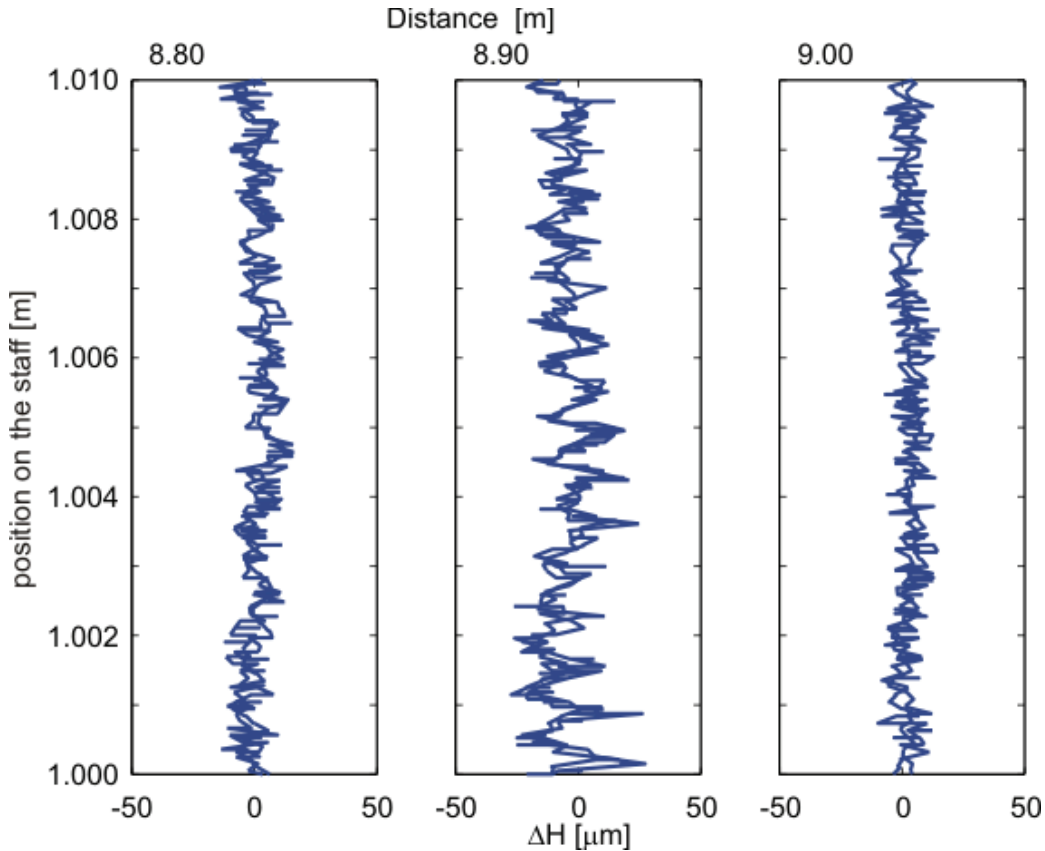

Figure 7: Measurements at and around the critical distance of 8.9 m with the DNA03.

3.3. Defocused Measurements

With the new instruments we use (Leica DNA03 and Trimble DiNi 12) the critical distances do not cause as large deviations as occurred with the old Leica Series. However if there is an additional error source like a slightly unfocused set-up these deviations are can become no longer negligible [7]. We have measured the critical distance of 10.98 m with a DiNi 12 once focused and once with a slightly defocused (focused 0.25 m behind the scale) set-up. This slight blurring is visually hardly recognizable but causes, in our experiment, a two times larger deviation at this critical distance with a range bigger than 0.1 mm, see Figure 8.
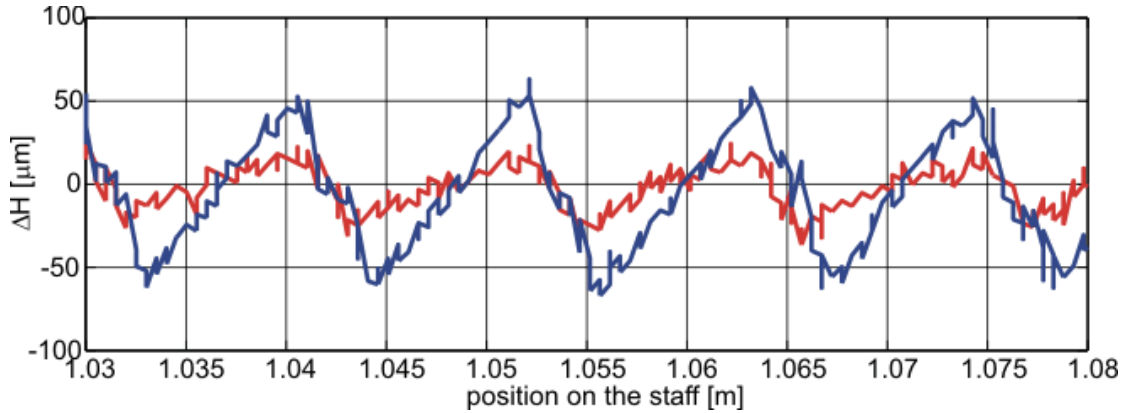

Figure 8: Measurements at a critical distance of 10.98 m with the DiNi 12. The red line shows the focused case, the blue line the slightly unfocused case (250 mm behind the scale).

3.4. End Section of the Staff

In practice the lower staff end is avoided due to refraction effects. Additionally if digital levels are used the upper end section has to be avoided. Intensive investigations carried out by Woschitz [7] showed that height deviations up to several millimeters can occur at the end sections of the rods. The reason is an asymmetric pixel image, therefore the level must detect and eliminate background texture and has only parts of the area visible to determine the height reading. Inaccurate measurements are the consequence, see Figure 9.

The DiNi 12 uses a maximal 300 mm section of the staff ([8], [9]) to determine the height reading (at close sighting distances up to 3.5 m a smaller section of the staff is used because the optic has an opening angle of 5°). The 2 m rod has a visible code section from 0.039 m to 1.940 m. Using only measurements when 300 mm of the scale are visible, the usable section on the 2 m rod ranges from 0.189 m to 1.790 m.

The Leica DNA03 does not use a fixed range on the staff for the final height reading but a section visible at an opening angle of 1°. When measuring at the staff end, that window is shifted into the visible code section, [10]. With measurements at the rod ends at several sighting distances up to 15 m, the following formula was determined to avoid rod end sections on the staff where corrupted measurements could occur [11].

For the lower end of the staff:

$$H_{\text{lower end}} \text{ [mm]} \quad = \text{start of visible code on the staff} + 20 + 7 \times \text{sighting distance [m]}$$

For the upper end of the staff:

$$H_{\text{upper end}} \text{ [mm]} \quad = \text{end of visible code on the staff} - 20 - 7 \times \text{sighting distance [m]}$$

Using a 2 m rod with the DNA03 at a sighting distance of 3 m this results in a usable code section from 0.078 m to 1.899 m.
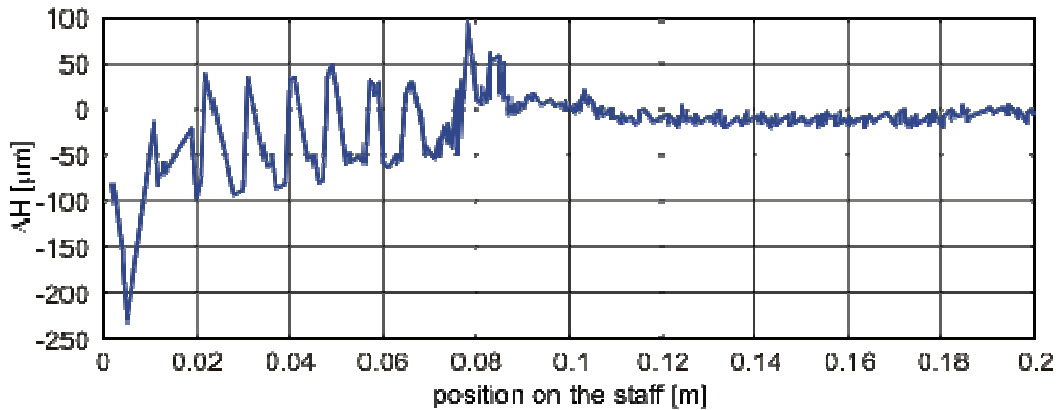

Figure 9: Results of height readings at the end sections of the staff with the DNA03 at a sighting distance of 7.5 m.

3.5. Illumination

Leveling instruments are passive measurement systems that use ambient light to read the rods. In tunnels, we use flashlights to illuminate the rods and allow measurements. Therefore tests with our instruments have to be carried out to find out if the inhomogeneous illumination of flashlights has an effect or not. Commercial Products from Trimble or Leica were not investigated here.

By taking more then 100 measurements at a sighting distance of 3 m, illuminating the staff with a flashlight (Black & Decker Snake Light) in front of the rod and up to an angle of about 45°, either no measurements were taken or the measurements were correct.

But taking measurements with the illumination at a very steep angle (about 5°, see Figure 10a) deviations of up to 0.1 mm could be invoked. This can be explained by a shadowing effect of the code elements. During the manufacturing process the whole scale is first covered with a black layer and then with a yellow layer. The top yellow layer is removed with a high energy laser to make the black color visible. Due to this process the code elements have a certain thickness of a few micrometers, [12].

Another solution for the illumination problem could be the self illuminating rod built by NEDO GmbH, the builder of most precision invar rods. The prototype consisted of an electroluminescent foil with an invar mask representing the code. The scale is inserted in a slightly modified NEDO aluminum housing. The self illuminating rod is based on work done by the Graz University of Technology [13].
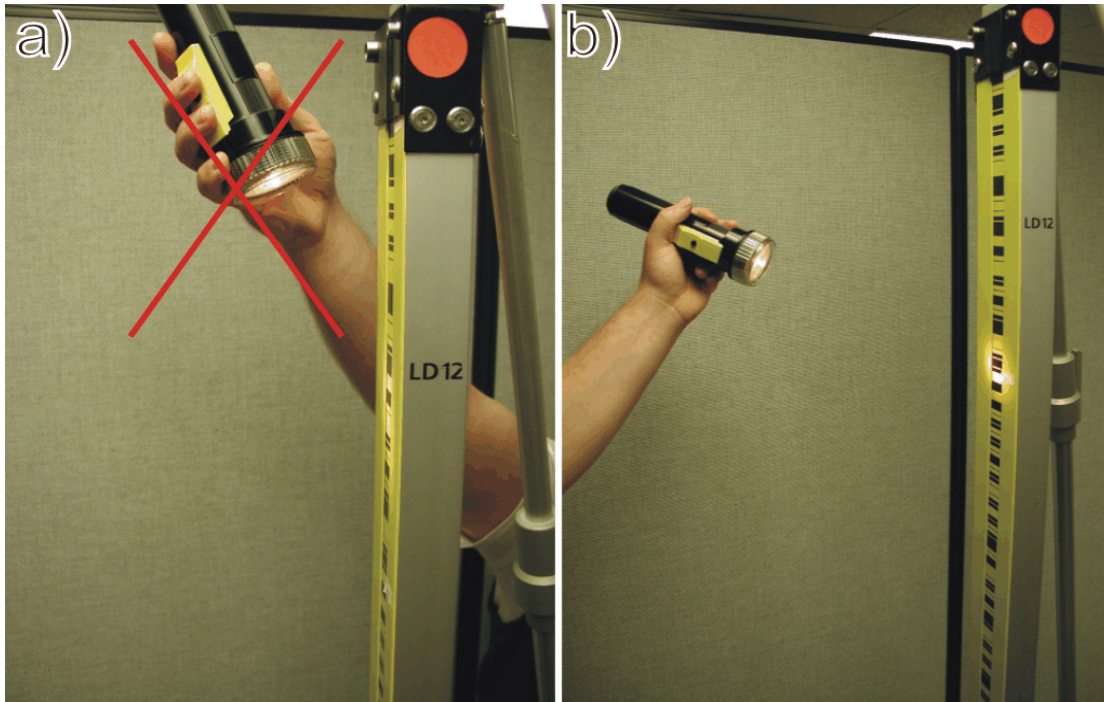
Figure 10: Illumination of the rod. With the angle of the illumination as depicted in picture a) wrong readings would be achieved. With the illumination as in picture b) the illumination did not cause wrong readings.

3.6. Offset

At SLAC, rods with different lengths have to be used within one measurement campaign. To link all height readings together the scale offset between the rods has to be determined. This can be performed with the vertical comparator. First we determine the offset for our short rods by measuring at several positions all over the rod in normal position and upside down, see Figure 11. During the measurements the position of the carriage is controlled by an interferometer. The offset is calculated by comparing the distance moved with the interferometer with the height readings of the digital level. The height differences measured with the digital level contains twice the offset between normal and upside down position.
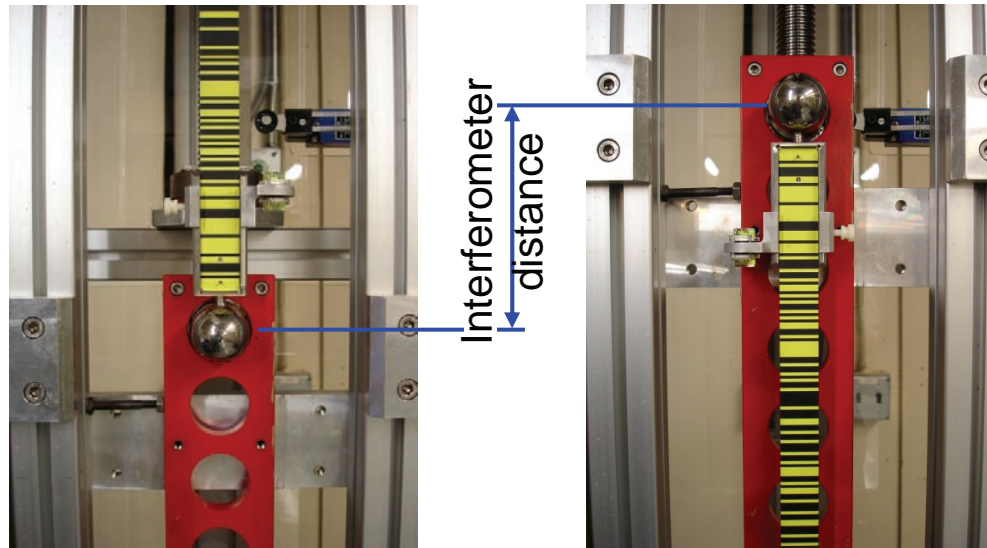
Figure 11: Determination of the offset for a short rod.

The offset of standard rods is determined by comparing them with the short rods, see Figure 12. The results with the NEDO rods in use at SLAC vary within 40 µm. This offset is not adjusted but it is taken into account for all computations.

Figure 12: Transfer of offsets form small rods to standard precision rods.

Acknowledgments

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