INVESTIGATIONS OF DIGITAL LEVELS AT THE SLAC VERTICAL COMPARATOR[1]

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1. INTRODUCTION

Digital levels deliver highly accurate and fast measurements in an automated measuring process. A shortcoming is that they give less accurate measurements in some cases.

There are several sources which are known to have a systematic effect on the height reading and therefore have to be investigated for our equipment. One parameter 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. With the findings of the experiments investigating the aforementioned error sources, rules for our fieldwork were established. The experiments were carried out with our instruments, a Trimble (formerly Zeiss) DiNi 12 (SW Version 1.21) and a Leica DNA03 (SW Version 3.40).

In some cases, when it is not possible to avoid a critical set-up with the digital leveling system, we use the analog level Wild NA3. Therefore the analog rods have to be also controlled. The calibration is performed with a CCD camera which automatically detects the edges in the image and compares them with the interferometer readings. The CCD camera system is also used to determine the height offset between rods.

2. DESIGN AND HARDWARE

The vertical comparator was built in 2003 in the SLAC Metrology laboratory and is situated in the old access tunnel to the linear accelerator below sector 10. Its walls are made of concrete and have a thickness of about 1 m. The whole laboratory, except the portal, is beneath the surface, which gives the laboratory excellent thermal stability. The laboratory and the pass through are both air conditioned to achieve a constant temperature of 20°C, which is the accepted temperature when calibrating instruments.

The facility is designed to calibrate up to 3 m long invar staffs, both for system calibration of digital levels and for traditional staff calibration.

2.1. System Calibration

The concept of the vertical comparator system was inspired by the TUG design [1] and realized in cooperation with the TUG. The concept is to mount the levelling rod in the position

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of use. The rod is moved in a carriage controlled by a laser interferometer, see Figure 1. Abbe's comparator principle was taken into account as shown in Figure 2b: the laser beam of the interferometer is in line with the scale of the rod. The digital level sits in a carriage (Figure 2a) and can be moved along a rail system on the ceiling continuously from 1.65 m to 30 m sighting distance.

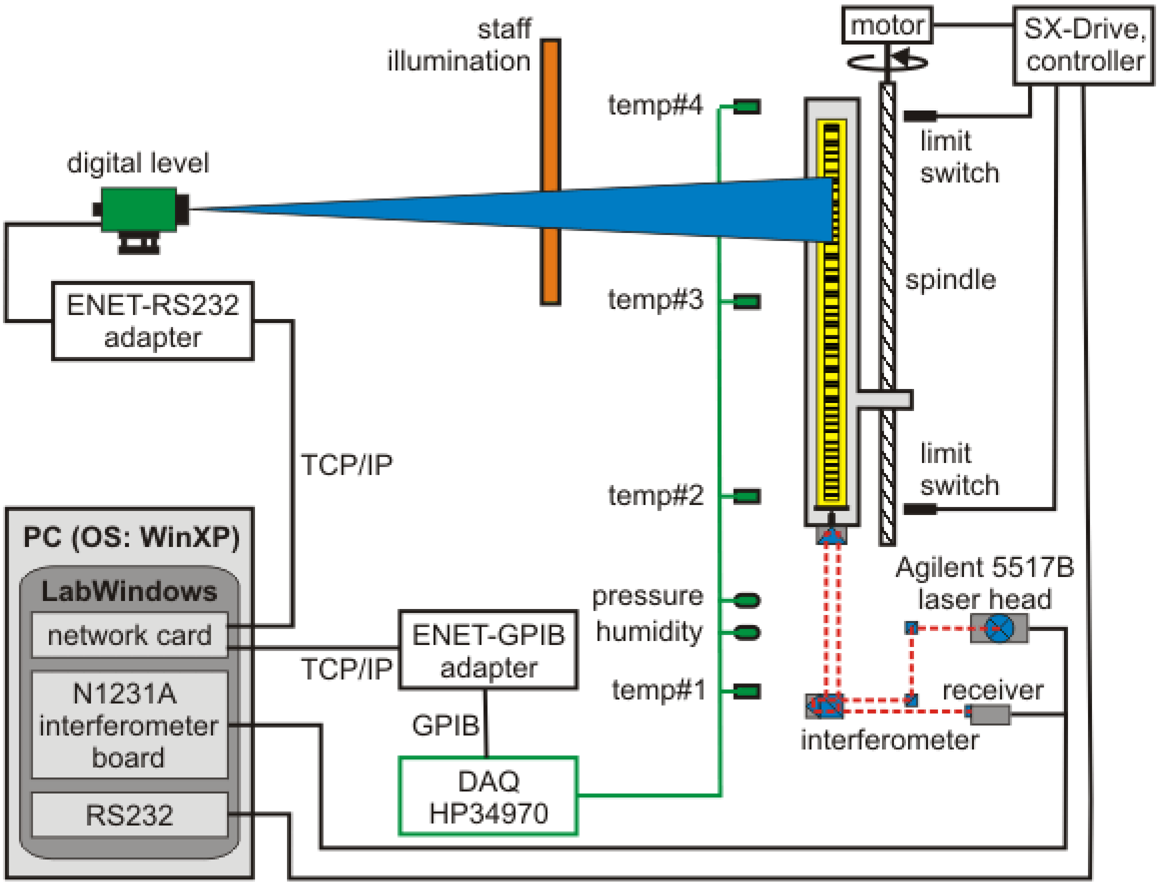

Figure 1 Schematic overview of the SLAC vertical comparator

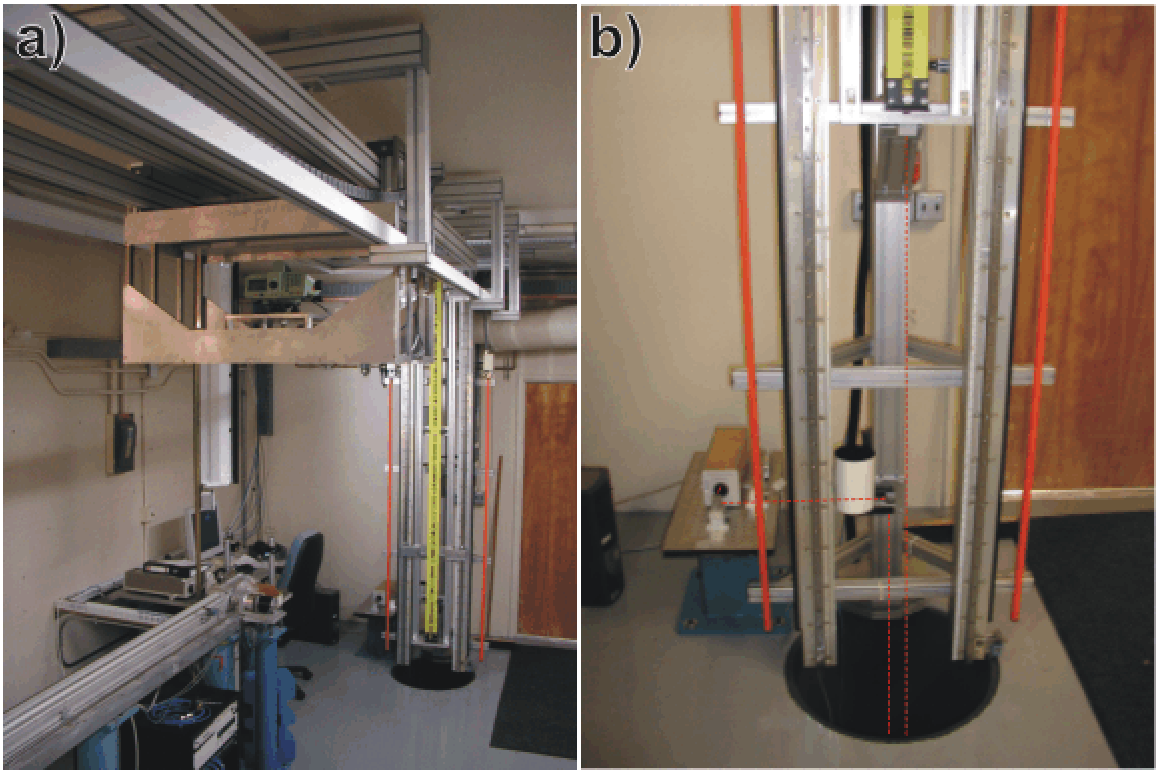

Figure 2: The vertical comparator with (a) the level carriage and (b) the interferometer path

2.2. Traditional staff calibration

The CCD camera calibration system is mounted on the ceiling, where its position is monitored by an interferometer and a tiltmeter, see Figure 3. Measurements with the CCD camera are taken while the rod is moving at 1 mm/s. To allow measurements with a moving target the CCD camera uses an exposure time of 2 ms during which the rod is illuminated with a flashlight. The CCD camera, the flashlight and the interferometer controlling the rod are electronically triggered with an I/O card. The images taken with the CCD camera are immediately analyzed and only the detected edges are stored into a file. In a post processing step all the detected edges are analyzed together allowing an estimate of CCD camera calibration parameters.

To get correct readings with the CCD camera calibration system the camera has to be levelled. This is achieved by monitoring a horizontal laser beam projected onto a homogenous surface at different sighting distances (within the depth of sharpness). Getting the same readings for different sighting distances indicates that the CCD camera is levelled. After the CCD camera is levelled, the tiltmeter is used to check the stability of the tilt and to correct the CCD camera measurements for small movements.

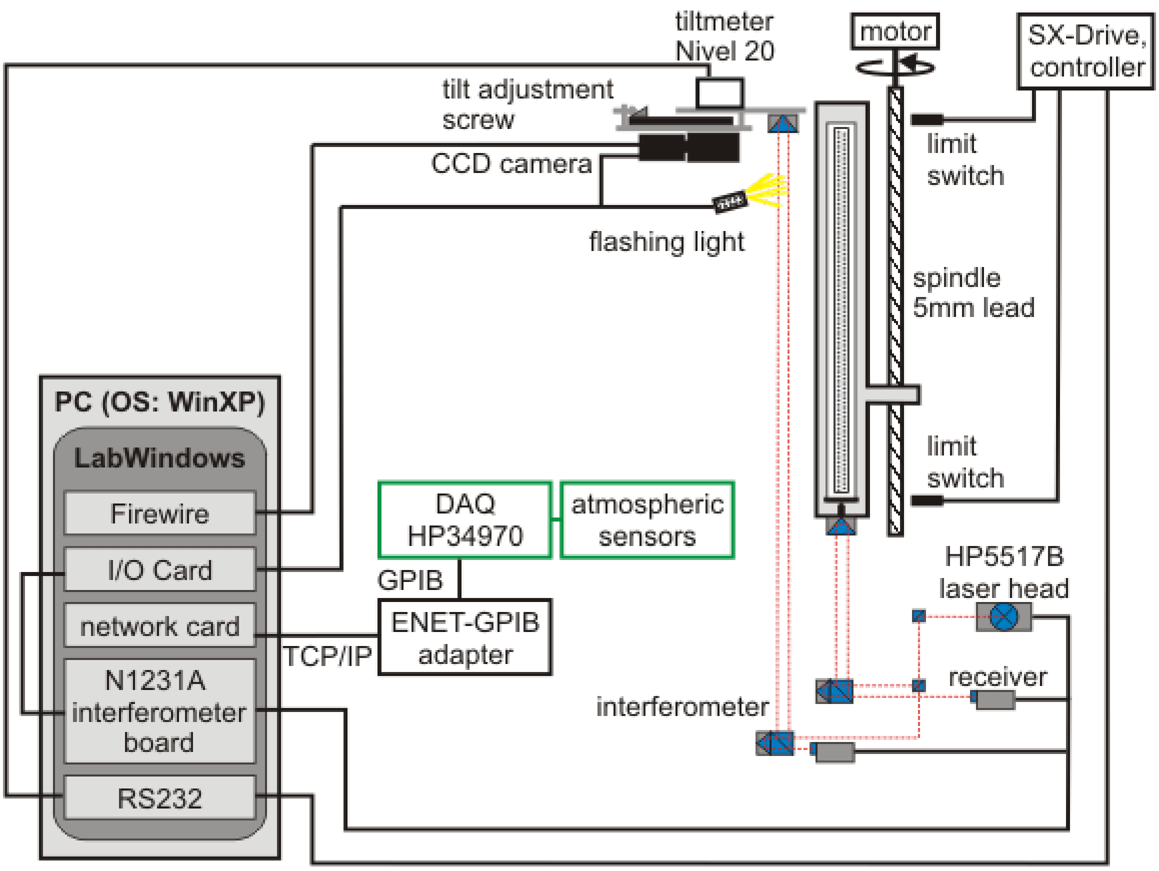

Figure 3: Schematic overview of the SLAC CCD camera vertical comparator

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, scale determination needs to be repeated regularly. In Figure 4a 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 4b, the deviation of 1ppm between the two systems is within the uncertainty. Results for an analog Kern Rod are given in Figure 5.

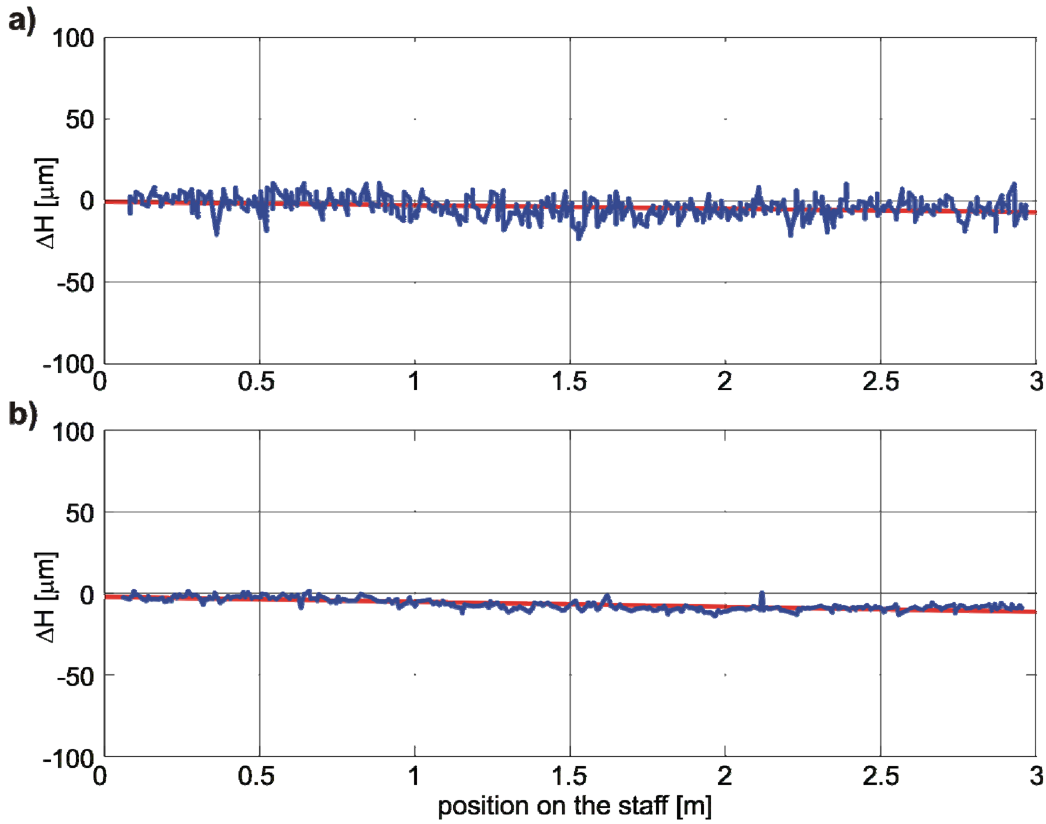

Figure 4: Scale factor for a 3 m rod (NEDO 9660); a) system calibration in combination with the Leica DNA03 : -2 ppm; b) with the CCD camera system: -3 ppm; the blue line gives the deviations of single height readings from the interferometer readings; the red line is the regression line.

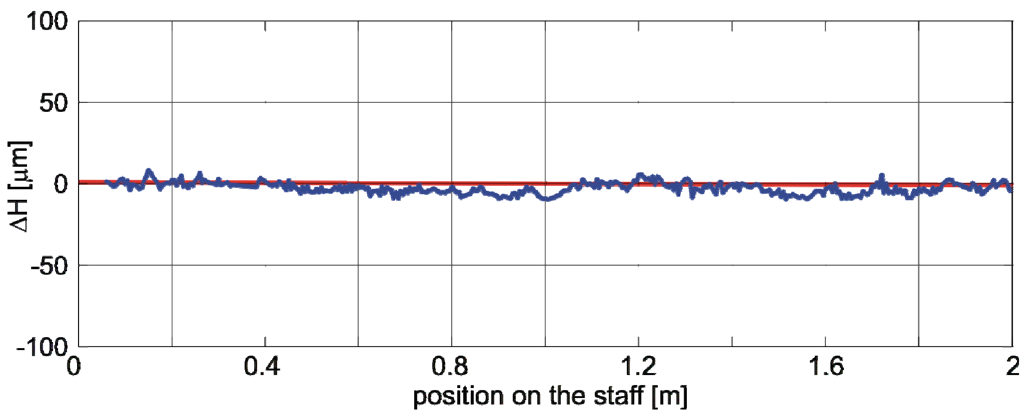

Figure 5: Scale factor for a 2 m Kern rod (S. Nr.: 330136) determined with the CCD camera system; scale factor: -1.5 ppm.

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, [2]. Woschitz [3] 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 also a deviation occurs. Taking these findings, we tested our instruments at their critical distances.

For the DNA03 one code element of the size of 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 (1 code element is projected onto 3 pixel). The results for the 13.35 m distance are given as an example in Figure 6. 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, to get a useful distribution of the edges a bi-phase code is used [4] leading to edges every 10mm. For short sighting distances (< 3.5 m) when not enough code is visible, an additional near-field-code is added, one code element has a width of 10mm. Are the near-field code and the standard code different, a 1 mm wide line is added in the middle of the corresponding standard code element. For example at a distance of 10.98 m one code element of the standard code is projected onto the CCD array with the same size as 38 pixels [3], results of this experiment are given in Figure 7.

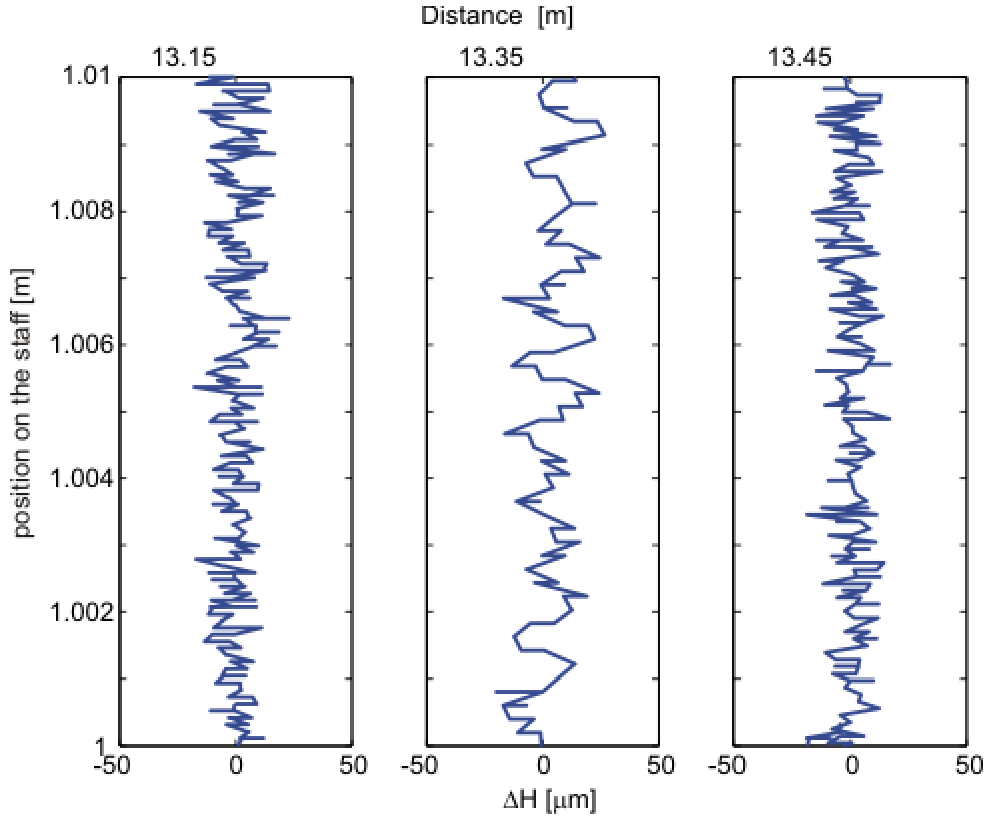

Figure 6: Measurements at and around the critical distance of 13.35 m with the DNA03.

3.3. Defocused Measurements

With the new instruments we use (Leica DNA03 and Trimble DiNi 12) the critical distances do not cause that large deviations like they occurred with the old Leica Series. Anyway if there is an additional error source like a slightly unfocused set-up these deviations are becoming no longer negligible [3]. 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 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 7.

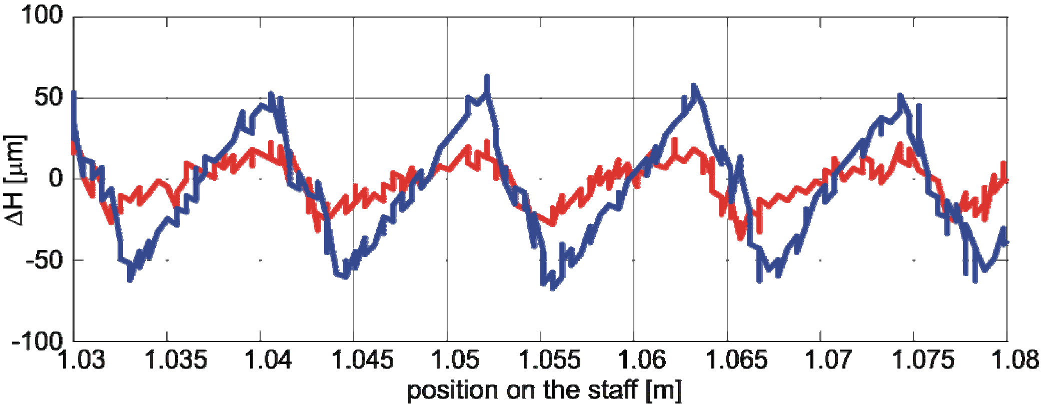

Figure 7: Measurements at a critical distance of 10.98 m with the DiNi 12. The red line shows the focused case, the blue line the slightly unfocused case (250 mm behind the scale).

3.4. End Section of the Staff

In practice the lower staff end is avoided due to refraction effects. Additionally with digital levels the upper end section has to be avoided. Intensive investigations carried out by Woschitz [3] showed that height deviations up to several millimetres can occur at the end sections of the rods. The reason is an unsymmetric 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 8.

The DiNi 12 uses a maximal 300 mm section of the staff ([5], [6]) 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 then, that window is shifted into the visible code section, [7]. 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.

For the lower end of the staff:

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

For the upper end of the staff:

$H_{upper\ end}$ [mm] = start of visible code on the staff – 20 – 7 * 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.

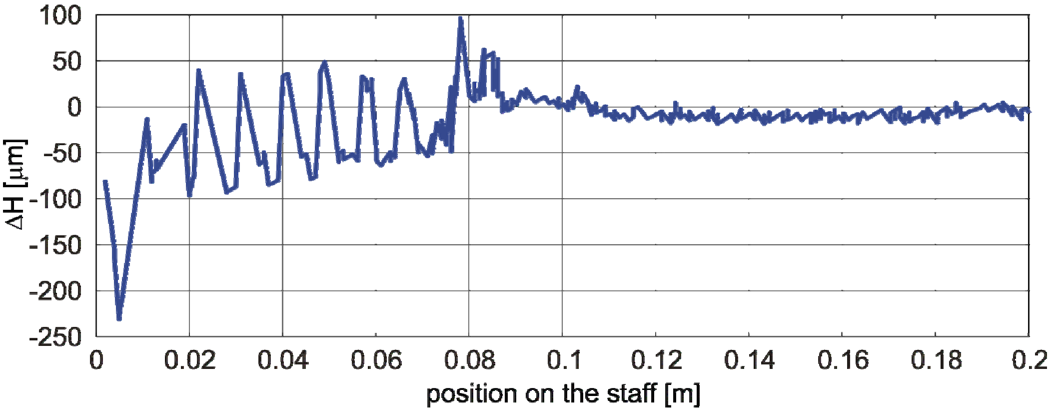

Figure 8: Results of height readings at the end sections of the staff with the DNA03 at a sighting distance of 7.5 m.

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 9a) 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, [8].

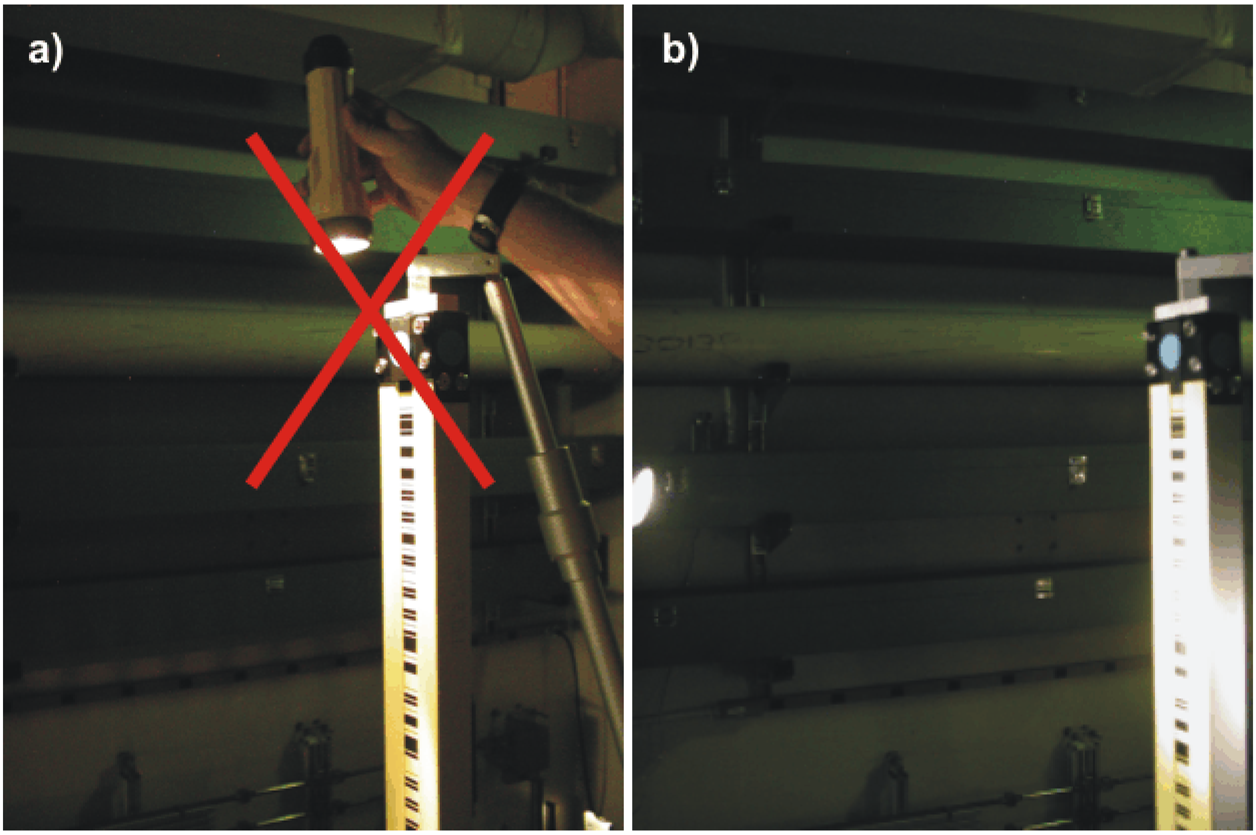

Figure 9: Illumination of the rod. With the angle of the illumination as depicted in picture a) wrong readings would be achieved. With the illumination as in picture b) the illumination did not cause wrong readings.

3.6. Offset

At SLAC, sometimes 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 using the CCD camera detecting the edges of the code lines or with the system calibration method measuring at several positions all over the rod. 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.

4. CONCLUSION

The experimental results show that without taking any precautions digital levels of the new generation can still yield to 0.25 mm erroneous readings. Taking But even much better results can be achieved by avoiding certain set-ups with the equipment.

Determination of the scale factor on a regular basis gives the confidence of quality checked measurements.

The convenience of taking measurements even without properly focusing can cause erroneous measurements. Therefore with the digital levels the same careful measurement procedures as with analog levels have to be carried out. The level has to be plumbed and properly focused. The rod end sections have to be avoided, not only the rod end section. Every obstruction covering the code section used for the height reading can cause the same effects.

In the case of artificial illumination with flashlights, it has to be taken into account that the code has a relief. Therefore illumination at a steep angle might cause a shadowing effect, resulting in erroneous height readings.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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