Investigations of Digital Levels for High Precision Measurements

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Abstract

At SLAC (Stanford Linear Accelerator Center) a fully automated vertical comparator for the calibration of digital levels and invar staffs was developed by the Metrology Department in cooperation with the Institute of Engineering Geodesy and Measurement Systems at the Graz University of Technology. This vertical comparator is the first in the US.

With the vertical comparator it is possible to perform System Calibration and CCD Camera Measurements of rods. System Calibration uses the height readings of the digital level at different positions of the rod and compares them with the reference readings obtained by the interferometer. In the case of CCD Camera Measurements, the position of the edges in the image is determined and again compared with the interferometer readings.

This document gives an overview over the current set-up of the SLAC vertical comparator and experimental results of critical applications like measurements at the end sections of the rod, at critical sighting distances, with unfocused measurements and under artificial illumination with the digital levels in use at SLAC.

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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 only carried out with our instruments, a Trimble DiNi12 (formerly Zeiss) and a Leica DNA03.

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. This part of the comparator is not further described here.

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. Even though, the laboratory is air conditioned to achieve a constant temperature of 20°C, which is the accepted temperature when calibrating instruments any time of the year.

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.

The concept of the vertical comparator system is to mount the leveling rod in the position of use. The rod is moved in a carriage controlled by a laser interferometer (Agilent 5517B), 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 continuously from 1.65 m to 30 m sighting distance.

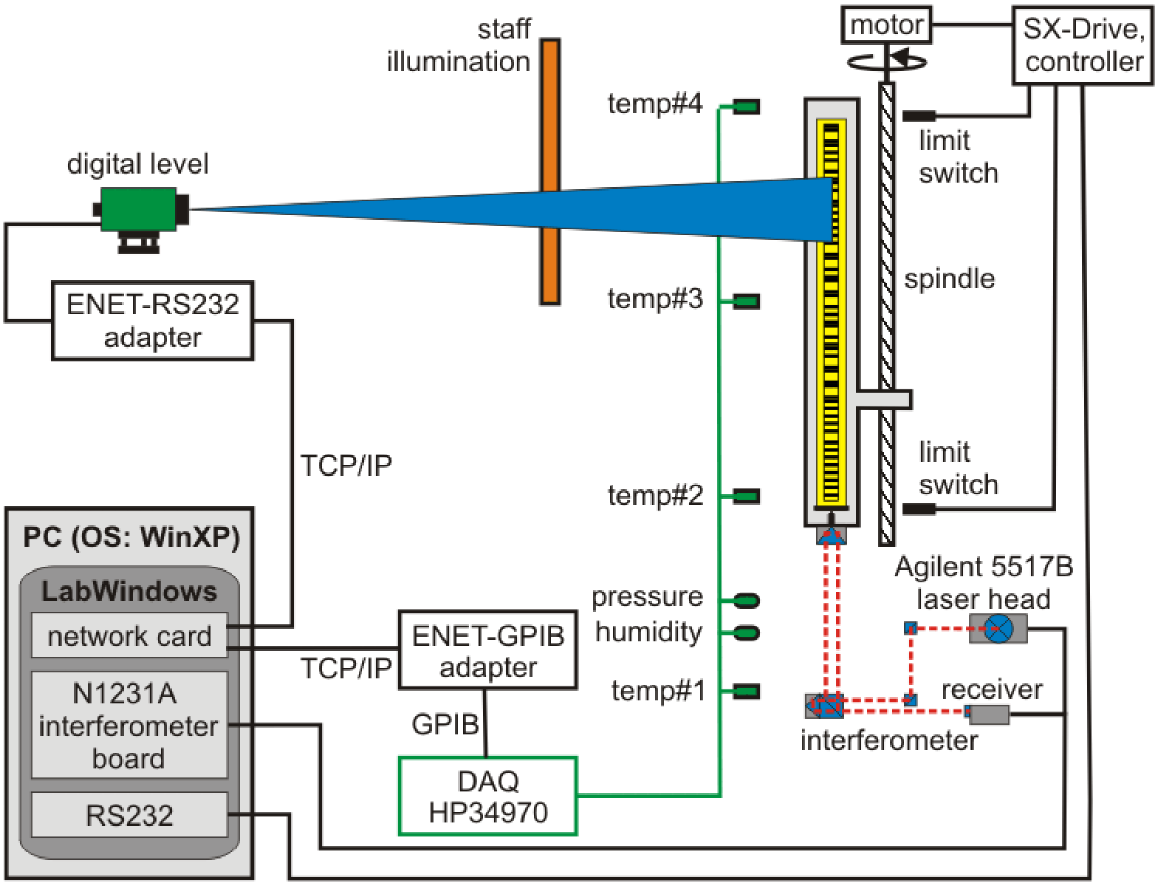

Figure 1: Schematic overview of the SLAC vertical comparator

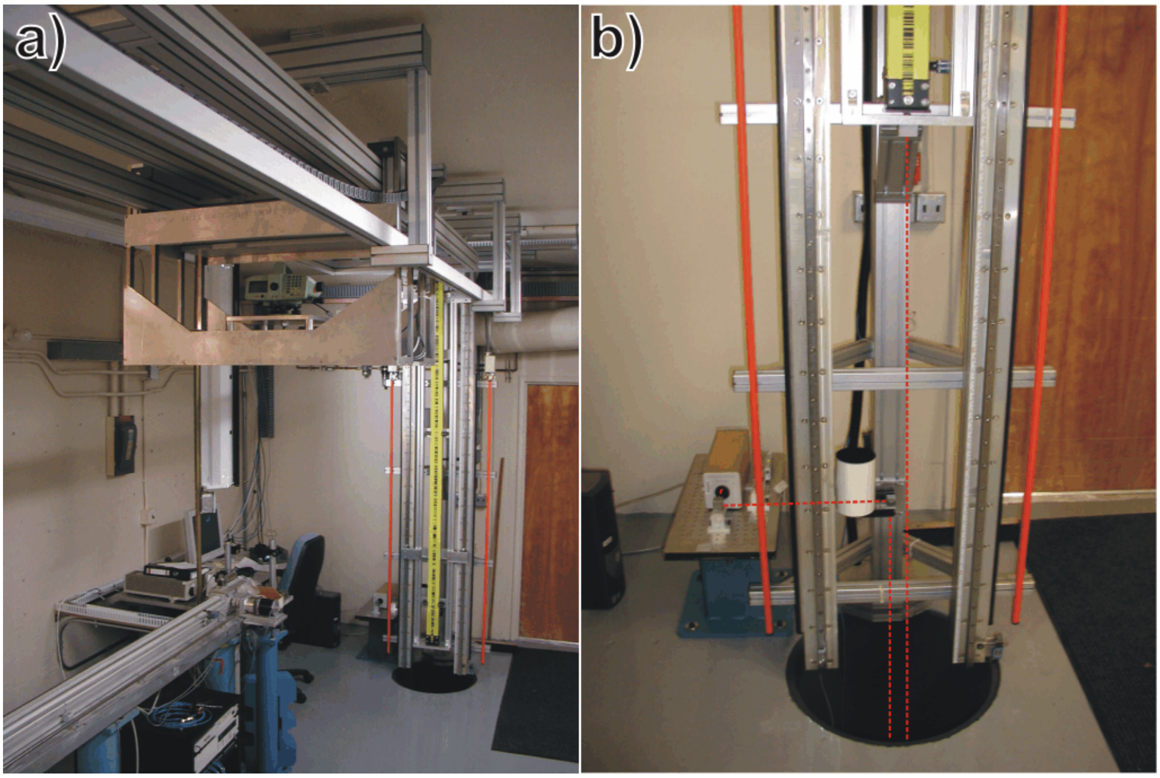

Figure 2: The vertical comparator with the level carriage (a) and the interferometer path (b)

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. This test needs to be repeated regularly to ensure that the equipment is working correctly. In Figure 3 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.

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 0.8 mm could occur, Reithofer et al. (1996). Woschitz (2003) has investigated this effect 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, but smaller. 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 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 8.9 m distance are given as an example in Figure 4. 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 DiNi12 where the code elements have a width of 10 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 (Woschitz, 2003), results of this experiment are given in Figure 5.

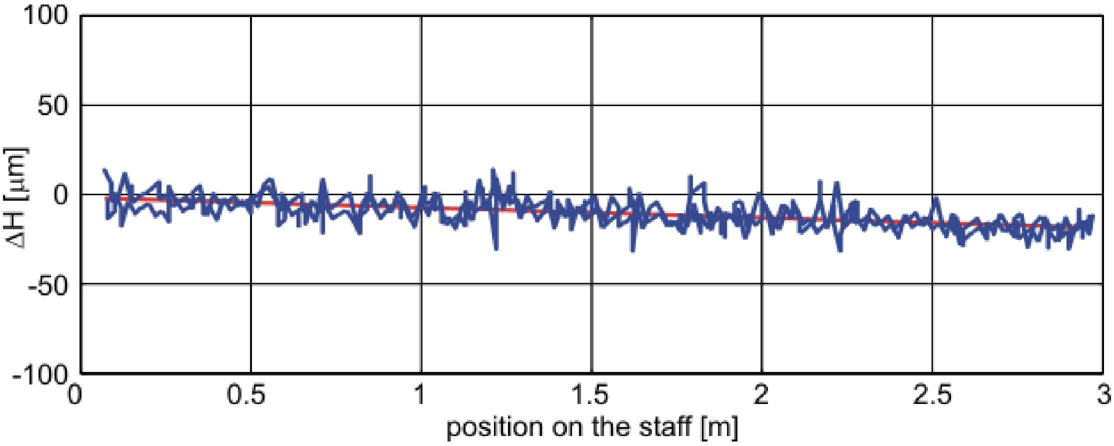

Figure 3: Scale factor of -6 ppm for the Leica DNA03 in combination with a 3 m rod (NEDO 9660); the blue line gives the deviations of single height readings from the interferometer readings; the red line is the regression line

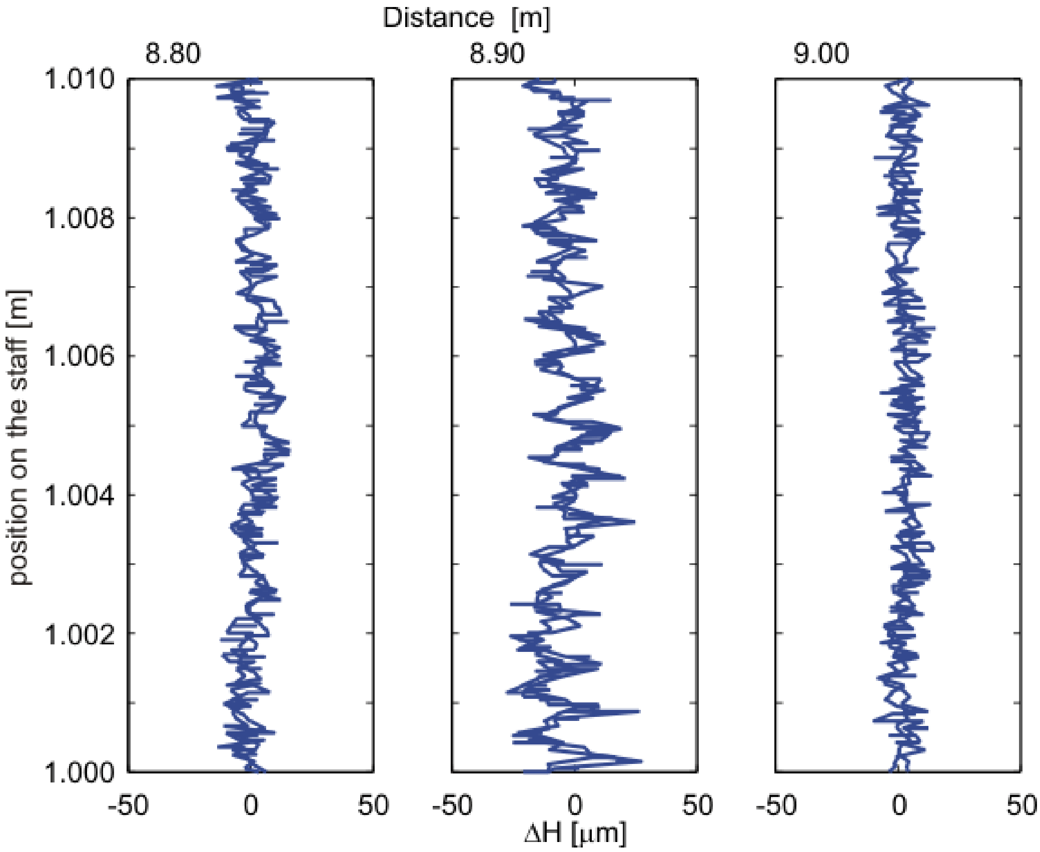

Figure 4: Measurements at and around the critical distance of 8.9 m with the DNA03

3.3 *Defocused Measurements*

With the new instruments we use (Leica DNA03 and Trimble DiNi12) the critical distances do not cause 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 (Woschitz, 2003). We have measured the critical distance of 10.98 m with a DiNi12 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 bigger deviation at this critical distance with a range bigger than 0.1 mm, see Figure 5.

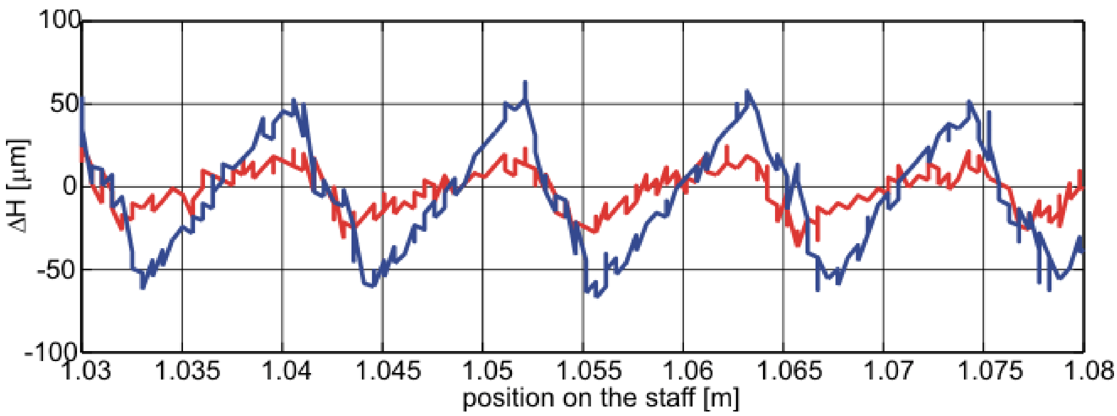

Figure 5: Measurements at a critical distance of 10.98 m with the DiNi12. The red line shows the focused case, the blue line the slightly unfocused case (250 mm behind the scale).

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. For the determination of the height reading, a certain area of the code on the leveling rod is used by the level. If only parts of this area are visible, as is the case at the end sections of the staff, inaccurate measurements are the consequence, see Figure 6.

The DiNi12 uses a maximal 300 mm section of the staff (Trimble, 2001) 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 1.1°. When measuring at the staff end then, that window is shifted into the visible code section, Schneider and Dixon (2002). 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.

H [mm] = start of visible code on the staff + 20 +6.9·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.

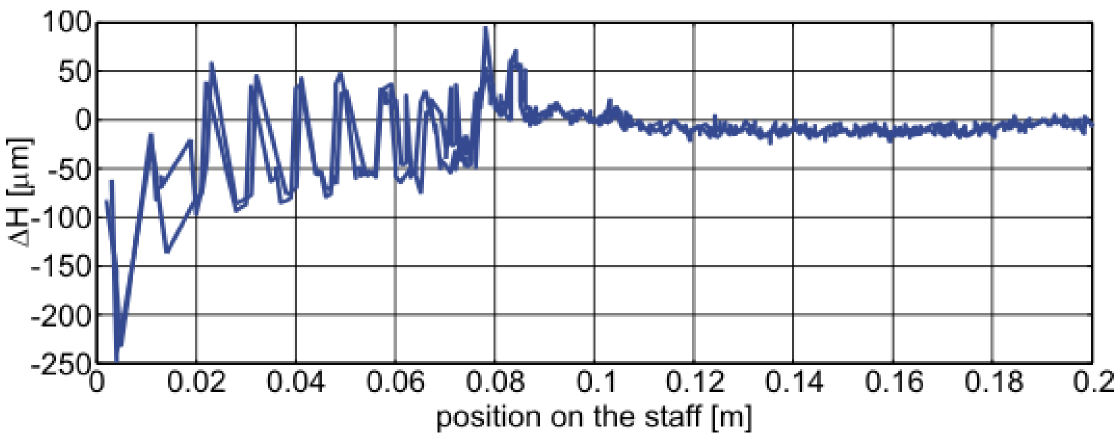

Figure 6: Results of height readings at the end section of the staff with the DNA03 at a sighting distance of 7.5 m.

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.

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 (see Figure 7) 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, Fischer and Fischer (1999).

3.6 Offset

At SLAC, sometimes rods with different length 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.

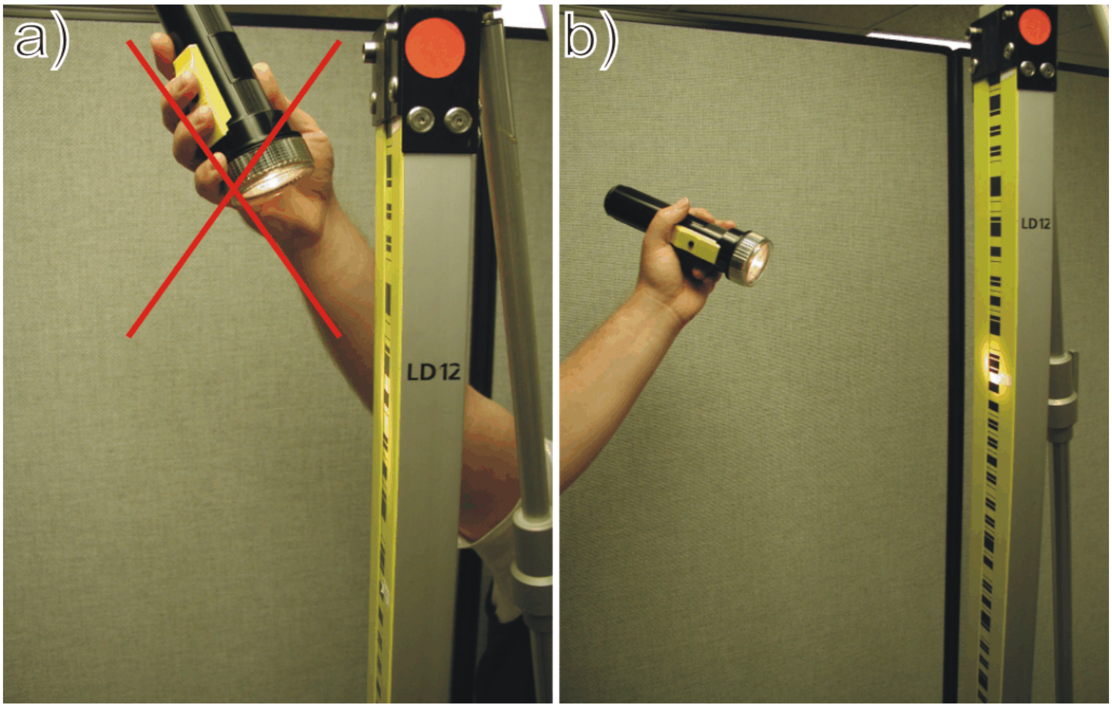

Figure 7: Illumination of the rod. With the angle of the illumination as depicted in picture a) wrong readings would be achieved. With the illumination as in picture b) the illumination did not cause wrong readings.

4 Conclusion

The experimental results show that our digital levels always give results within the specification of 0.3 mm claimed by the manufacturers. 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 leveled and properly focused. The rod end sections have to be avoided, but 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 it has to be taken into account that the code has a relief. Therefore illumination at a steep angle causes a shadowing effect, resulting in erroneous height readings.

5 Acknowledgements

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