

A new standard for line-scale calibrations in the Netherlands

Extremely accurate calibration of (line) scales requires dedicated equipment and measurement conditions that are usually only implemented at the national metrology institutes. The Dutch metrology institute VSL has several facilities to calibrate scales from small micrometer scales up to leveling rods and tape measures with lengths over tens of meters to high accuracy. In order to ensure that VSL can continue to provide services for the ever increasing demand for higher accuracies, these facilities are continuously improved. This paper describes the efforts that have been undertaken recently to improve VSL's capabilities for the calibration of high-precision line scales as well as the motivation for the choices that have been made during this process.

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Line scales are important physical standards of length, used for accurate positioning or measurement in one, two or three dimensions. Depending on the application, line scales can have dimensions from fractions of a millimeter to several tens of meters. For example, small scales are used to calibrate the field of view of optical microscopes. Scales with dimensions in the meter range are used to read out the position of machine tools and measuring machines, while leveling rods find their use in geodetic surveying.

Calibration of high-precision line scales

Until recently, precision line scales were calibrated manually at VSL using a 400 mm SIP measuring machine,

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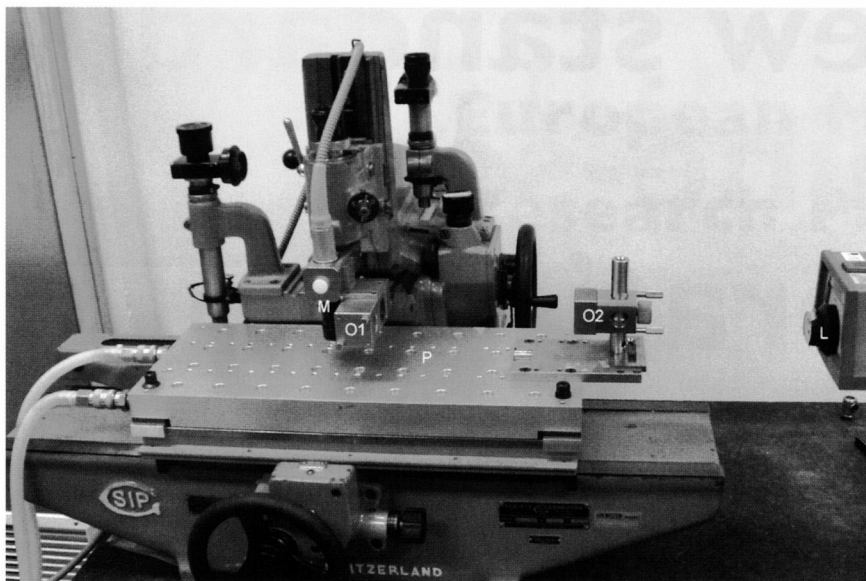


Figure 1. Previous facility at VSL to manually calibrate line scales up to 400 mm. The position of the platform P with the scale (not shown) is manually translated with respect to a video microscope M and measured by a laser interferometer consisting of laser L and optical components O1 and O2. For improved temperature stability the temperature of the platform can be controlled separately.

see Figure 1. Although this machine has three axes, only one of them is used during the calibration process. The measuring machine is equipped with a camera system to visualize the scale markers and a laser interferometer system to measure the position of the camera relative to the scale.

During the calibration procedure the image from the camera is converted to a single curve that represents the intensity of the image features – manual alignment of the scale marker to the exact centre of the image is performed by adjusting this curve to its mirror image. After each alignment step the position of the camera with respect to the scale is stored manually.

The uncertainty that has been realized by this facility and that is registered as part of VSL's calibration and measurement capabilities in the CMC database at BIPM [1] is $100 \text{ nm} + 10^{-6}L$ where L is the length of the scale.

During the past decade this facility has been upgraded, but due to mechanical, optical, thermal and electronic limitations further improvements are not feasible without major modifications. Additionally, this facility has the drawback that it requires realignment of the entire optics for the laser interferometer for each scale. Finally, given the fact that a large part of the calibration procedure is performed manually, the amount of scale markers that can be calibrated is limited due to time constraints.

New calibration set-up

In order to improve the quality for precision line-scale calibrations, it was therefore decided to design and build a new facility. This facility should enable lowering the measurement

uncertainty to $30 \text{ nm} + 5 \cdot 10^{-7}L$ for an increased measurement range of 1,000 mm. To minimize the manual labour during the calibration process, the measurement sequence should be fully automated, allowing calibration of every marker on the line scale. The basic design concept chosen for the new line-scale set-up is similar to that realized at the Finnish metrology institute MIKES [2].

A schematic overview of the new set-up is shown in Figure 2. The system can be divided into four main parts: a granite guide, an actuation mechanism, a movable vision system and a laser interferometer. The vision system captures images of the scale markers on the fly while moving over the line scale on an air-bearing platform that is translated by the actuation mechanism. Along with the image acquisition of the line-scale markers the position of the vision system is captured synchronously by a laser interferometer. In the following sections the individual components will be described in more detail.

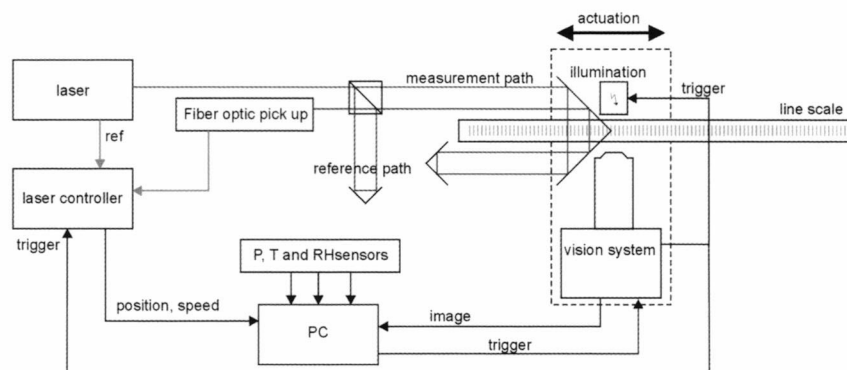


Figure 2. Schematic view of the new set-up. The vision system is mounted on an air-bearing platform that is connected to a motor by a wire. The position of the platform with respect to the stationary line scale is measured by a laser interferometer.

Pitch, yaw and roll after post-processing

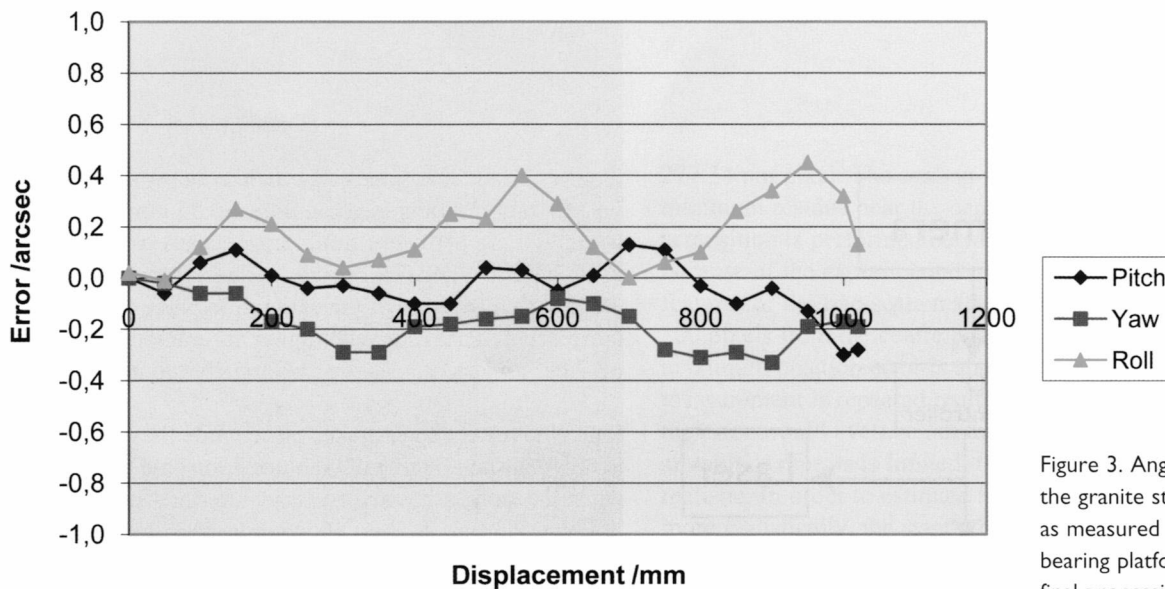


Figure 3. Angular errors of the granite straight guide as measured on the air-bearing platform after the final processing step.

Granite straight guide

The straight guide is part of a granite stone measuring $2,000 \times 1,000 \times 400 \text{ mm}^3$. The straight guide defines the movement of the air-bearing platform that holds the vision system. Shape deviations in the guide result in pitch, yaw and roll motion of the air-bearing platform and therefore result in changes in the directions of view of the vision system. Especially pitch rotates the view in the direction of measurement resulting in a measurement error. Given the total measurement uncertainty for the complete set-up, VSL's requirement for the maximum angular errors (pitch, yaw and roll) is 0.4 arcsec (approximately $2 \mu\text{rad}$), which was met after the granite guide was post-processed by the supplier [3] in the VSL laboratory; see Figure 3.

The thickness of the granite was determined by the boundary condition for the stability of the entire set-up. When the granite deforms due to the moving platform, the supporting points of the scale will pivot and translate the scale during the calibration. A constraint of 2 nm for the maximum displacement of the scale restricts the bending of the granite to 30 nm, resulting in a thickness of the granite block of 400 mm.

During calibration the line scale is supported at the Bessel points, ensuring minimal change in the length of the scale. Since the remaining bending of the granite will result in opposite pivoting of the supports, the scale might slip on the contact points and change the position of the scale with respect to the measurement system in a non-reversible way. To avoid this, materials with different friction coefficients for the two supporting points were selected.

The stability of granite reference flats is largely determined by the stability of the vertical temperature gradient along the thickness of the granite [4]. A vertical temperature gradient of 0.1°C will result in a flatness error of about $1 \mu\text{m}$ that produces $1 \mu\text{rad}$ angular error over 1,000 mm. Therefore, besides conditioning the laboratory, the power dissipation in and around the set-up should be kept to a minimum. This was achieved by using low-power components (high-efficiency LED [5, 6] in pulsed mode, low-power dc motors [7]) and placing the dissipating equipment outside the measurement area.

Actuation

The air-bearing platform is translated over the full range of 1,000 mm using a kevlar wire that is connected to a low-power dc motor [7]. The air supply is connected to the platform by relatively stiff plastic tubing. During the travel over 1,000 mm these tubes change shape and therefore exert changing forces on the platform that could distort the linear translation. In order to avoid this, a second, smaller platform on a conventional ball-bearing guide was realized that moves synchronously to the main platform to stabilize the shape of the tubing and ensure that the movement of the main platform is not distorted.

The measurement system

During the calibration sequence, the measurement platform with the vision system is moving continuously. The position of the scale markers is calculated from both the image information and the position information, so it is very important that these two are acquired synchronously. The data-acquisition timing scheme is shown in Figure 4.

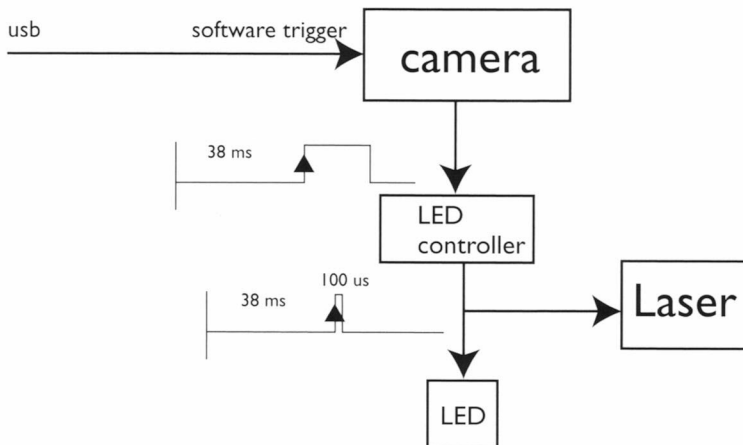


Figure 4. The synchronization of the data acquisition is critical and is initiated by a software trigger of the camera of the vision system. The camera has to prepare for acquisition and after 38 ms releases a trigger that starts the LED flash illumination and latches the momentary position information of the laser interferometer. The trade-off between acceptable image blurring and sufficient exposure of the frame has finally resulted in an optimized flash duration of 100 μ s.

The vision system consists of a microscope with zooming capability [8] and a camera [9] with a resolution of 1,280 pixels x 1,024 pixels. The microscope is equipped with a quarter-wave plate to maximize the contrast of the relevant

features on the line scales. The field of view at the highest magnification setting is about 0.28 x 0.35 mm², yielding about 270 nm per pixel. Initial image analysis is performed using a basic algorithm on-line during the measurement, in order to detect errors of the calibration process itself. A more detailed analysis with higher accuracy is performed off-line, because this is computationally too intensive.

Since the measurement takes place while the vision system is moving, the image will be blurred to some extent. Only when the camera has a very fast shutter or when the illumination time is short enough, the blurring will become acceptable. It was decided to use pulsed illumination – for an acceptable image contrast it was observed that a pulse duration of at least 100 μ s is necessary. For the measurement speed of 0.2 mm/s the blurring therefore becomes 20 nm. Since the blurring should be equal for every scale marker it does not contribute directly to the measurement uncertainty. It is the fluctuations in the actual measurement speed, determined to be about 10% of the speed, which will cause different blurring for different markers. The final contribution due to image blurring to the measurement uncertainty is therefore 2 nm.

The image acquisition during the calibration process is adjusted such that the relevant information of the scale marker is close to the centre of the image, in order to minimize the influence of measurement errors due to the

Residue after calibration of the vision system

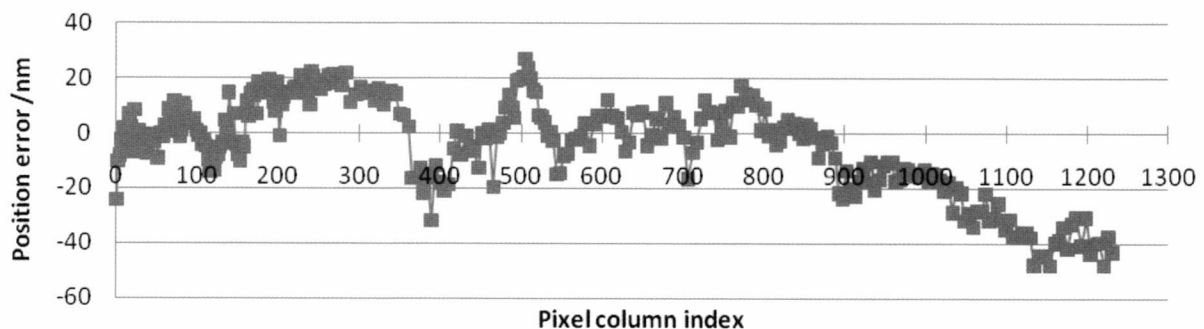


Figure 5. The residual errors of the vision system after calibration with the laser interferometer along all pixel columns. The graph shows slightly less columns than the actual 1,280 because for the first and last few columns the line-scale marker is not completely imaged. The calibration has been optimized for the central region of the vision system between pixel columns 540 and 740.

