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Progress of nanopositioning and nanomeasuring machines for cross-scale measurement with sub-nanometre precision

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Abstract

Nanopositioning and nanomeasuring machines (NPM-machines), developed at Technische Universität Ilmenau, have provided high-precision measurement and positioning of objects across ten decades, from 20 pm resolution up to 200 mm measuring range. They work on the basis of the error-minimal, extended six degrees of freedom Abbe-comparator principle, with high-precision fibre-coupled laser interferometers and optical or atomic force probes. These machines are suitable not only for measuring but also for positioning with an outstanding sub-nanometre performance.

Measurements on precision step heights up to 5 mm show a repeatability of 20 pm. Consecutive step positioning of 80 pm can be demonstrated. With the new approach of an atomic clock-stabilized He–Ne-laser via a high-stable-frequency comb, we achieve a frequency stability of less than 300 Hz, respectively $0.6 \cdot 10^{-12}$ relative frequency stability within 1 h at an integration time of 1 s. For the first time, we can demonstrate a direct, permanent and unbroken chain of traceability between the laser interferometric measurement within an NPM-machine and a GPS satellite-based atomic clock. This paper presents a closer insight into the scientific and metrological background as well as unrivalled measurement results, and discusses the great possibilities of this new technology.

Keywords: nanometrology, nanopositioning and nanomeasuring machine, laser interferometer, frequency comb

(Some figures may appear in colour only in the online journal)

1. Introduction

Today's developments in science and technology are more than ever influenced by nanoscience and nanotechnology.

The transition from the geometrical and equivalent scaling of the International Technology Roadmap of Semiconductors (ITRS) (2001–2014) to system-level roadmapping (ITRS 2.0) has not lost its pace of technological development [1]. The structures produced reach atomic level, with invariably new architectural structures. 'Moore's law', already declared dead several times, is updated by new challenges like 'More Moore', 'Beyond Moore' or 'More than Moore'. In addition to constantly developing optical nanolithography, more and more new alternative nanofabrication technologies are appearing. All these technologies require highly developed measuring and positioning technology over ever larger measuring ranges (>100 mm) with ever better precision at the subatomic level. The importance of nanopositioning and nanometrology as enabling technology is undisputedly increasing more and more. For the continuation of basic and applied research in the fields of nanosciences, nanoengineering and nanomedicine, new approaches for nano- and sub-nanometrology are already being sought. Research at an atomic level requires methods incorporating nano- and picometre-length scales.

In order to solve these far-reaching requirements, the Institute of Process Measurement and Sensor Technology (IPMS) at the Technische Universität Ilmenau has been working for many years in the field of nanopositioning and nanomeasuring machines (NPM-machines). The NMM-1 NPM-machine [2], which has been produced by SIOS Meßtechnik GmbH for years, with a measuring range of 25 mm × 25 mm × 5 mm, is now successfully used in various national metrological institutes [3–5] and has successfully applied for various international dimensional comparisons [6].

Based on this, the next generation, the NPMM-200 with a 200 mm × 200 mm × 25 mm measuring range, was developed at the IPMS [7] on the basis of SIOS fibre-coupled laser interferometry. With a resolution of 20 pm, a cross-scale metrology over ten decades can be achieved. Two such high-precision machines are now in operation at IPMS at the Technische Universität Ilmenau and at the Institute of Technical Optics at the University of Stuttgart.

Two main objectives are addressed in this paper: what is the basis of the exceptional accuracy of the length measurement and how can it be further developed through the use of frequency comb technology? In this paper, the scientifictechnical approaches for the achievement of these goals are described, the outstanding performance is presented in the same way as the metrological capability is demonstrated and future objectives are discussed.

2. High-precision approach

In 1987, NIST started a high-risk project for the development of the so called molecular measuring machine (M^3) capable of positioning and measuring with atomic scale accuracies over an area of 25 cm^2. The design goal was to obtain a point-to-point spatial resolution of 0.1 nm in a volume of 50 mm × 50 mm × 100 µm [8]. At the end of the 1990s, scientists of the IPMS started with the systematic development of NPM-machines [7].

The basic approach of the implementation of an error-minimal measuring concept—the so-called Abbe's principle—for all three measuring axes was described [2] followed by many recent developments and applications [9–14]. In contrast to other micro-/nanoCMM [15–17], in the NPMM, a mechatronic control engineering approach is pursued from the outset. The unavoidable tilting angles are measured and then adjusted by means of electromechanical actuators in a closed control loop. We call this approach 'extended 3D-Abbe comparator principle'. On this basis, i.e. by using (additional) angle measuring technology, a higher precision can be achieved than high-precision guide elements would allow. In the NMM-1, autocollimation measurement achieves control deviations of $< 0.05''$. Here, an improvement over air bearings by a factor of 20–40 can be achieved.

Laser interferometric methods figure among the most accurate measurement methods. The basis is the laser wavelength in vacuum or the laser frequency. Frequency-stabilized He–Ne lasers have established themselves here, achieving a frequency stability from 10^{-8} to $2 \cdot 10^{-9}$ [18]. The large external dimensions as well as the thermal load of these lasers are not very advantageous for use in precision machines. Since the 1980s, the IPMS at the Technische Universität Ilmenau has been working on the scientific principles of fibre-optic coupled laser interferometers [19], which are also successfully produced [20]. The laser interferometers have a high thermal stability and are small and compact. The resolution of the laser interferometers is 20 picometers. The optical fibre coupling between the He–Ne laser and interferometer together with an original plane mirror interferometer concept [21] enables the realization of the 3D Abbe comparator principle in the most ideal way. Here, the wavefront errors are clearly in the subnanometer range due to the design of the beam expansion system.

Of course, in order to be able to use the laser wavelength as a measuring standard of the highest accuracy, the refractive index dependence of the wavelength in air must be corrected by measuring the essential influence variables, air temperature, air pressure and water vapour partial pressure, and using the modified Edlén formula [22, 23].

To extend the measuring range to 200 mm × 200 mm × 25 mm, the NPMM-200 was developed at IPMS [7]. In order to keep the Abbe error small, the angle deviations are now measured with three additional angle interferometers and adjusted with significantly lower uncertainty. This means that the NPMM-200 now uses a six-axis fibre-coupled laser interferometer system (see figure 1).

With this approach, we achieve an angular measuring resolution of 0.0002 arcsec and a measuring stability of 0.0005 arcsec.

Figure 2 shows the overall structure of the NPMM-200. The six-axis laser interferometers are fibre-coupled and mounted on a solid and thermally stable metrological frame made of Zerodur [7]. The upper part of the metrological frame provides space for the implementation of various nanosensors or nanotools. Here, a laser focus sensor is integrated. The mirror plate is equipped with a measuring object holding plate to protect it from any mechanical impact. In order to keep the heat influence of the voice coil actuators on the mirror corner to a minimum, they are arranged on the outside. The permanent magnets are fixed to the movable measuring table mounted on rolling element guides. The planar voice coil systems have additional water channels where the heat input generated by the voice coil current can be dissipated. Additional gravitational compensation systems relieve the three vertical voice coil systems (not shown in the picture). With the latter, not only the z-movement but also the angle control around the x- and y-axis takes place.

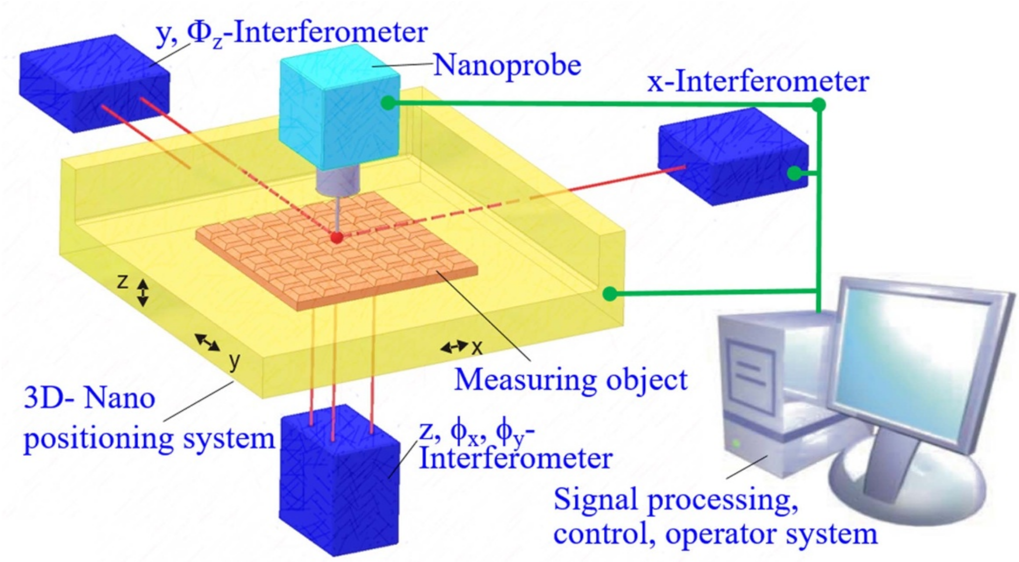

Figure 1. Measuring approach of NPMM-200.

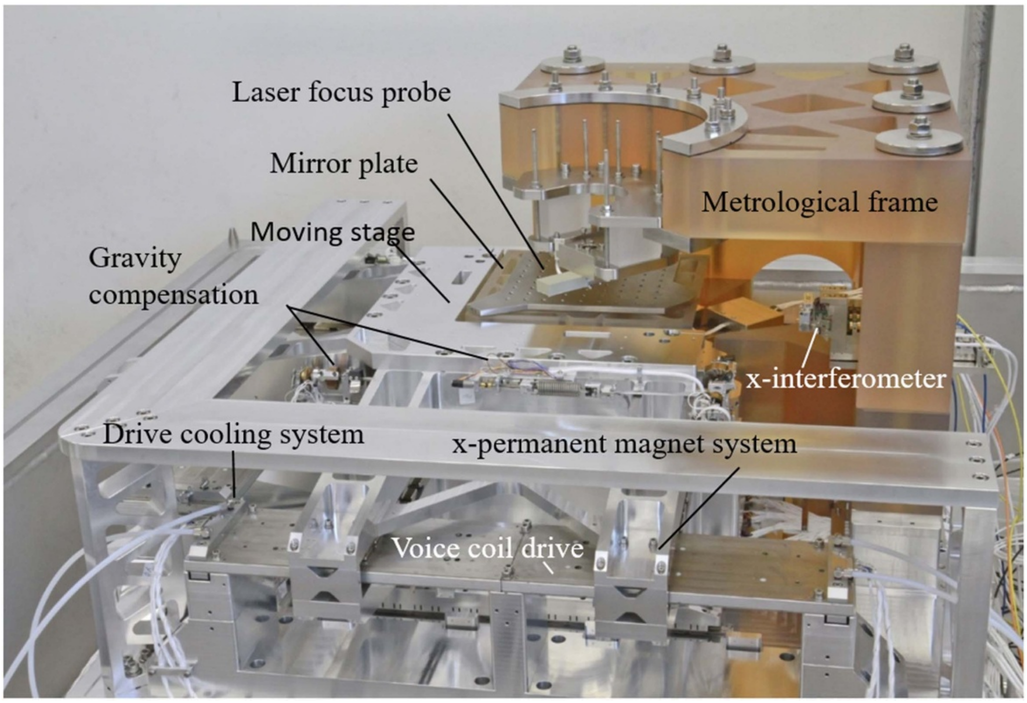

Figure 2. Opto-electro-mechanical system of NPMM-200. Adapted from Jäger *et al* [7]. © IOP Publishing Ltd. All rights reserved.

In order to keep the measuring uncertainty of the NPMM-200 small, despite a large measuring range, the potential to operate the machine in a vacuum was made possible. With a reduction of the air pressure to approximately 1 mbar, the relative temperature influence on the refractive index fluctuations of the air is reduced by a factor of 1000 to 10^{-10} K^{-1}.

3. Measurement results

The measurement scale of the NPMM-200 is defined by the laser wavelength of the stabilized He–Ne laser. The typical frequency stability over 1 h is $2 \cdot 10^{-9}$ [24].

This stability is also achieved over a longer period of time, for example, 120 h (see figure 3). The stability of the plane mirror interferometers used in the NPMM-200 for a fixed measuring mirror and a short optical path difference can be seen in figure 4. Here, the influence of the laser frequency noise can be neglected. Rather, mechanical, thermal and refractive index fluctuations are responsible for this noise. The p-p value is $\pm$100 pm and a standard deviation of $\pm$25 pm can be achieved. Furthermore, an advanced signal processing guarantees a high constancy of the photoelectric signals and thus enables the electronic compensation of non-linearities to a high degree [25].

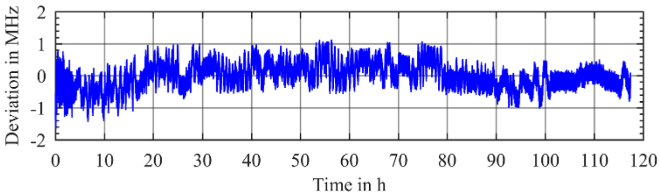

Figure 3. He–Ne laser frequency stability within 120 h ($\Delta f = 1$ MHz $\hat{=}$ $\Delta f/f = 2 \cdot 10^{-9}$).

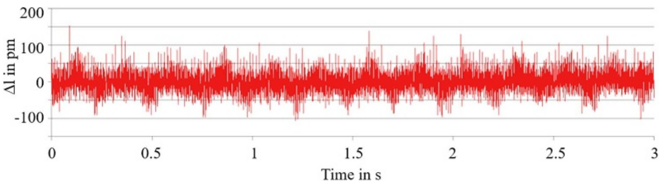

Figure 4. Short-term stability of a plane mirror interferometer.

The big difference between a micro/nano CMM and our NPMM-approach is the high positioning capability. The machine is able to approach any point within the measuring volume (200 mm × 200 mm × 25 mm) with a positioning repeatability of less than 4 nm. At the same time, the machine can carry out the smallest steps in a sub-nanometre range. In figure 5, several consecutive steps of (a) 1 nm and (b) 80 pm were carried out in the z-direction up- and downwards. The noise on every plateau is mostly less than ±60 pm—sometimes less than ±30 pm. It is worth noting that the z-table with a weight of approximately 24 kg is lifted and controlled with this sensitivity at every step.

It is not trivial to prove the high metrological potential of the NPMM-200 by suitable metrological investigations. The DIN EN ISO 10360–2 [26] addresses the acceptance check of coordinate measuring machines, and the VDI guideline VDI/VDE 2617 part 12.1 [27] deals, in particular, with the testing of micro-geometries.

Both guidelines provide for testing by using calibrated test specimens traced back to the unit of length of metres. Today, test specimens, such as gauge blocks, can be calibrated at National Metrology Institutes with a minimum measurement uncertainty of 22 nm [28]. In [29], a number of measuring standards for the acceptance test of micro-CMM are considered. The uncertainties of all these artefacts are ultimately greater than the potential of the NPMM-200.

There are several step height standards available, especially for the calibration of scanning probe microscopes. The international state of nano step comparison measurements from 7 nm 1000 nm step height standards is very well represented in [6], at least with uncertainties of 1 nm ($k = 2$). To further investigate the stability and repeatability of our machine, we used special, very stable step height standards made from quartz in the range of 1–5 mm. The probing of the step heights was done with a laser focus sensor, also developed at the Technische Universität Ilmenau [30] and nowadays also commercially available from SIOS Messtechnik GmbH.

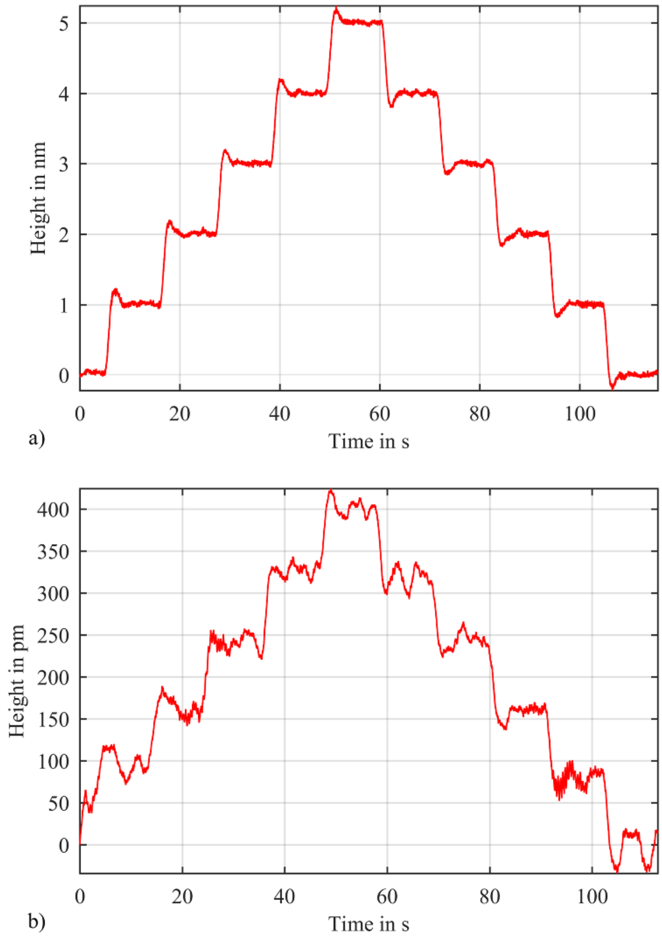

Figure 5. (a) 1 nm and (b) 80 pm steps carried out by the NPMM-stage.

Figure 6 shows an example of the deviations from the mean value of 18 repeat measurements on a 5 mm step height standard. The measurements and data evaluation were carried out according to DIN EN ISO 5436–1. We determined a p-p-deviation of ±37 pm, which corresponds to a standard deviation of only ±20 pm or a relative repeatability of $4 \cdot 10^{-9}$. In comparison with the frequency stability of $2 \cdot 10^{-9}$ of the He–Ne lasers used, this means that all measuring conditions in the machine were very constant.

The verification of measurement accuracy for lateral measurements is much more difficult. The laser spot of the laser focus probe used is about 1 µm at the detection point, and the detection of microstructures is therefore limited. Nevertheless, even lateral structures with resolutions in the sub-10 nm range can be reproducibly sensed [31]. It must be taken into account that the fiducial marks themselves show uncertainties in the sub-micrometre range, especially due to the manufacturing process. The optimization of lateral edge structures for optical sensors, for example, on mask substrates, is an important task. There is great interest in conducting further research to better understand and master the complete measurement chain. This also includes model-based optical probing methods [32–34], which can further improve the potential of NPM machines. Of course, the use of scanning probe microscopes

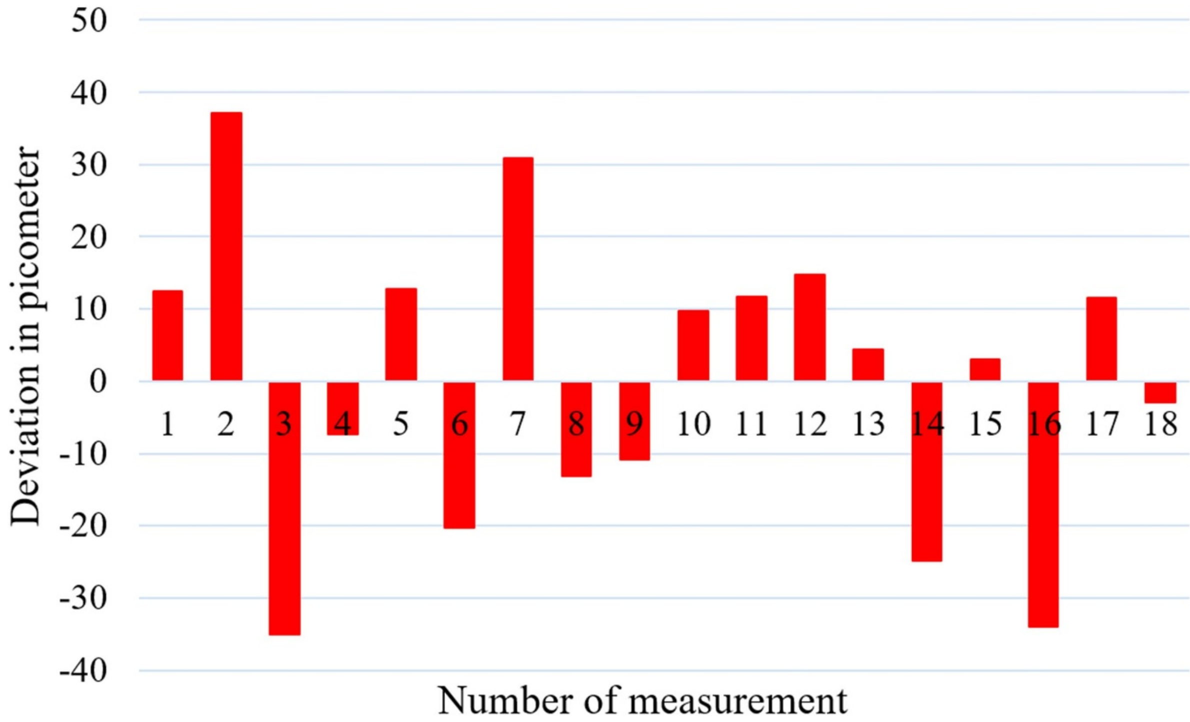

Figure 6. Repeatability of 18 single step height measurements at a 5 mm step height standard.

in the NPMM-200 is also possible and has already been tested. More precise measurement results are expected in the near future.

4. Direct and permanent traceability by frequency comb technology

The NPMM-200 is already capable of 20 pm resolution in a measuring range of 200 mm. This corresponds to a relative length resolution of 10^{-10}. We have shown the stability of the He–Ne lasers used in the NPMM-200 of $2 \cdot 10^{-9}$ within 120 h. The long-term stability of stabilized He–Ne lasers is currently 10^{-8} without a regular recalibration of the laser. Nevertheless, the discrepancy between measurement resolution and available frequency stability is obvious. The decisive factor is not the stability, but the absolute frequency value of the laser. The laser frequency noise in the order of 1 MHz (figure 3) leads to a length variation of 400 pm at the end of the measuring range of the measuring machine of 200 mm, although the potential of laser interferometers used is 25 pm (figure 4).

The uncertainty of the iodine-stabilized He–Ne laser wavelength standards is specified to a relative stability of $2.5 \cdot 10^{-11}$ [35]. However, the practical calibration of I_2-He–Ne lasers is limited to 10^{-10}. In addition, the output power of these lasers is too low to be used directly for displacement laser interferometry.

The potential for a further improvement in the frequency stability has arisen with the advent of optical frequency comb technology [36]. Currently, most applications of optical frequency combs (OFC) are related to their properties as transfer oscillators linking different frequency ranges and the ultraprecise determination of optical frequencies [37].

Our approach utilizes the frequency comb to create a permanent link between the frequency of an atomic clock and the frequency of a He–Ne-laser. This is accomplished by stabilizing our He–Ne-lasers of the NPMM-200 to a comb line of the OFC.

Here, we used a commercially available system (model: FS1500-250-WG, MenloSystems) [38] (figure 7). The frequency stability of this system is limited by the performance of the applied RF-reference [39]. In our case, a GPS disciplined oscillator is used providing a relative Allan deviation better than $4 \cdot 10^{-12}$ ($\tau = 1$ s) [40].

The working scheme is shown in figure 7. In the first step, we stabilize a He–Ne laser by linking its frequency to one of the lines of the frequency comb. This laser serves as an inhouse ‘secondary standard’. In the second step, another He–Ne laser, with a comparable transfer behaviour, our ‘metrology laser’, is offset-locked to the secondary standard [41]. Finally, the stabilized laser radiation is made available to the NPMM via optical fibres. This development forms the backbone to provide highly precise length measurements at the NPM-machine, which are directly traced back to the SI unit ‘second’ and do not suffer from laser frequency changes.

In figure 8(a), the variation of the beat frequency between this secondary standard and the respective comb line is shown as a blue curve. Over a time window of 1 h, a peak-to-peak variation of 1350 Hz was observed. The relative Allan deviation, shown as a blue curve in figure 8(b), was calculated from a measurement series over 20 h and revealed a value of $0.6 \cdot 10^{-12}$ ($\tau = 1$ s, $\Delta f = 300$ Hz) [42]. The beat frequency variation and Allan deviation of the phase-locked metrology laser are shown as red curves. Here, we achieve a peak-to-peak

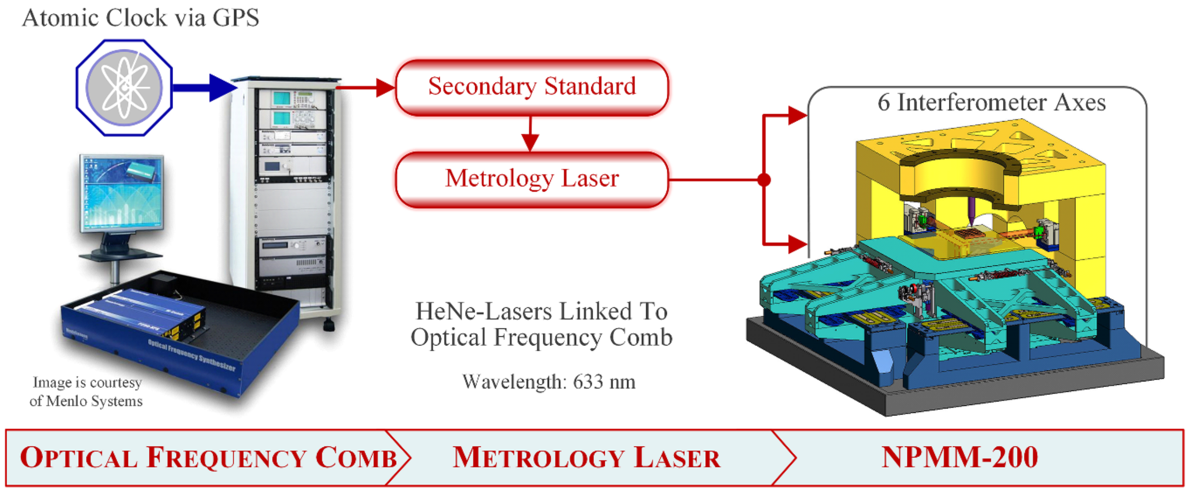

Figure 7. Coupling of NPMM-lasers to an atomic clock via a frequency comb.

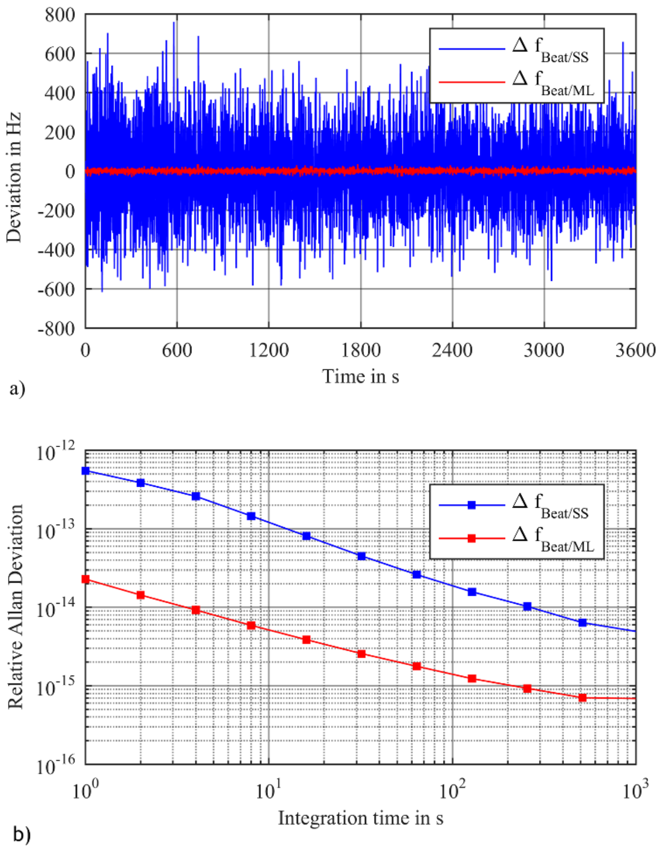

Figure 8. (a) Frequency stability at a data acquisition rate of 1 Hz and (b) Allan deviation of the secondary standard and metrology laser.

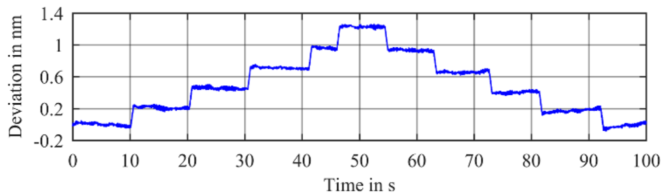

Figure 9. Interferometer length change due to laser frequency jumps of 1.25 MHz at 100 mm path difference (integration time 0.5 s).

variation of 73 Hz within the presented time window and a relative Allan deviation of $2 \cdot 10^{-14}$ ($\tau = 1$ s, $\Delta f = 98$ Hz). This demonstrates that the closed-loop control system of the secondary standard laser is able to follow the comb line, where the limited dynamic of the laser control systems is expected to produce some low-pass filtering effects on high frequency distortions of the comb line.

The metrology laser is now used as a laser source of the *x*- and *y*-interferometers of the NPMM-200. To show the response of the laser interferometer, we introduced certain frequency equidistant steps onto the beat frequency of the metrology laser that is locked to the secondary standard.

As a result, an apparent but ostensible change in length at the laser interferometers at a constant optical path difference of 100 mm is observed for five consecutive up and down frequency steps of 1.25 MHz in figure 9. The corresponding length change is (0.25 ± 0.03) nm. This means a relative length change of $2.5 \cdot 10^{-9}$ and the relative deviations are in the order of $3 \cdot 10^{-10}$.

The deviations from an ideal staircase indicate further disturbances, in particular thermal fluctuations, refractive index changes, acoustic influences and mechanical residual vibrations. Nevertheless, hereby it could be shown how frequency changes of the He–Ne laser have a direct effect on length changes. The measurements were carried out under normal atmospheric conditions at 20 °C.

5. Conclusion and outlook

The new nanopositioning and nanomeasuring machine NPMM-200 represents a major progress in the further development of ultra-precision measuring machines. The positionability of the smallest steps of 80 pm was demonstrated, achieving standard deviations up to 28 pm, i.e. a tenth of an atomic lattice distance, with the aid of a positioning stage of 24 kg weight. An outstanding measurement repeatability of step height measurements of 20 pm at 5 mm height was shown. A comparison of the absolute values of height measurements as well as an investigation of the lateral measurement uncertainty is in the pipeline.

The direct and permanent traceability of the laser interferometric measurement to the SI unit second, represented by GPS satellite-based atomic clock reference and frequency comb technology, takes precision length measurement to a new qualitative level. It represents an important new step in the overall system of SI units and an important milestone for the further development of NPM technology.

The NPM machine can also be operated with a vacuum to decrease the influence of the refractive index of air, especially on temperature. Further investigations will follow shortly. In the future, further investigations in a vacuum and new approaches for refractive index measurement and correction on the basis of frequency comb technology will be applied, for example [43]. We believe that the implementation of optical frequency comb technology in precision measurement systems will become a state-of-the-art technique in the near future to realize interferometer measurements in the sub-nanometre range.

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