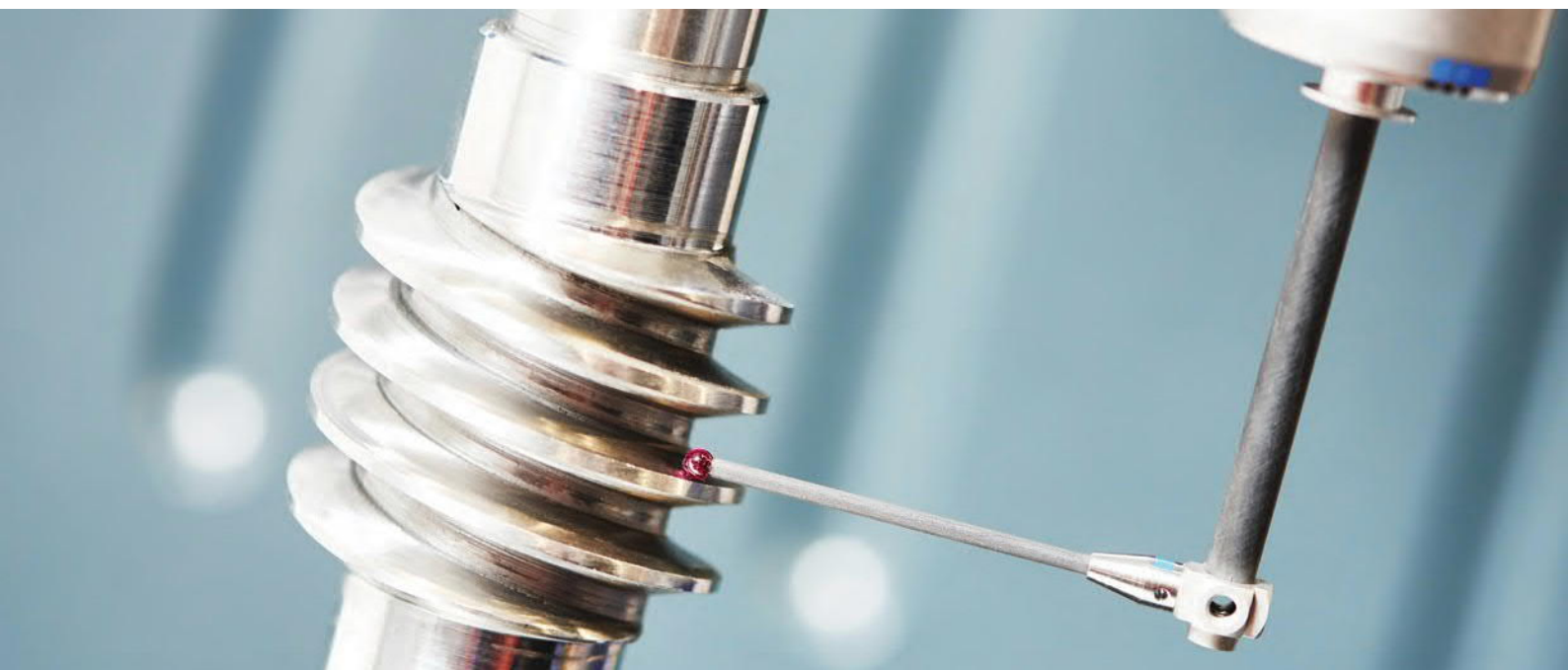


Calibration Services

Length and angle

VTT MIKES





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VTT MIKES

Length and angle

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Quantitative Microscopy – Atomic Force Microscope

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Development and research in nanotechnology has increased the need for accurate measurements in research institutes and industry. Different kinds of Scanning Probe Microscope (SPM) measurements are commonly used in many institutes and companies. In order to guarantee accurate and reliable dimensional measurements at nanometre range, VTT MIKES has a traceably calibrated Atomic Force Microscope (AFM). Thus, VTT MIKES can provide customers with traceable measurements also at nanometre range.

VTT MIKES provides accurate AFM measurement services to match the needs of customers. In addition, we calibrate SPM transfer standards.

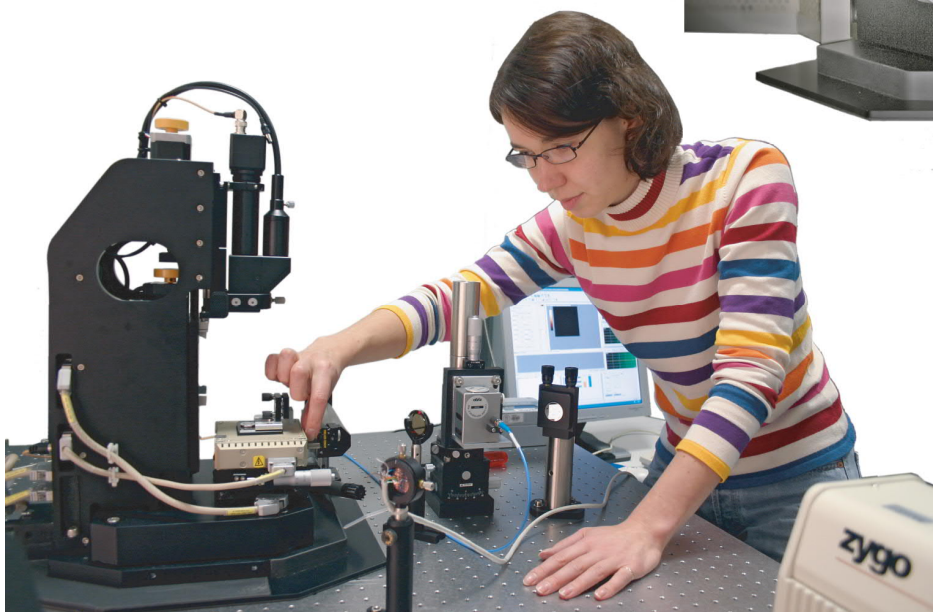


Figure 1. Alignment of laser beams for interferometric calibration of y-axis of the AFM.

VTT MIKES has a PSIA XE-100 AFM, which is calibrated interferometrically and with grating calibrated by laser diffraction at VTT MIKES. The AFM is traceable to the definition of the metre. The xy-movements of the AFM are mechanically separated from the z-movements. This increases the linearity of the movements, decreases out of plane movements and eliminates crosstalk. The structure of the device allows rather large samples to be measured. Measurements can also be done using the most usual measurement modes: contact, non-contact, tapping and lateral force. The measurement results can be analysed using SPIP software ¹.

Scale errors of uncalibrated SPMs typically range from 2 % to 20 %. In addition, measurement errors may cause distortions in the measured figure, which might be difficult to detect from the figure. Therefore, the device has to be calibrated. New, more advanced SPMs have increased measurement precision, but the development does not remove need for calibration. Especially in all quantitative form measurements, the measurements should be traceable to the definition of the metre. Usually, SPMs are calibrated by using calibrated transfer standards.

¹ The Scanning Probe Image Processor SPIP™
<http://www.imagemet.com>

| Property | Data |
|--|--|
| Sample size | <100 mm × 100 mm |
| Sample thickness | <20 mm |
| Sample mass | <500 g |
| Measurement range (xy) | 100 μm × 100 μm |
| Measurement range (z) | 12 μm |
| Resolution (xy) | 0.15 nm 0.02 nm (low voltage mode*) |
| Resolution (z) | 0.05 nm 0.01 nm (low voltage mode*) |
| Uncertainty (k=2), x and y directions | Q [3; 2 L/μm] nm |
| Uncertainty (k=2), z direction | Q [3; 2 L/μm] nm |
| | Q [x; y] = (x ² + y ²) ^{1/2} |

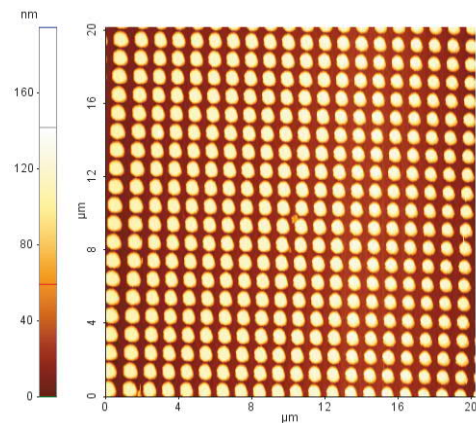


Figure 2. 2-D grid standard.

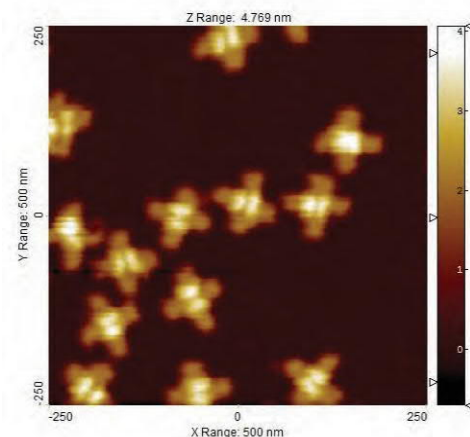
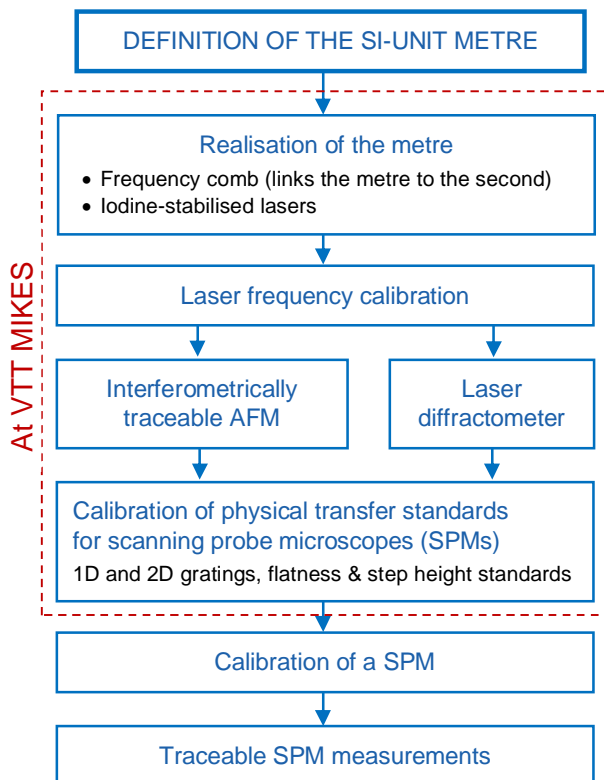


Figure 3. AFM image of Seeman tile type DNA nano-origami structures.

Characterization of nanoparticles

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Nanoparticles are widely used in many applications. Accurate characterization of the nanoparticles is important in research, production and applications in several fields including industry, health, safety and related regulation. At VTT MIKES, the particles can be characterized using two different methods: Dynamic Light Scattering (DLS) and atomic force microscopy (AFM). The measurements are traceable to the definition of the metre via VTT MIKES interferometrically traceable metrological atomic force microscope (IT-MAFM). Both methods have advantages and limitations. DLS is fast method and the results are statistically representative. In DSL measurements, even a small number of large particles can prevent detection of small particles. AFM can be used to measure both size and shape of single particles. The disadvantage of AFM measurements is that only limited number of particles can be measured which leads to poor statistics. Tip sample interaction is important especially when measuring small particles. In addition, sample preparation might be challenging.

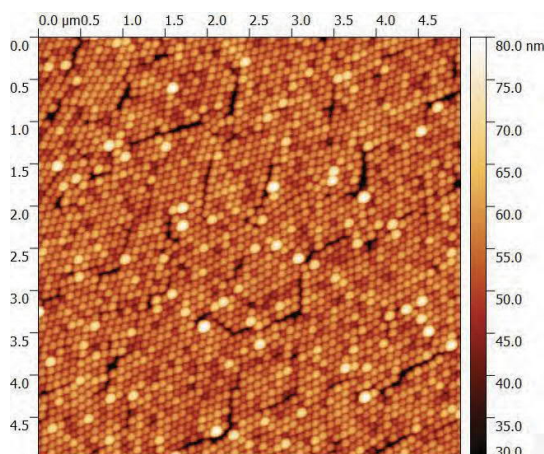


Figure 1. AFM image of 100 nm nanoparticles.

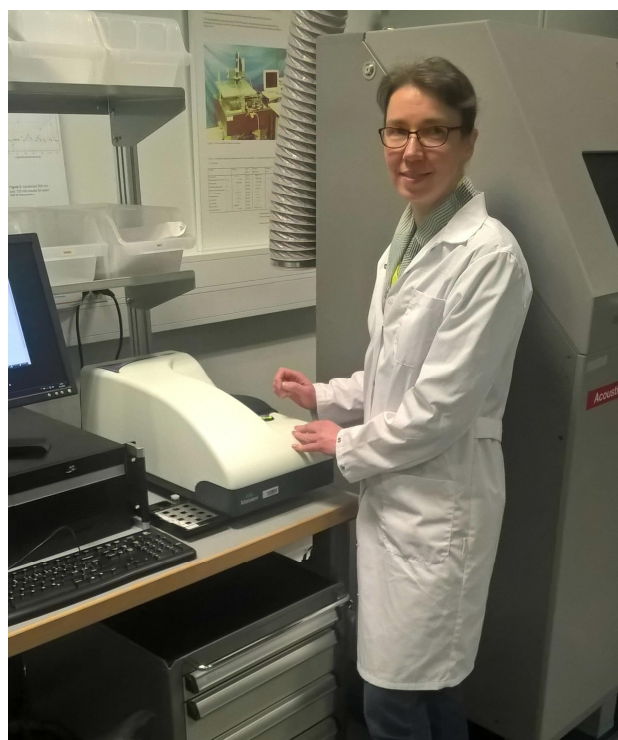


Figure 2. DLS measurements.

Table 1. VTT MIKES has two instruments suitable for nano-particle measurements.

| Instrument | Zetasizer Nano | PSiA XE-100 |
|-------------------------|-------------------------------------|------------------------|
| Measurement method | DLS | AFM |
| Measurands | Size distribution Zeta potential | Size Shape |
| Measurement range | 0.3 nm – 10 μm | 5 nm – 5 μm |
| Measurement uncertainty | 2 % | from 1 nm |

Zetasizer Nano

Dynamic Light Scattering is used to measure particle and molecule sizes. This technique measures the diffusion of particles moving under Brownian motion, and converts this to size and a size distribution using the Stokes-Einstein relationship.

Laser Doppler Micro-electrophoresis is used to measure zeta potential. An electric field is applied to a solution of molecules or a dispersion of particles, which then move with a velocity related to their zeta potential.

Services for nanoparticle characterization

- Nanoparticle size and shape measurements using AFM
- Nanoparticle size distribution in solution using DLS
- Nanoparticle surface charge (Zeta-potential) measurements in solution

Atomic force microscopy (AFM)

An AFM uses a cantilever with a very sharp tip to scan over a sample surface. As the tip approaches the surface, the close-range, attractive force between the surface and the tip cause the cantilever to deflect towards the surface. However, as the cantilever is brought even closer to the surface, such that the tip makes contact with it, increasingly repulsive force takes over and causes the cantilever to deflect away from the surface.

In AFM images the topography of a sample surface by scanning the cantilever over a region of interest. The raised and lowered features on the sample surface influence the deflection of the cantilever, which is monitored by a position-sensitive photo diode (PSPD). By using a feedback loop to control the height of the tip above the surface the AFM can generate an accurate topographic map of the surface features.

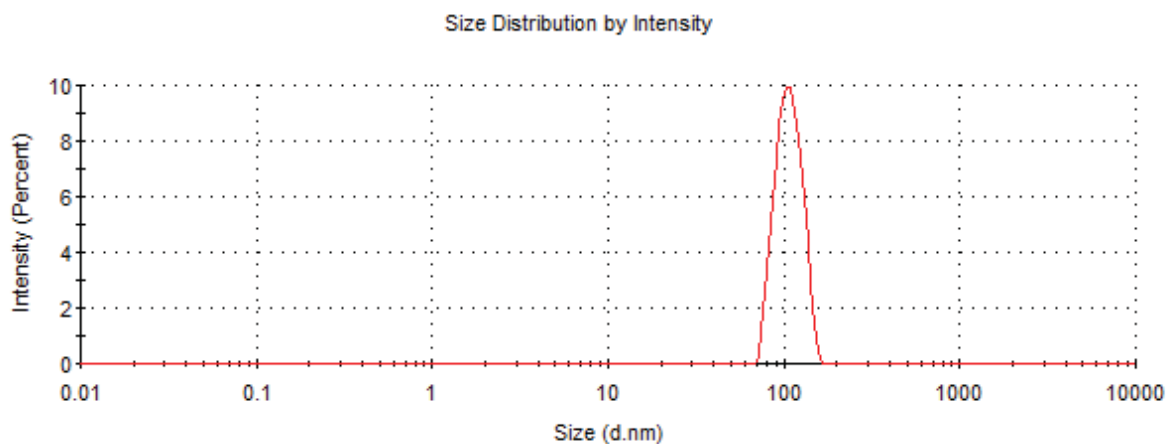


Figure 3. DLS results of ~100 nm nanoparticles.

Calibration of laser interferometers

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Laser interferometers together with gauge blocks are the most important measurement standards in modern length metrology. At 1980s a common understanding was that laser interferometers are accurate and hence do not need any calibration. However, ever-increasing demand for accuracy and long experience on usage of laser interferometers have shown that it is necessary to calibrate laser interferometers, also. At VTT MIKES, we have traceable procedures to calibrate laser interferometers. The calibration of laser interferometers improves their reliability and accuracy essentially.



Figure 1. Functional testing of a laser interferometer.

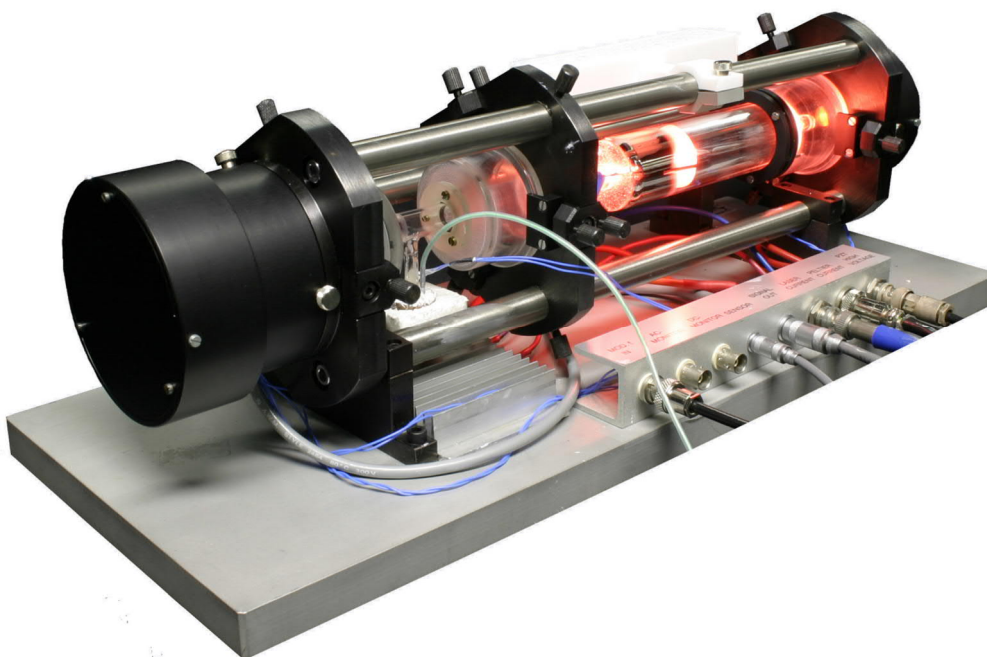


Figure 2. An iodine-stabile HeNe-laser used for the practical realisation of the metre.

Calibration procedure

Calibration of laser frequency

The vacuum wavelength of lasers used in laser interferometers is calibrated using iodine-stabilised lasers. Traceability to the definition of the metre is guaranteed as frequencies (vacuum wavelength) of the iodine-stabilised lasers are determined by an optical frequency comb referenced to an atomic clock.

VTT MIKES maintains the following lasers that are locked to iodine absorption lines according to international recommendations: He-Ne lasers at wavelengths: 633 nm (Figure 2) and 543.5 nm and a Nd:YAG-laser at 532 nm. These laser have a relative frequency uncertainty better than 10^{-10} (expanded uncertainty, $k=2$).

The frequency of the laser under calibration is compared to the frequency of an iodine-stabilized laser. The calibration includes a long-term frequency (vacuum wavelength) calibration and repeatability measurements. Moreover, the frequency difference of the horizontally and vertically polarised lights is determined and the separation of the polarisation planes inspected. Together these measurements provide good indication of the frequency stability of the laser under calibration. Lasers that operate at wavelengths not reachable by iodine-stabilized lasers can be calibrated using a frequency comb.

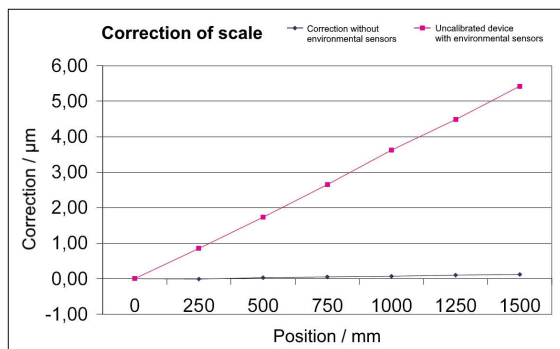


Figure 3. Errors in environmental sensors can have remarkable effects on the readings of a laser interferometer.

Table 1. Uncertainty of calibration.

| Quantity | Measuring range | Uncertainty ($k=2$) |
|----------------------|-----------------------------------|---------------------------|
| Wavelength | 633 nm; 543.5 nm; 532 nm | $\sim 10^{-9}$ (relative) |
| Air pressure | 970...1050 hPa (730 ... 790 mmHg) | 40 Pa |
| Air temperature | 17...25 °C | 0.10 °C |
| Material temperature | 15...25 °C | 0.050 °C |
| Combined uncertainty | 0...30 m | Q[0,02 μm, 05E-6L] |

Calibration and functional testing of environmental sensors

In addition to laser vacuum wavelength calibration, the environmental sensors are calibrated and their operation tested. These measurements are necessary to achieve the naturally good measurement accuracy of a laser interferometer. Especially, by calibrating the environmental sensors order of magnitude better measurement accuracy can be achieved for a laser interferometer.

The calibration of environmental sensors includes the calibration of air temperature sensors, atmospheric pressure sensors and material temperature sensors. The functional testing is performed in a temperature-stabilised laboratory room by measuring the locations of a moving carriage equipped with a retroreflector with the laser interferometer under calibration and with a reference laser interferometer (Figure 1). In these measurements, both laser beams travel through the same optical components and data is collected with and without the environmental sensors operating. In addition, the angle scale is tested using a reference laser. If necessary, the quality of the optical components is tested with a flatness interferometer.

If the readings of the environmental sensors deviate remarkably from readings of the reference instruments, they should be adjusted. By adjusting, the accuracy of the laser interferometer can easily be improved (Figure 3), e.g., the adjustment is relatively easy to perform in Agilent laser interferometers.

Traceability

The frequencies of the iodine-stabilised lasers that are the national measurement standards of length are determined using an optical frequency comb referenced to VTT MIKES atomic clocks. Instruments used in the calibration of environmental sensors are calibrated in the corresponding national standards laboratories. Thus, the measurements are traceable to the corresponding definitions of the units.

Interferometric calibration of gauge blocks

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Calibration of gauge blocks

Gauge blocks are the most important measurement standards of length in industry. Interferometric measurement of gauge blocks provides an absolute calibration method. By using interferometers, the practical realisation of the metre is transferred to a gauge block via the calibrated wavelength of the frequency-stabilised laser used in the interferometer. Gauge blocks calibrated by comparison must be traceable to gauge blocks calibrated by interferometry. The length of a gauge block is defined in an ISO standard as the distance from the centre of the gauge face to an auxiliary reference plane wrung to the other end of the gauge block at 20 °C temperature and at 1013.25 hPa barometric pressure. Gauge block sets calibrated by interferometry give a lower uncertainty for mechanical calibrations e.g. in accredited calibration laboratories.

Interferometers at VTT MIKES

VTT MIKES have gauge block interferometers for short (0...300 mm) and for long (100...1000 mm) gauge blocks and end standards. The interferometers are located in a laboratory room having well stabilised environmental conditions and they are equipped with temperature, humidity and pressure sensors. Low uncertainties for refractive index of air and for thermal expansion compensation can be achieved with a precise control and monitoring of the environmental conditions. Difference in surface roughness between the gauge block face and the reference plane is measured and corrected for in results. The parallelism and flatness of the surfaces can be measured, also.

The VTT MIKES PSIGB interferometer for short gauge blocks (Fig. 1) uses stabilised He-Ne lasers at 633 nm and 543.5 nm. The interferometer is equipped with a large wringing bed, which enables fast and automated calibration of even 14 gauge blocks in sequence. In the Tesa interferometer, the gauge blocks are positioned vertically.



Figure 1. VTT MIKES PSIGB gauge block interferometer and wringing station.

The long gauge block interferometer (Fig. 2) utilises white light and 633-nm laser light interference patterns. By using white light, beforehand knowledge of the length of the end standard is not required. The end standards and gauge blocks are positioned horizontally and supported at the Bessel points in such a way that the weight of the reference plane is compensated for.

Calibration services

Gauge block interferometers can be used to measure even other artefacts whose surfaces are flat and smooth enough; e.g., to determine the thermal expansion coefficient of ceramic sealings and to measure the air gap between two parallel glass plates. Interferometric calibration sets also demands for gauge blocks: their end surfaces must be parallel, flat and without scratches. VTT MIKES calibrates gauge blocks of grades K (00) and 0 and end standards, e.g. quartz metres, according to the following table.

Traceability

The regular calibration of length standards and length measuring equipment is a necessary part of measurement quality control. Traceable calibrations and knowledge on the measurement uncertainty are basic demands for good and constant quality. The traceability to gauge block calibrations is achieved by calibrating the wavelengths of lasers used in the interferometers against national measurement standards of length, iodine-stabilised He-Ne lasers. Measuring devices for temperature, humidity and pressure used in the interferometers are calibrated in corresponding VTT MIKES laboratories. The reliability of calibrations are verified by taking regularly part in international comparisons.

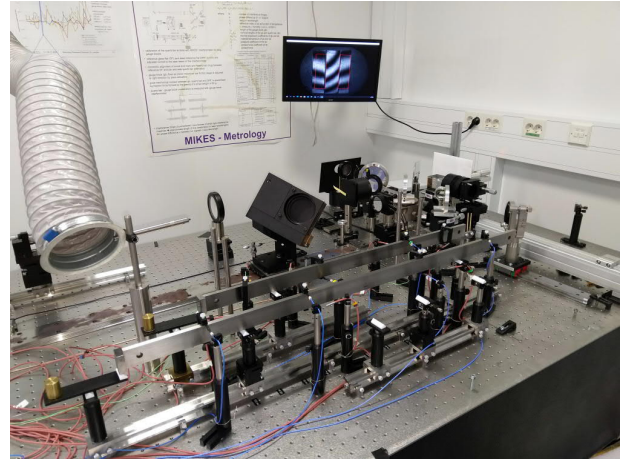


Figure 2. VTT MIKES length bar interferometer for calibration of long gauge blocks.

References:

- Byman, V., & Lassila, A. (2015) MIKES' primary phase stepping gauge block interferometer. *Measurement Science and Technology* **26**(8), [084009].
<https://doi.org/10.1088/0957-0233/26/8/084009>
- Ikonen, E. & Riski, K. (1993) Gauge-block Interferometer Based on One Stabilized Laser and a White-light Source, *Metrologia* **30**, 95–104.

Table 1. Calibration subjects and measurement uncertainties.

| Device | Measurement range | Uncertainty ($k=2$)* |
|---|--------------------|------------------------|
| Gauge blocks, short | 0.5 mm ... 200 mm | Q[20 nm, 190E-9L]** |
| Gauge blocks, short, length difference of GB pair | 0.5 mm ... 100 mm | 18 nm |
| Gauge blocks, long | 100 mm ... 1000 mm | Q[22 nm, 110E-9L]** |
| Quartz meters | 1000 mm | 72 nm |

L = Nominal length

*Uncertainty is often larger due to uncertainty caused by properties of the device under calibration

** $Q[x; y] = (x^2 + y^2)^{1/2}$

Calibration of gauge blocks by mechanical comparison

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Mechanical comparison measurement is the most common way to determine the length of a gauge block. In this method, the length of the gauge block under calibration is compared to the length of a calibrated gauge block with same nominal length by using a specific comparator, Figure 1.

Gauge block measurement

Comparison measurements of gauge blocks that have the same nominal length and that are of the same material are simple, reliable, fast and inexpensive. The method is also applicable to gauge blocks whose surfaces have been worn-out in use. VTT MIKES calibrates steel, hard metal, and ceramic gauge blocks in lengths 0.1 ... 1000 mm (Table 1). In calibration, we check the flatness of the surfaces and remove splatters that could prevent reliable use of the gauge blocks. A regular inspection of gauge blocks prevents a possible damage to affect the whole set. The use of uncalibrated gauge blocks in production quality control and in calibration of measurement equipment causes extra risks and costs

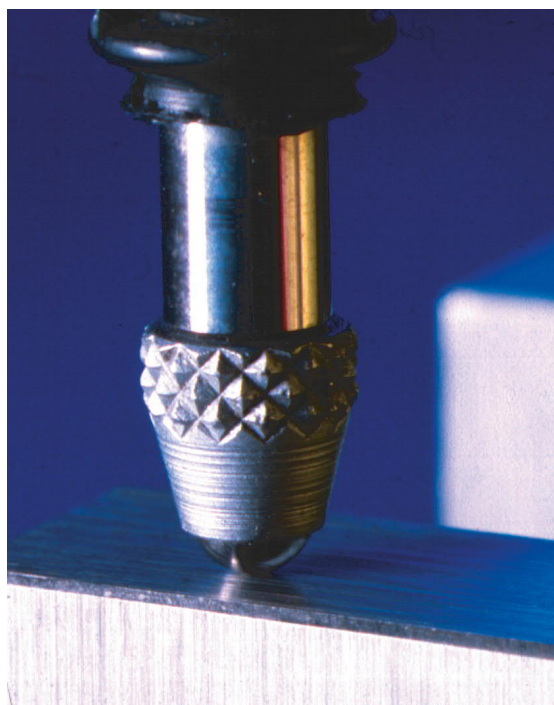


Figure 1. The sensor of the gauge block comparator identifies the location of the surface by using 0.6 Nm measurement force.

Table 1. Calibration of gauge blocks by mechanical comparison.

| Measurement device | Measurement range | Uncertainty |
|--|--------------------|---------------------|
| Tesa gauge block comparator | 0.1 mm ... 100 mm | Q[50 nm, 0.87E-6L] |
| MIKES comparator for long gauge blocks | 100 mm ... 1000 mm | Q[100 nm, 0.87E-6L] |

L is the nominal length

Traceability

The reference gauge blocks used in mechanical comparison measurements are regularly calibrated using VTT MIKES gauge block interferometers. The wavelengths of lasers used in these interferometers are calibrated by national measurement standard of length, iodine-stabilised He-Ne lasers

Table 2. Accuracy grades of ISO 3650:1998 standard.

| Nominal length range mm | | Calibration grade K mm | | Grade 0 mm | | Grade 1 mm | | Grade 2 mm | |
|-------------------------|--------------|------------------------|-------|------------|-------|------------|-------|------------|-------|
| Lower length | Upper length | $\pm t_e$ | t_v | $\pm t_e$ | t_v | $\pm t_e$ | t_v | $\pm t_e$ | t_v |
| 0.5 | 10 | 0.20 | 0.05 | 0.12 | 0.10 | 0.20 | 0.16 | 0.45 | 0.30 |
| 10 | 25 | 0.30 | 0.05 | 0.14 | 0.10 | 0.30 | 0.16 | 0.60 | 0.30 |
| 25 | 50 | 0.40 | 0.06 | 0.20 | 0.10 | 0.40 | 0.18 | 0.80 | 0.30 |
| 50 | 75 | 0.50 | 0.06 | 0.25 | 0.12 | 0.50 | 0.18 | 1.00 | 0.35 |
| 75 | 100 | 0.60 | 0.07 | 0.30 | 0.12 | 0.60 | 0.20 | 1.20 | 0.35 |
| 100 | 150 | 0.80 | 0.08 | 0.40 | 0.14 | 0.80 | 0.20 | 1.60 | 0.40 |
| 150 | 200 | 1.00 | 0.09 | 0.50 | 0.16 | 1.00 | 0.25 | 2.00 | 0.40 |
| 200 | 250 | 1.20 | 0.10 | 0.60 | 0.16 | 1.20 | 0.25 | 2.40 | 0.45 |
| 250 | 300 | 1.40 | 0.10 | 0.70 | 0.18 | 1.40 | 0.25 | 2.80 | 0.50 |
| 300 | 400 | 1.80 | 0.12 | 0.90 | 0.20 | 1.80 | 0.30 | 3.60 | 0.50 |
| 400 | 500 | 2.20 | 0.14 | 1.10 | 0.25 | 2.20 | 0.35 | 4.40 | 0.60 |
| 500 | 600 | 2.60 | 0.16 | 1.30 | 0.25 | 2.60 | 0.40 | 5.00 | 0.70 |
| 600 | 700 | 3.00 | 0.18 | 1.50 | 0.30 | 3.00 | 0.45 | 6.00 | 0.70 |
| 700 | 800 | 3.40 | 0.20 | 1.70 | 0.30 | 3.40 | 0.50 | 6.50 | 0.80 |
| 800 | 900 | 3.80 | 0.20 | 1.90 | 0.35 | 3.80 | 0.50 | 7.50 | 0.90 |
| 900 | 1000 | 4.20 | 0.25 | 2.00 | 0.40 | 4.20 | 0.60 | 8.00 | 1.00 |

Abbreviations in the table:

t_e = deviation of length from nominal length

t_v = variation in length

2D and 3D measurement of form and surface roughness

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The manufacturing tolerances of modern products and the aim to high quality require the ability to measure different form measurands of small artefacts having complicated shapes. Examples of such form measurands are straightness, parallelism, radius of curvature and surface roughness. VTT MIKES measurement and calibration services using a computer controlled form and surface texture instrument provides one solution to these measurement problems.

Form measurement

The form measurement instrument can detect form deviations even as small as 0.6 nm. Examples of typical form measurements are accurate measurements of straightness, inner and outer determinations of radiation of curvatures and diverse dimensional measurements of small artefacts (Figure 1). These include determinations of grooves lengths and depths and inner and outer angle measurements. The most important technical specifications of the Taylor Hobson Form Talysurf instrument are gathered in table 1.

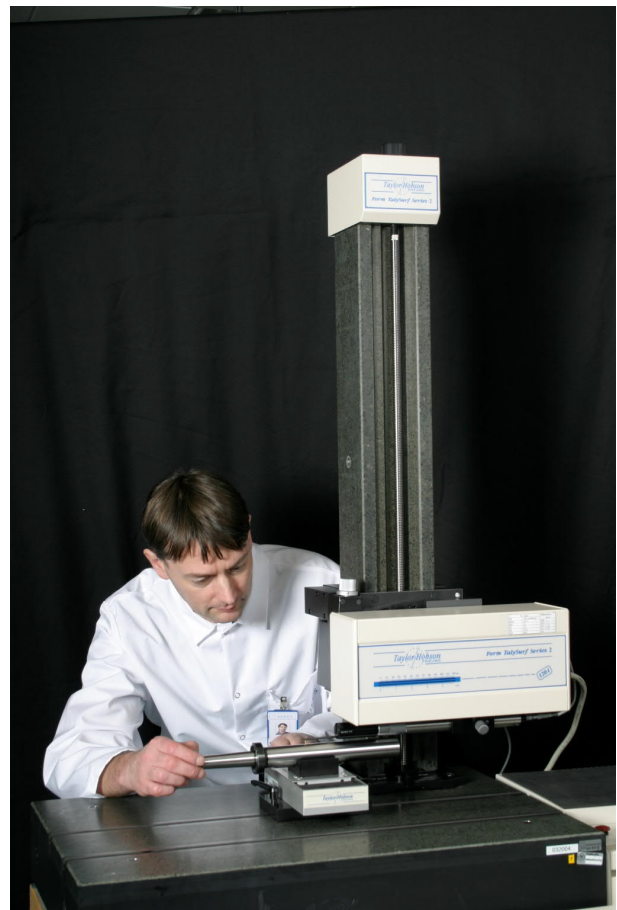


Figure 1. Straightness measurement on a cylindrical surface.

Surface roughness measurements

In addition to calibration of surface roughness standards, the surface texture instrument at VTT MIKES is used for tasks related to quality control and product development. The surface roughness measurements at VTT MIKES are based on the following standards: ISO 5436-1 and ISO 4287.

Measurement subjects

- traceable calibration of surface roughness standards
- diverse measurements in development of prosthesis in health care industry
- measurement of tribological samples
- profile measurements of blades of excavation machinery
- geometrical measurements in product development and quality control of electronic components
- product development and quality control measurements of metal packings and components in hydraulics and pneumatics.

Traceability

Traceability to the form measurement instrument comes from interferometrically calibrated gauge blocks, a line scale, an optical flat and a sphere.

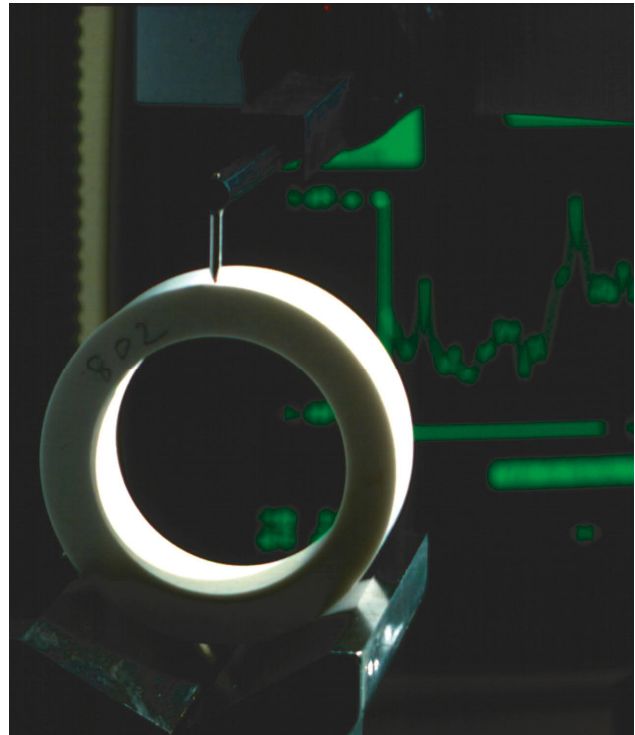


Figure 2. Measurement of sideline.

Table 1. The most important technical specifications of the Taylor Hobson Form Talysurf instrument.

| Property | Information |
|--------------------------------------|---|
| Instrument and operational principle | Taylor Hobson Form Talysurf Ser. 2, Type 112/2815-02, inductive |
| Measurement tips | Diamond tip, radius 0.002 mm, Spherical sapphire tip, radius 0.397 mm. |
| Measurement forces | 1.0 mN (using diamond tip), 15–20 mN (using sapphire tip) |
| Surface texture parameters | R3y, R3z, Ra, Rc, Rda, Rdc, Rdq, RHSC, Rku, Rln, RLo, RIq, Rmr, Rmr(c), Rp, RPc, Rq, RS, Rsk, RSm, Rt, Rv, RVo, Rz, Rz(JIS). In addition, a series of waviness parameters. |
| Longest measurement length | 120 mm |
| Maximum height of artefact | 700 mm, maximum width in 3D measurement is 50 mm |
| Largest allowed deviation | 28 mm (120 mm arm) |
| Measurement speed | 1 mm/s |
| Resolution | 0.0006 μm |
| Lowest uncertainty | $Q[10 \text{ nm}, 0.02P]$ where P is the deviation from flatness |

Optical measurement of surface microstructures

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Micro to millimetre range structures can be measured at VTT MIKES using scanning white light interference microscope (SWLI).

The SWLI has sub-nm vertical and μm level horizontal resolution. It can measure square mm areas in a single scan. Benefit of SWLI compared to other instruments with similar vertical resolution include large measurement area ability to measure high steps and ability to measure overlapping surfaces inside of transparent structures. See table 1 for more properties of the instrument.

Real life measurement uncertainty is case dependent and depends on measurement environment, properties of instrument and properties of measured sample. At VTT MIKES, we take care that the sample is clean, sample temperature is known and the sample is well attached and properly aligned. Measurements are done traceably under consistent conditions and results are well documented.

Examples of potential measurement objects:

- Bearings, contact surfaces, surface topography and wear
- Semiconductors and MEMS
- Medical instruments and implants
- Optical components
- Precision machined components

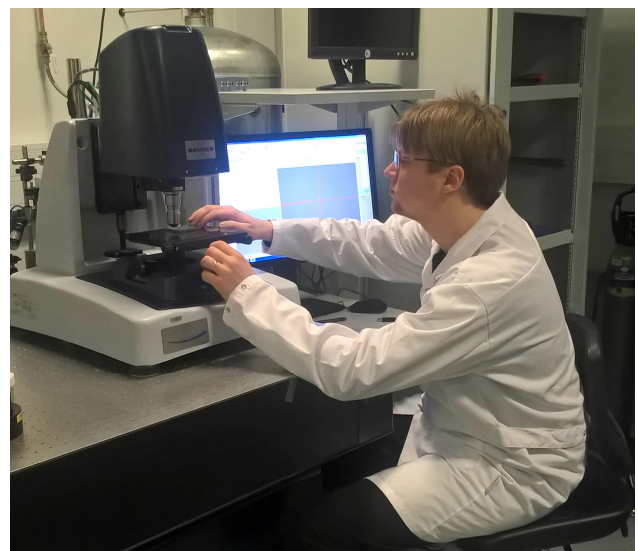


Figure 1. Bruker ContourGT-K scanning white light interferometer.

We do different measurements using the SWLI

- Different type of objects
 - surface shape measurements
 - x,y,z dimensions of details on a surface
 - film thickness measurement, layer separation
 - surface roughness (2D and 3D ISO roughness parameters), flatness, deviation from a shape
- Calibration of different instruments
- Calibration of reference artefacts
 - step heights, air gap artefacts, film thickness artefacts

Optical measurements of surface microstructures

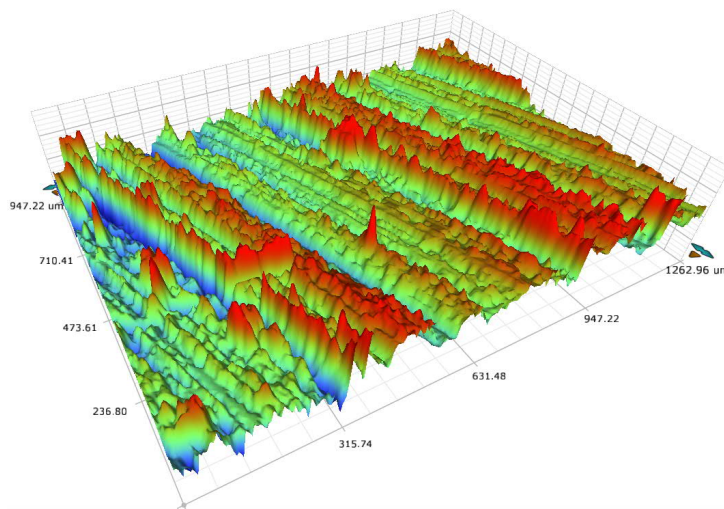


Figure 2. Measurement of machined aluminium surface

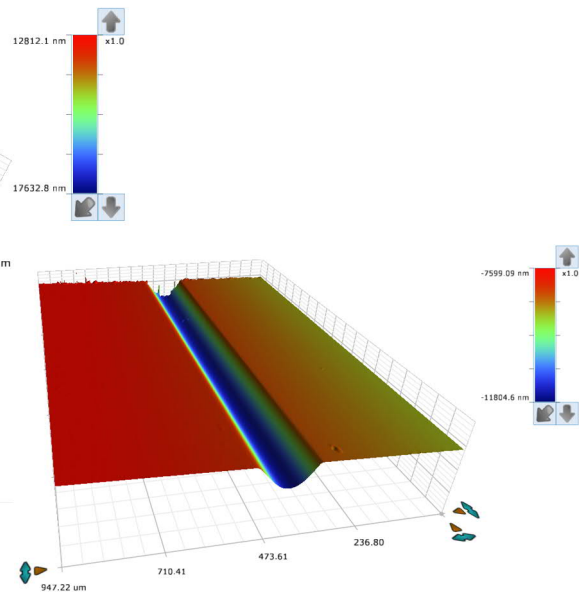


Figure 3. Measurement of a groove on a glass surface.

Optimal measurement condition

SWLI is in underground measurement room with (20 ± 0.1) °C temperature. Most heat sources in the room have been eliminated by venting warm air out.

Traceability

SWLI is traceable to the SI-metre through VTT MIKES's own transfer standards such as step height standards, gauge blocks and laser interferometer.

Table 1. Properties of SWLI

| Property | Information |
|--|--|
| Optical x-y resolution | 3.8 – 0.7 μm |
| Pixel size | 7.2 – 0.2 μm |
| Vertical resolution | < 0.1 nm |
| Step height measurement: | |
| • repeatability | < 0.1 % |
| • accuracy | < 0.75 % |
| Sample reflectivity: | 0.05 % – 100 % |
| Maximum surface tilt (smooth samples): | 3° (2.5x objective), 18.9° (20x objective) |
| Magnifications | 2.5x and 20x objectives, 0.55x, 1x and 2x zoom lenses |
| Measurement area ($X \times Y \times Z \text{ mm}^3$): | Measurement area ($X \times Y \times Z \text{ mm}^3$): |
| smallest magnification | 3.5 \times 4.6 \times 3.5 |
| largest magnification | 0.4 \times 0.6 \times 3.5 |
| Measurement area in pixels | 640 \times 480 |
| Programs | Vision64 Analysis Software, MountainsMap, MatLab |
| Maximum size of measured object | 10 cm high \times 20 cm wide, one dimension can be longer |
| Ability to measure overlapping surfaces | 2 surfaces in single measurement Maximum depth is dependent on refractive index, geometry and magnification, e.g. it is possible to measure through 0.3 mm thick glass. 7 mm maximum depth limited by working distance. |

Measurements of accurate inner and outer dimensions

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Measurements using SIP length measuring machine

Precise measurements of inner and outer diameters are performed using MAHR length measuring machine either by using its own scale or by referencing to a standard of equal length (Figure 2). In the measurement, a contact is made using a ceramic spherical measuring probe, a flat tip or in inner measurements a lever probe. If the measurement depth in inner measurements is over 15 mm, special hook-shaped jaws are used. The measuring force can be tuned between 0.3...11 N. By measuring with several different forces, the deformations due to the measuring forces can be eliminated from calculations and the result given at so-called zero-force.

This is essential when the reference and the artefact under calibration are made of different materials or have different shapes.

Measurements are performed in a well-controlled laboratory room at temperature $+20\text{ °C} \pm 0.1\text{ °C}$. Different types of heat sources are eliminated by using vent pipes, heat shields, and when necessary with a separate laminar flow. In addition to the measurement length, the measurement uncertainty depends on the measured artefact (shape and surface texture), on measuring instrument, measurement conditions, and on the method used.

In addition to diameter measurements, the MAHR length measuring machine is used for thread measurements and tolerance comparisons. The inner threads are measured using spherical probes and in outer thread measurements, three-wire method is used.

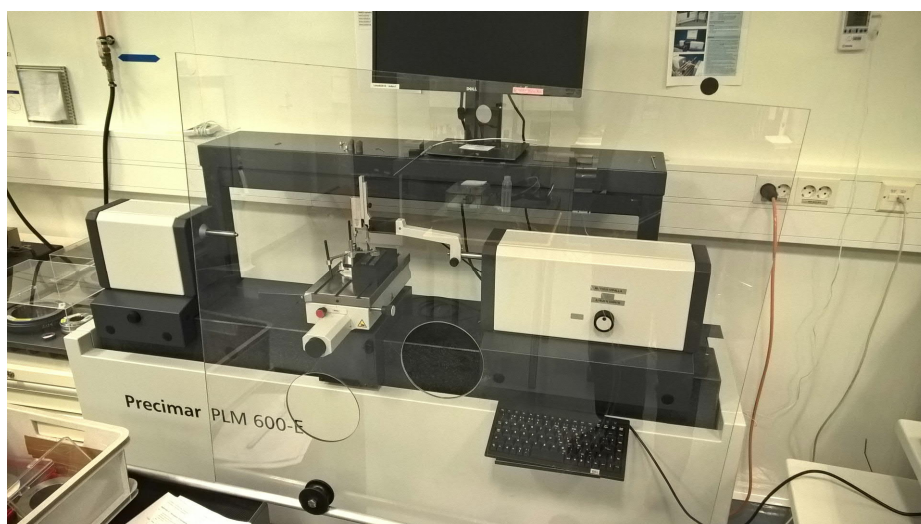


Figure 1. Measurement using MAHR length measuring machine.

Measurements supplementing diameter measurements

In order to get a precise picture of the features of an axially symmetrical artefact that is under measurement, one should also measure its roundness, surface roughness and straightness of sides using appropriate instruments.

Traceability

Measurements made using the SIP length measuring machine are traceable to corresponding transfer standards that are calibrated at VTT MIKES. The linear scale is calibrated using a laser interferometer, the reference gauge blocks are calibrated interferometrically, and the temperature sensors are calibrated in temperature baths against reference Pt25 thermocouples.



Figure 2. Mounting side by side the artefact under calibration and the reference in a comparison measurement.

Table 1. Measurement uncertainties achievable in diameter measurements.

| Measurement artefact | Measurement uncertainty ($k=2$) |
|--------------------------|-----------------------------------|
| Thread plug 0 – 550 mm | Q[0.2 μm , 0.87E-6L] |
| Ring gauge 1 – 500 mm | Q[0.2 μm , 0.87E-6L] |
| Sphere 0.2 mm ... 200 mm | Q[0.15 μm , 0.7E-6L] |
| | L nominal diameter |

Coordinate measurement

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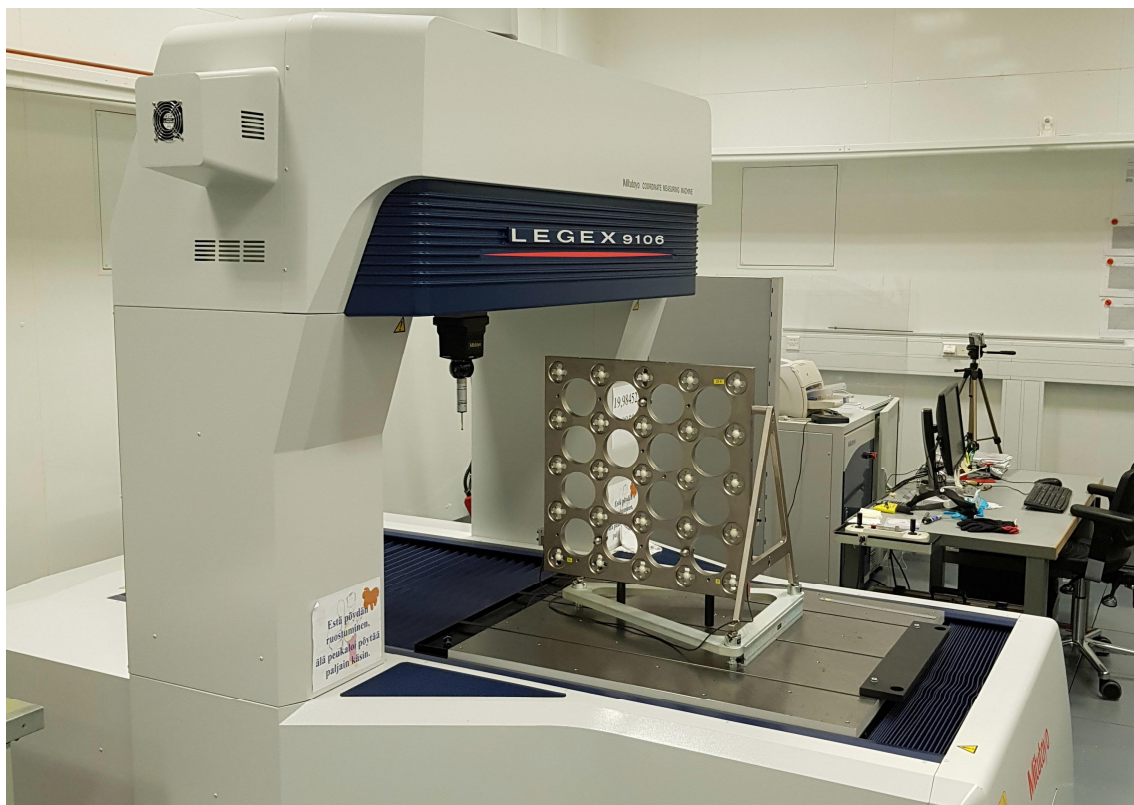
The coordinate measuring services at VTT MIKES include measurements with an optical coordinate measuring machine and with a high-accuracy industrial size contact probe coordinate measuring machine.

Contacting coordinate measurement

The basic properties of VTT MIKES coordinate measuring machine are accuracy, flexibility, speed, and automatic calculation of results.

The VTT MIKES 3D coordinate measuring machine is a Mitutoyo Legex 9106 with portal structure (Figure 1). Further information on this machine can be found in Table 1. The true measurement uncertainty is always case-specific and depends on the environmental conditions, on the machine, and on the properties of the work piece. We pay special attention in our working on surface cleanliness, temperature, mounting (Figure 2), alignment, measuring system, and on the documentation of results.

Figure 1. Mitutoyo Legex coordinate measuring machine.



The coordinate measuring machine is used for:

- custom measurements of 3D-workpieces (figure 3) and difficult shapes
 - scanning
 - digitizing point clouds
- various calibration of measurement devices
 - rulers, surface plates, gauges, cones, squares
- calibration of transfer standards for coordinate machines
 - step gauges, ball cubes.

Optimal measurement conditions underground

The coordinate measuring machine is located in a large volume underground laboratory room held at $(20 \pm 0.2) ^\circ\text{C}$ constant temperature. Most of the heat sources in the laboratory are eliminated using vent pipes. Moreover, the room is equipped with a 1000-kg load lifter on rails and a lift with 4000 kg maximum load capacity can be used to haul the goods into the laboratory.

Traceability

In commissioning, various laser and gauge block measurement were carried out on the coordinate measuring machine. Furthermore, the machine is regularly calibrated using our own measurement standards: step gauges, ball plates, and a laser interferometer. The measurement uncertainty and traceability are verified in each case separately using so-called substitute method, i.e. results are corrected using the results of a calibrated standard.

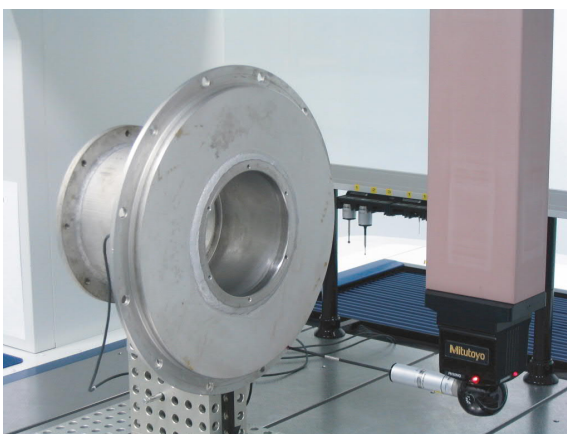


Figure 3. A typical artefact that can be measured using a coordinate measuring machine.



Figure 2. The proper mounting of work pieces is important.

Table 1. The main properties of the coordinate measuring machine.

| Property | Data |
|---|---|
| Performance checked according to ISO 10360-2: <ul style="list-style-type: none"> • maximum error in length measurements • maximum 3D contact deviation • maximum error in scanning measurement | $MPE_e = (0.35 + L / 1000) \mu\text{m}$, $L = \text{mm}$ $MPE_P = 0.35 \mu\text{m}$ $MPE_{thp} = 1.4 \mu\text{m}$ |
| Error of laser scanner head | 1.8 μm |
| Scales | Mitutoyo Zerodur scales with floating mounting, resolution 0.01 μm . |
| Travelling length | X-910 mm, Y-1010 mm and Z-610 mm |
| Contact probe | Renishaw indexing head PH10MQ Renishaw SP25M contact and scanning probe |
| Measuring force | 0.03 N...0.09 N |
| Software | Mitutoyo COSMOS software <ul style="list-style-type: none"> • Geopak-Win geometry program • Statpak-Win geostatistical analysis for quality control • Scanpak-Win form measurement • 3Dtol-Win/ MCAD300 comparison with CAD models and importing CAD data |
| Laser head | SurfaceMeasure 201FS |
| Max. workpiece mass | 800 kg |
| Diameter of probes | 0.5 mm...30 mm |

Optical coordinate measuring – vision measuring

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The manufacturing tolerances of modern products and the aim for high quality require ability to make precise measurement of dimensional measurands on small artefacts of complicated shapes. The use of vision measuring machines and machine vision is well established in non-contact high-precision measurement.

VTT MIKES have a Mitutoyo Quickvision Hyper QV-350 vision measuring machine (optical CMM or video measuring machine) that is equipped with a CCD-camera as well as with a contact probe. In non-contact optical measurements, the machine takes advantage of the measurement point location detected by the CCD camera and location information from the precise scales attached to mechanical guides.

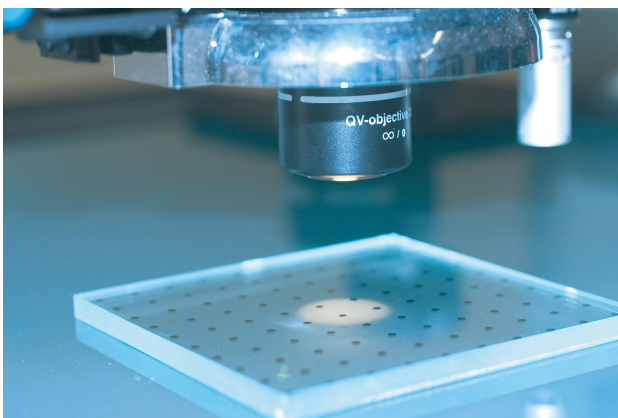


Figure 2. The artefact under study can be illuminated with ring, coaxial or stage light.



Figure 1. VTT MIKES vision co-ordinate measuring machine.

The machine is computer-controlled and measurements are fully automated. The machine is capable to measure length, diameter, angle, straightness, flatness, parallelism, and roundness.

The machine is especially suitable for measurements of circuit boards, thin-walled fragile plastic and metallic artefacts, and other artefacts that are inconvenient or impossible to measure with techniques using contact probes.

The artefact under study can be illuminated with ring, coaxial or stage light. There are four controllable segments in the ring light and its height can be adjusted.

VTT MIKES provides precise optical and contact dimensional measurements tailored according to customers' needs. Depending on the work order, a calibration certificate or a field log is provided.

Table 1. Properties of the vision measuring machine.

| Property | Data |
|--|--|
| Measuring volume | 350 mm x 350 mm x 150 mm |
| Size of the bench | 490 mm x 550 mm |
| Max. workpiece mass | 15 kg |
| Lowest measurement uncertainty ($k=2$), optical mode | U1XY = $(0.8 + 2 L/1000) \mu\text{m}^*$ U2XY = $(1.4 + 3 L/1000) \mu\text{m}^*$ U1Z = $(3 + 2 L/1000) \mu\text{m}^*$ |
| Lowest measurement uncertainty ($k=2$), contact mode | U1XY = $(1.8 + 2 L/1000) \mu\text{m}^*$ |
| Max. speed (rapid travel) | 100 mm/s |
| Maximum acceleration | 490 mm/s ² |

* L is length in mm. U1 uncertainty along one axel, U2 along two axels.

High-accuracy line scale calibrations

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Line scale interferometer

VTT MIKES interferometer for high accuracy calibration of line scales provides highest class measurement accuracy up to 1.12 m. The instrument is situated in air-conditioned laboratory: air temperature is $20\text{ °C} \pm 0.05\text{ °C}$ and relative humidity is $45 \pm 5\%$.

The instrument measures line distances automatically utilizing a special interferometer and a CCD camera with microscope. The line scale is positioned under the microscope with support from Airy points to keep bending in minimum. The refractive index of air is determined with air temperature, pressure and humidity meters and an updated Edlen formula. Thermal expansion correction is made using material temperature data from 4 Pt-100 sensors.

The line distance to be calibrated can vary from $10\text{ }\mu\text{m}$ to 1.12 m. The instrument is suitable for metallic line scales, for glass microscope graticules and for high accuracy LTEC quartz or Zerodur scales.

Automated and dynamic measurement method enables measurement of all line distances on the scale with economic cost. When using line scale as transfer standard of meter it's good to understand that also line scales suffer from nonlinearity i.e. the only position of calibrated lines is well known.

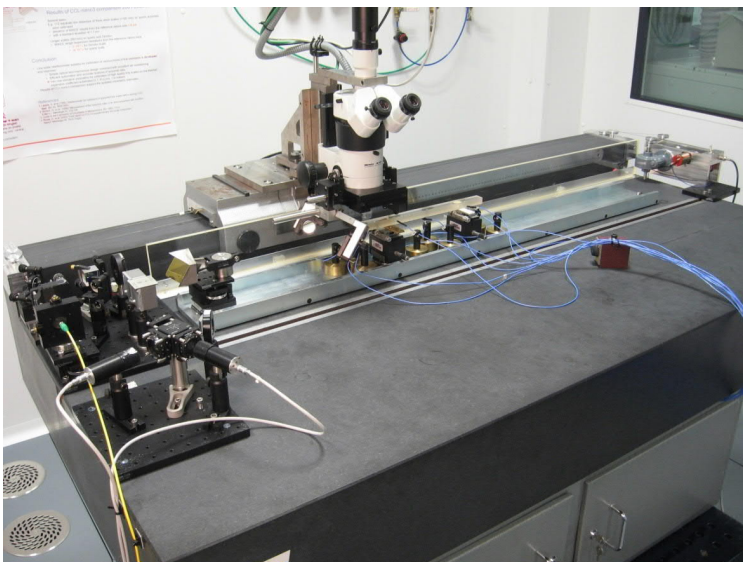


Figure 1. VTT MIKES line scale interferometer.

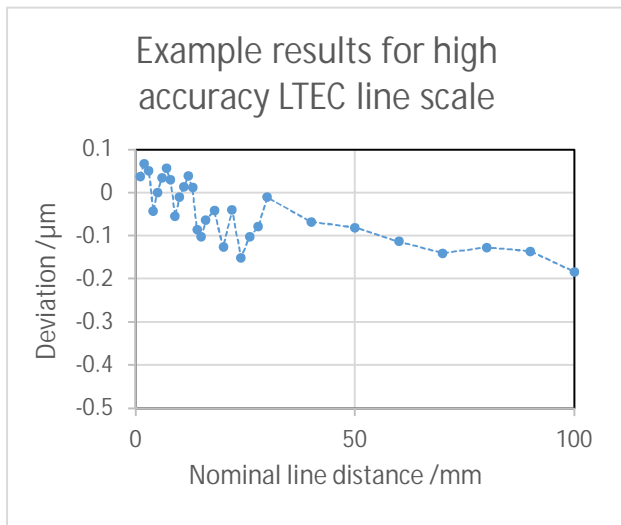


Figure 2. Results of a high quality LTEC line scale reveals nonlinear error of the intermediate line distances. Note area from 0 to 25 mm with denser calibration points.

Calibration service and uncertainty

Calibration assignment is started by agreeing nominal line distances to be calibrated, location and width of measurement area and targeted uncertainty level. By repeating measurement in different locations and positions it's possible to reduce some of the measurement errors e.g. related to Abbe error and refractive index of air.

Traceability

The vacuum wavelength of the laser used in line scale interferometer is calibrated against national reference standard iodine stabilized He-Ne laser. Also, temperature, pressure and humidity meters are calibrated against VTT MIKES references.

The correct operation of the line scale interferometer is ensured by regular participation to EURAMET TC-Length of CCL key comparisons.

Best measurement uncertainty is reached with LTEC line scale with excellent graduation mark quality, i.e. line edge straightness and width are regular. Also guidelines to show the position of the measurement area will improve reproducibility of the measurements. If small uncertainty is seek also the flatness deviation of the line scale surface should be excellent and at least better than 50 µm.

Customer may choose economic basic calibration or high accuracy calibration whatever he/she needs most. Also amount of line distance to be measured has effect to service price. However, basic price includes at least 50 line distances.

In table 1 there are uncertainties for different services.

References:

Lassila, A. (2012). MIKES fibre-coupled differential dynamic line scale interferometer. *Measurement Science and Technology* **23**(9), [094011].
<https://doi.org/10.1088/0957-0233/23/9/094011>

Table 1. Uncertainties in line scale calibrations.

| Standard | Range | Expanded uncertainty ($k=2$)* |
|--|------------------|---------------------------------|
| Regular line scales, basic calibration | 10 µm ... 1.12 m | 0.2...0.5 µm |
| Accurate lines scale, better accuracy calibration | 10 µm ... 1.12 m | 0.05...0.15 µm |
| High accuracy line scales, best accuracy calibration | 10 µm ... 1.12 m | Q[6.2 nm, 82E-09 L] ** |

L = Nominal length

*Uncertainty is often larger due to uncertainty caused by properties of the device under calibration

** $Q[x; y] = (x^2 + y^2)^{1/2}$

Accurate calibration of step gauges

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Step gauge interferometer

VTT MIKES purposed built step gauge interferometer enables calibration at state of art accuracy up to 2 m length (figure 1). The instrument is situated in air-conditioned laboratory: air temperature is $20\text{ °C} \pm 0,05\text{ °C}$ and relative humidity is $45 \pm 5\%$.

The interferometer measures the distances between step gauge surfaces automatically using double pass interferometer and purpose-built measuring head. The step gauge is adjusted accurately to correct position and direction with aid of an integrated 3d position sensor. The refractive index of air is determined

with air temperature, pressure and humidity meters and an updated Edlen formula. Thermal expansion correction is made using material temperature data from 4 Pt-100 sensors.

The instrument is suitable to many kinds of step gauges e.g. Koba and Mitutoyo type step gauges can be calibrated with it. Automatic measurement method with high quality laboratory conditions enables economic high accuracy calibration.



Figure 1. VTT MIKES interferometer for calibration of step gauges.

Calibration service and uncertainty

Calibration assignment is started by agreeing targeted uncertainty level. By repeating measurement in different locations and positions it's possible to reduce some of the measurement errors e.g. related to Abbe error and refractive index of air.

Customer may choose economic basic calibration or high accuracy calibration whatever he/she needs most.

Table 1 shows uncertainties for different services.

Table 1. Measurement uncertainty.

| Service | Range | Uncertainty ($k=2$)* |
|----------------------------|---------------|------------------------|
| Economic basic calibration | 10 mm... 2 m | 0.3 µm/m |
| Accurate calibration | 10 mm ...2 m | 0.15 µm/m |
| High-accuracy calibration | 10 mm ... 2 m | Q[64 nm, 88E-9 L]** |

L = Nominal length

*Uncertainty is often larger due to uncertainty caused by properties of the device under calibration

** $Q[x; y] = (x^2 + y^2)^{1/2}$

References:

Byman, V., Jaakkola, T., Palosuo, I., & Lassila, A. (2018). High accuracy step gauge interferometer. *Measurement Science and Technology* **29**(5), [054003]. <https://doi.org/10.1088/1361-6501/aaad32>

Coveney, T., et al., Calibration of 1-D CMM artefacts: step gauges (EURAMET.L-K5.2016) et al, 2020, *Metrologia* **57** 04002. <https://doi.org/10.1088/0026-1394/57/1A/04002>

Traceability

The vacuum wavelength of the laser used in the step interferometer is calibrated against national reference standard iodine stabilized He-Ne laser. Also, temperature, pressure and humidity meters are calibrated against VTT MIKES references.

The correct operation of the step gauge interferometer is ensured by regular participation to EURAMET TC-Length of CCL key comparisons.

Calibration of rulers, tapes and distance meters

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Calibration of rulers, tapes and distance meters

30-m measuring rail

VTT MIKES 30-m measuring rail (Figure 2) offers good possibilities for calibration of precise length measuring devices. The temperature of the measurement room is kept at $(20 \pm 0.5)^\circ\text{C}$ and the relative humidity at $(45 \pm 5) \%$. The 30-m rail is realised using a high-quality linear motion guide and a movable measurement carriage. A microscope, a CCD camera and a monitor used in line scale measurements are mounted on the carriage. The position of the microscope is measured using a laser interferometer.

The temperature stability of the measurement room and precise gauges & sensors allow precise thermal expansion and refractive index of air compensation. The rail is suitable for calibration of various length standards. The calibrated devices can be physical artefacts like tapes and machinist scales or e.g. optical distance meters. Tapes and other flexible length standards are tensioned using a standardized force, a force given by the manufacturer or a force separately agreed with customer. Most commonly a 50-Nm force of is used for tapes.

For thermal expansion compensation, a measured temperature and a coefficient given by the manufacturer or by the customer are used.



Figure 1. 30 interferometric bench.

Traceability

The wavelengths of the lasers used in the 30-m measuring rail are calibrated using national measurement standard of length, iodine-stabilized He-Ne laser. The temperature, pressure, and humidity sensors used in the measuring rail are calibrated at VTT MIKES.

Table 1. Line scales, measuring ranges and measurement uncertainties.

| Device | Measuring range | Uncertainty* ($k=2$) |
|------------------|----------------------------------|------------------------------|
| Tapes, wires | 0.001 m ... 30 m, (60, 90 ...) m | $Q[35; 2L] \mu\text{m}^{**}$ |
| Machinist scales | 0.001 m ... 5 m | 10 μm |
| Circometer | 0.1 m ... 9.55 m (diameter) | $Q[7; 2D] \mu\text{m}^{**}$ |
| Plumb tapes | 1 m ... 30, (60, 90) m | $Q[250; 5L] \text{mm}^{**}$ |
| Other devices | 0 m ... 30 m | (case dependent) |

L = measured length or corresponding diameter in meters

*The uncertainty of calibration is often larger than the aforementioned uncertainties due to the uncertainty resulting from the device to be calibrated.

**Calculation of uncertainty $Q[x; y] = (x^2 + y^2)^{1/2}$

Interferometric measurement of flatness and form

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Flatness

The surface structure and especially the flatness of the surface are important features of various components used in different areas of technology and physics. Examples of these include silicon wafers in semiconductor industry, sealing faces, bearing areas, contact surfaces in contact measurement methods and surfaces of optical flats and lenses used for reflecting and refracting light.

An optical flat is an easy to use transfer standard for flatness. In industry, optical flats are used, e.g. for

flatness measurements of gauge blocks and contact surfaces of micrometre gauges. In these cases, the quality of the surfaces of optical flats is of essential importance for successful measurements of subject surfaces. Moreover, optical flats are used to transfer flatness to interferometers measuring flatness and to other devices inspecting flatness in industry.

VTT MIKES provides aforementioned measurements and metrological traceability with its equipment for flatness and form measurements (Figure 1).

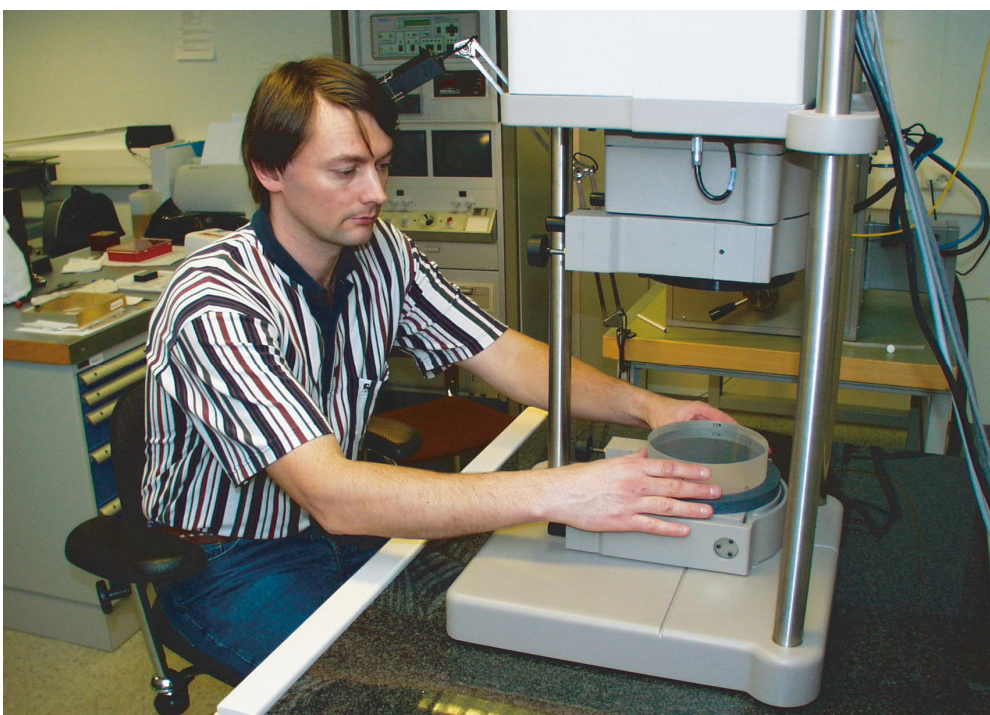


Figure 1. Calibration of an optical flat.

Measurement method

The measurement device for flatness at VTT MIKES is a Fizeau interferometer that uses a He-Ne laser at wavelength 633nm as a light source. Interference fringes are obtained by adjusting a small angle between the reference plane and the plane to be measured. The shapes of the interference fringes are analysed by using a so-called phase stepping method. As a result, one receives deviations of the plane under inspection from the reference plane (Figure 2). The advantages of the method are speed, precision, and the fact that the entire measurement area is measured at once.

Traceability

The reference plane of the optical flat used in the interferometer is of high quality: deviations from a perfect plane are less than 20 nm. The reference plane is calculated either by using an absolute three-point method or by comparing it to a liquid plane. Optical flats having different reflection coefficients are available which allows inspections of mirror surfaces as well as glass surfaces.

Measurement services

The VTT MIKES equipment (Zygo GPI) can be used for surface profile measurements of objects that have diameters below 150 mm, best available measurement precision being 45 nm. A prerequisite for such measurements is that the height variations of the artefact are less than 12 μm and slowly varying. As the method is based on interference of light and thus it is a non-contacting method, it is also applicable for fragile materials. Moreover, it is applicable for very demanding measurement tasks due to its precision.

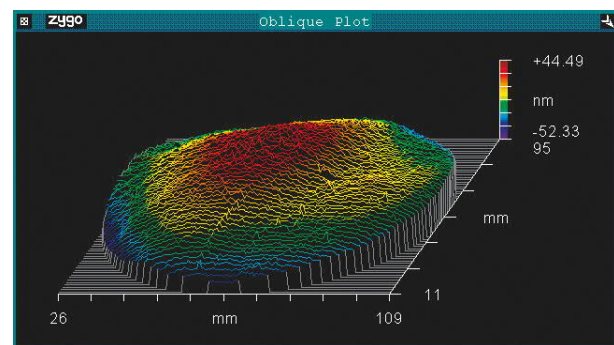


Figure 2. An example of measured surface profile of an optical flat.

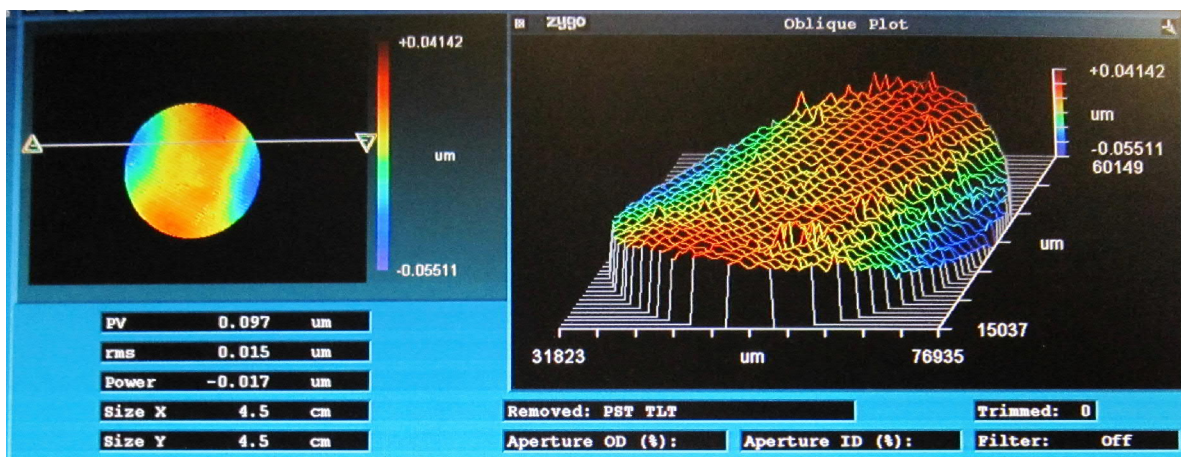


Figure 2. An example of measured surface profile of an optical flat.

Machine tool measurements

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Demands of production and quality systems require knowledge on the precision of machine tools. Different measurements are performed on machine tools during acceptance inspection, in connection with transfers, and when striving for preventive maintenance. VTT MIKES provides its wide experience on dimensional and geometrical measurements, positioning and repeatability accuracy measurements, and measurements on machine-tooled test work pieces.

The competent and experienced personnel of VTT MIKES, modern equipment and continuous development of new measurement methods guarantee customers' precise measurements performed according to standards.

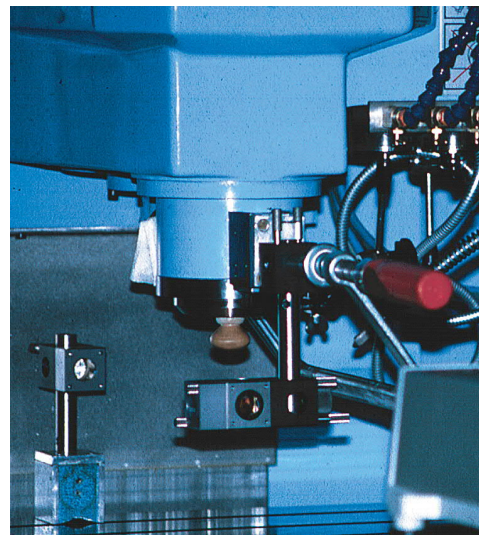


Figure 1. Scale measurement for a machine tool.

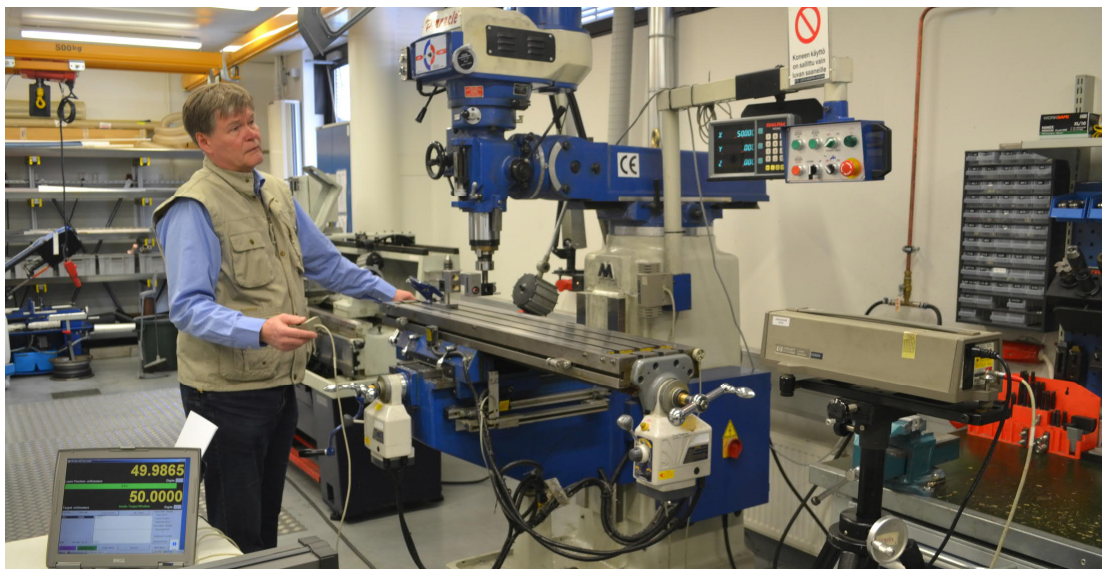


Figure 2. Setup for machine tool measurements.

Geometrical measurements

Geometrical measurements are used for finding out the form defects in the most important organs of a machine tool and the mutual locations and positions of the organs. VTT MIKES performs geometrical measurements according to ISO and DIN standards. The most important measurements subjects are measurement of spindle runout, the parallelism between the spindle and the machine, perpendicularity measurements, and straightness and perpendicularity measurements of machine movements.

Accurate positioning and repeatability measurements

Spindle positioning and repeatability measurements reveal errors at different points of the spindle. Errors in spindle movement can be compensated for by giving the compensation values to the control unit memory of the machine tool. The positioning measurement performed using VTT MIKES laser interferometer is a fast and precise way to adjust the spindle movements of a machine (Figure 3); the measurement precision is at its best below 0.001 mm/m.

Measurement of test workpieces

Machine-tooling tests are used to find out the precision of the machine in true machining circumstances. VTT MIKES geometrical measurements and measurements on work pieces made in machine-tooling tests

complement each other. The work pieces are measured in a temperature-controlled laboratory room using versatile and modern measurement devices and methods. VTT MIKES have a variety of the most common workshop measurement equipment and a selection of special tools (see Table 1).

Traceability

All measurement standards used in machine tool measurements are calibrated using similar but more accurate VTT MIKES transfer standards.

Table 1. Devices used in machine tool measurements.

| Geometrical, positioning and repeatability measurements: | Measurements of test workpieces |
|--|--|
| – laser interferometers | – surface structure, form, roundness and length measuring machines |
| – autocollimators | – inductive sensors |
| – electronic spirit level | – common workshop measurement devices |
| – inductive sensors | – coordinate measuring machine |
| – plumb | |
| – other devices | |

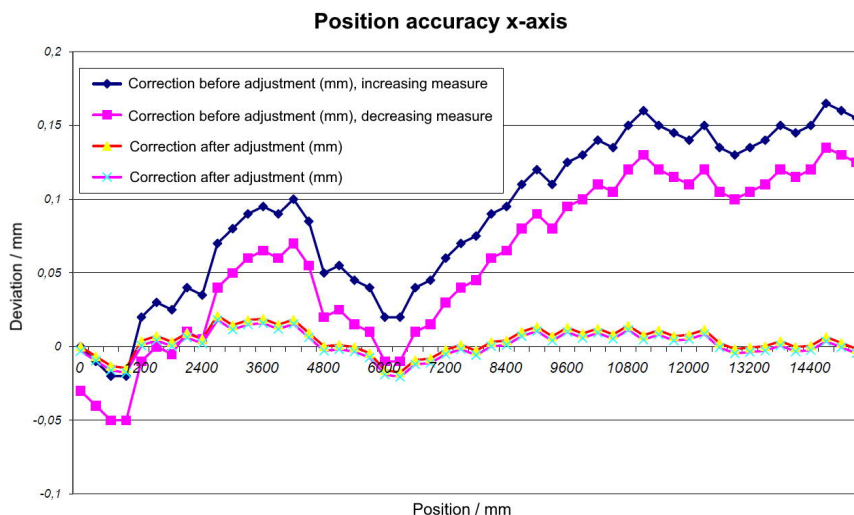


Figure 3. X-axis errors of a broaching machine before laser measurement and adjustment and after.

Measurement of roundness

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Roundness in mechanical engineering industry

Approximately 80 % of machined work pieces have elements with surfaces of revolution. Roundness has an important role for guaranteeing faultless operation of machines and devices. This is even emphasized when reliability, longevity, low operating costs, and friendliness to the environmental are required.

At VTT MIKES, we perform measurements of roundness on ring gauges, screw-plug gauges, slide bearings, metallic packings and hydraulic and pneumatic components. We also measure runout eccentricity, coaxiality, parallelism and straightness (Figure 1).

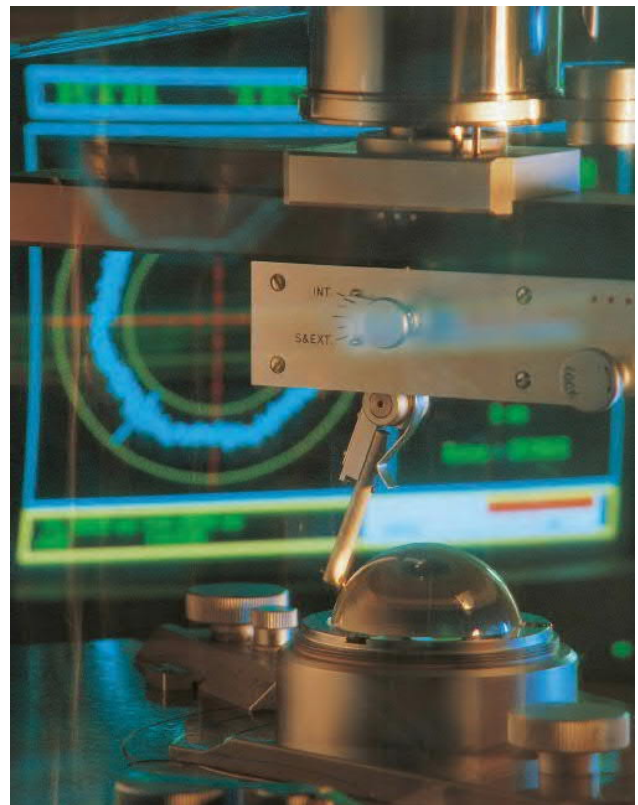


Figure 1. Roundness measurement is an essential part of workshop manufacturing.

Measurement potential

Roundness is measured either by using a rotating spindle or by using a roundness measurement instrument equipped with a rotating table. Measurements can be performed using several different filters according to the ISO 1101 standard's definition (MZ) or other computing methods (MC, MI, and LS). The use of two alternative machines guarantees the customer that the artefacts can be measured properly and cost effectively. More information on the machines can be found in table 1.

Cylindricity is measured using a machine equipped with a rotating table (Figure 2); with almost the same settings, the following measurement can be performed, also: coaxiality, runout eccentricity, parallelism and straightness. Cylindricity measurements are a part of the calibration of ring gauges and screw-plug gauges.

Traceability

Traceability to the sensors in both machines comes from magnification standards that are calibrated using VTT MIKES form measurement instrument which in turn gets its traceability from gauge blocks calibrated using an interferometer. The guide bars and shafts in the machines are calibrated using error separation.



Figure 2. Measurement instrument Talyrond 262 for roundness and cylindricity.

Table 1. VTT MIKES roundness and cylindricity measurement instruments.

| Model | Rotating part | Maximum height of the artefact mm | Maximum inner/outer diameter of the artefact mm | Maximum mass of the artefact kg | Other | Expanded uncertainty ($k=2$) |
|---------------------------|---------------|-----------------------------------|---|---------------------------------|--|--|
| Talyrond 73HR roundness | spindle | 400 | 175 / 300 | 100 | surface can be discontinuous or asymmetrical | $Q[10 \text{ nm}, 0.01 \text{ R}]$ |
| Talyrond 262 cylindricity | table | 500 | – / 350 | 50 | surface can be discontinuous | $Q[0.1 \text{ } \mu\text{m}, 0.001 \text{ L}]$ |

R is the deviation from roundness; L is the height of the cylinder in metres; $Q[x; y] = (x^2 + y^2)^{1/2}$

Calibration of microscopes and calibration standards

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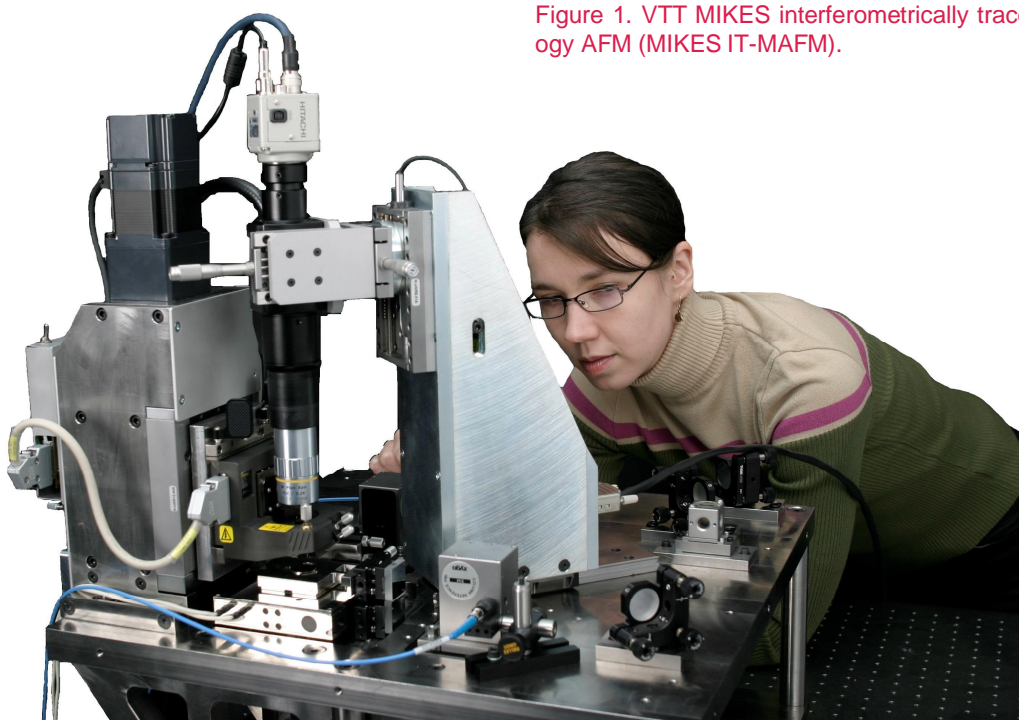
Reliable measurement results in research, manufacture and quality control require knowledge of accuracy of measurement instruments. Calibration is the best way to check the accuracy and stability of the instrument. The calibration can be done with calibrated transfer standards. Official calibration certificate guarantees traceability to the definition of the metre.

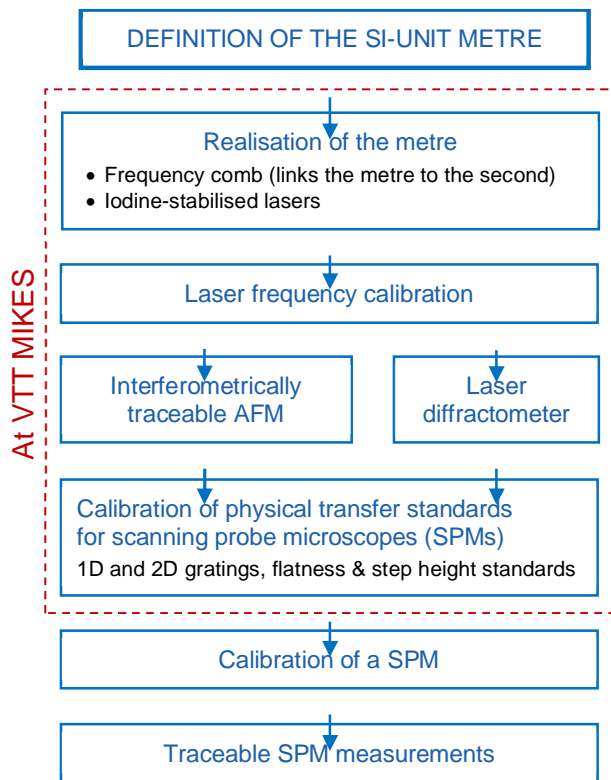
For optical microscopes VTT MIKES provides calibration of high-quality line scales.

Scanning probe microscopes (SPMs) can be calibrated using several kinds of transfer standards [1,2], which can be calibrated at VTT MIKES. 1-D and 2-D gratings are calibrated either by laser diffraction or by metrology atomic force microscope (MAFM). Pitch and orthogonality of the grid can be measured. Step height standards or z scale of 1-D or 2-D gratings can be calibrated.

- [1] Guideline VDI/VDE 2656 Part 1 (Draft): Determination of geometric quantities by Scanning Probe Microscopes - Calibration of Measurement Systems.
- [2] V. Korpelainen and A. Lassila, Calibration of a commercial AFM: traceability for a coordinate system, Meas. Sci. Technol. 18 (2007) 395–403.

Figure 1. VTT MIKES interferometrically traceable metrology AFM (MIKES IT-MAFM).





Calibration itself gives information about the accuracy of the instrument. Accuracy of the measurement can be increased by corrections of the errors detected in the calibration either directly in the measurement software or after the measurement with separate software.

The first step in the calibration is measurement of x and y scale errors by 1-D or 2-D gratings and z scale errors by step height standards. The calibration of the x and y scales gives also information about the linearity of the scales. The linearity of the z scale needs to be checked by several different step height

standards. Orthogonality errors can be detected by 2-D grids. Out-of-plane errors can be measured using a flatness standard. In the most accurate calibrations also some other error types has to be measured and corrected; e.g. orthogonality of z-axis, rotational and other guiding errors. There are also other error sources, which should be taken into account, e.g. tip-sample interactions, vibrations, noise and thermal drift. Calibration period depends on the stability of the device, e.g. microscopes with open loop scanner need calibration before and after each measurement.

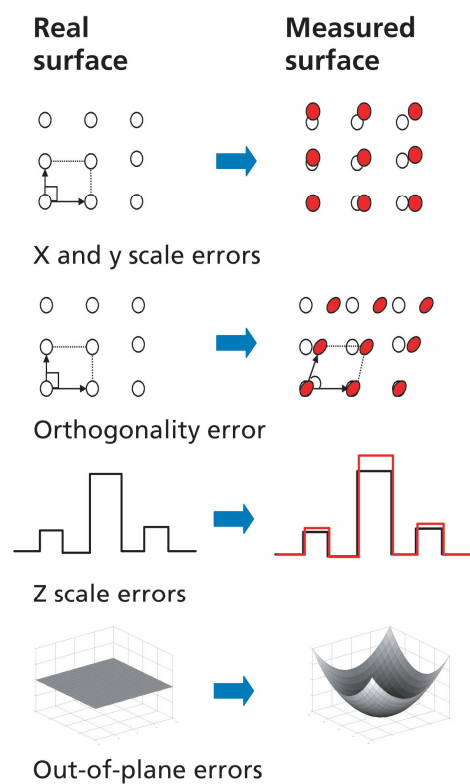


Figure 3. Some error types of SPMs.

Table 1. Calibration services for SPM standards.

| | | Range | Uncertainty |
|------------------------------------|------------------|-----------------|----------------------------------|
| 1-D grid (diffraction measurement) | | | |
| | Pitch | 300 nm – 10 µm | 50 – 100 pm |
| 2-D grid (diffraction measurement) | | | |
| | Pitch | 300 nm – 10 µm | 50 – 100 pm |
| | Orthogonality | | |
| 1-D grid (AFM measurement) | | | |
| | Pitch, p | 100 nm – 10 µm | Q [3.4, 0.2 $p/\mu\text{m}$] nm |
| | Orthogonality | | 14 mrad |
| | Step height, h | 10 nm – 2 µm | Q [2, 0.2 $h/\mu\text{m}$] nm |
| | Flatness | 100 µm × 100 µm | 5 nm |
| Step height standard | | 10 nm – 2 µm | Q [2, 0.2 $h/\mu\text{m}$] nm |
| Flatness standard | | 100 µm × 100 µm | 5 nm |

Angle and perpendicularity measurements

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Angle measurements are important in all mechanical engineering and construction industry. The significance of angle measurements is increased also in dimensional measurements when dimensions increase. Perpendicularity that is related to right angles and square blocks is an important special case of angle measurement.

The SI-unit for angle is radian (rad) but depending on the branch of industry and the measurement subject other units are commonly used. In mechanical engineering angles are normally expressed in degrees [°], minutes ['] and seconds ["], in geodesy the most commonly used unit is gon [gon] (also referred to as grade). In earth-moving work and for small angles the unit [mm/m] is generally used. The diverse group of units for angle include also the following ways to express the angle: percent [%] and length ratios.

Perpendicularity according to the ISO1101 standard:

- As a result the width t of tolerance zone is given
- One side is defined as the reference side and only against this side the perpendicularity is determined.

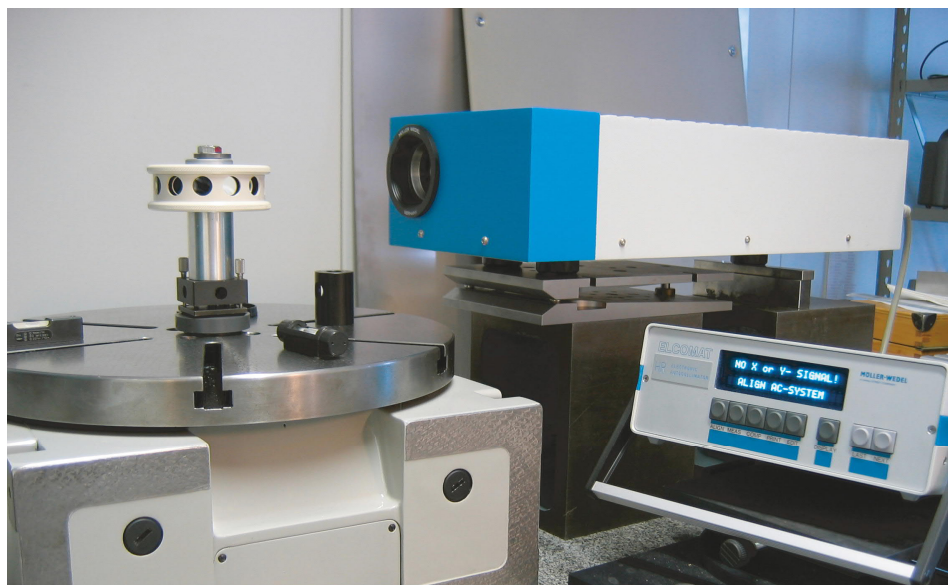
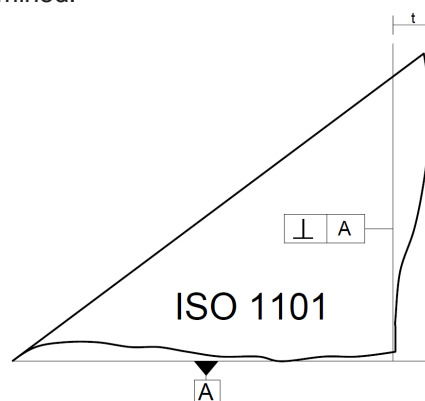


Figure 1. Polygon attached to a rotary table. Errors from the rotary table and the polyhedron can be separated by performing a measurement series using a Moller Wedel HPR autocollimator.

Instruments for measuring angle

The most typical objects of calibration in mechanical workshops are rotary tables of machine tools and measuring machines, universal bevel protractors, angle blocks, and different kinds of spirit (bubble) levels. Typical angle measurement instruments used in machine installation and in construction engineering are e.g. electronic levels, theodolites, levelling instruments, tacheometers, laser interferometers, autocollimators and polygons.

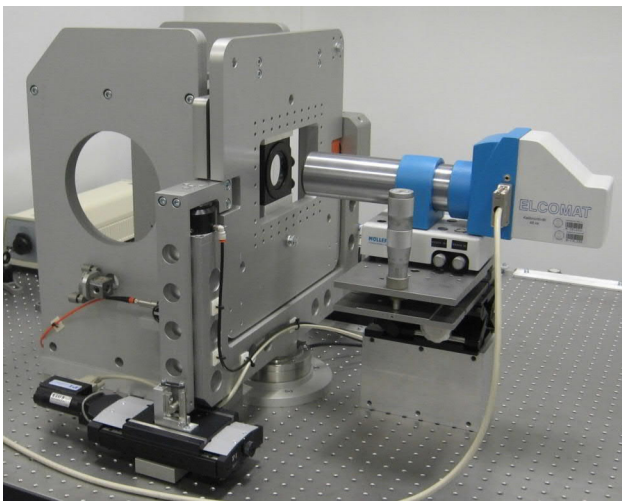


Figure 2. Interferometric 2D small angle generator for calibration of autocollimators developed at VTT MIKES.

Measurement uncertainty

All measurements are performed in a well-controlled laboratory room at temperature $+20\text{ °C} \pm 0.1\text{ °C}$. The achievable measurement uncertainty depends critically on the artefact under calibration and its properties (e.g. form errors and surface roughness)

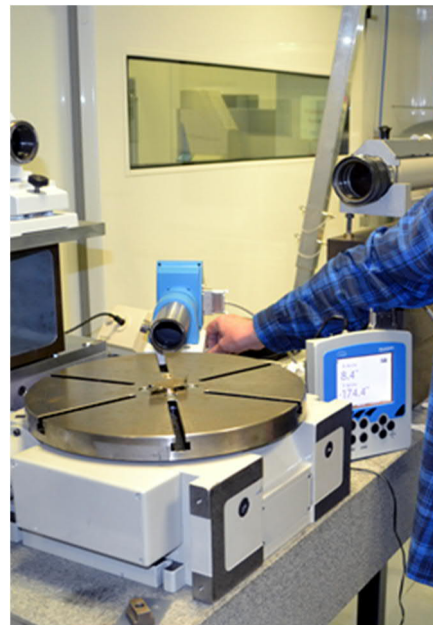


Figure 3. Preparation of angle measurements.

Table 1. Examples of lowest uncertainties for angle measurement instruments.

| Instrument | Measuring range | Measurement uncertainty ($k=2$) | Limitations |
|--------------------------|-----------------------|-----------------------------------|--------------------------------------|
| Optical polygons | $0^\circ - 360^\circ$ | 0.2" | |
| Rotary index table | $0^\circ - 360^\circ$ | 0.5" | indexing angle $n \times 15^\circ$ |
| Rotary table | $0^\circ - 360^\circ$ | 0.2" | |
| Autocollimator | $0^\circ - 1^\circ$ | 0.02" | |
| Electronic level | $0^\circ - 360^\circ$ | 0.2" | |
| Theodolite | $0^\circ - 360^\circ$ | 0.2" | instrument limits the vertical angle |
| Angle block | $0^\circ - 360^\circ$ | 0.2" | |
| Steel or granite squares | 90° | 0.5" | maximum length 1 m |
| Cylinder square | 90° | 0.5" | maximum length 1 m |
| Optical right angle | 90° | 0.5" | |

Calibration of tachymeters

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MIKES calibrates angle and distance measurements functions of tacheometers.

Calibration of a distance metre in a 30-metre measuring rail

Readings from a distance meter of a tachymeter is compared to readings from a laser interferometer of the 30-metre measuring rail. The measurement axis of the tachymeter and the laser interferometer are aligned to be parallel. The reading of the interferometer is set to zero at the beginning of the measuring rail. The observed reading of the distance meter at the zero point of the interferometer is subtracted from

the readings of the distance meter. In the calibration certificate, the deviations from the references distances and the expanded measurement uncertainty are given for each target point. The target point can be a prism, a reflector tape or a target plate. The measurement uncertainty depends on the scatter of the measurement results and is typically between 0.05 – 0.25 mm for accurate distance meters.



Figure 1. MIKES 30-m measuring rail.

Calibration of angle measurements by using a rotary table and collimation tubes

The vertical and horizontal scales of a tachymeter are calibrated by using an Eimeldingen rotary table as a reference. The rotary table is calibrated using polygons and collimation tubes.

In the calibration of the horizontal scale, the tachymeter is placed to the rotary table in such a way that the vertical axis is aligned to the rotational axis of the table (Figure 2). The table is rotated 360° in 30° steps and at each step the reading of the tachymeter that has been targeted to the collimation tube are recorded.

The vertical scale of the tachymeter is calibrated in the same way but now the rotary table is turned to vertical position by using optomechanics that have been designed especially for this purpose.



Figure 2. Calibration of the horizontal plane of a tachymeter in an Eimeldingen rotary table with a collimation tube as a target point.

| Contents of tacheometer calibration | Typical measurement uncertainty |
|--|---------------------------------|
| Calibration of length scale | |
| <i>Deviation from reference</i> | |
| precision target | 0.15 mm |
| spherical target | 0.15 mm |
| reflector tape | 0.20 mm |
| without target | |
| <i>Calibration of angle scale</i> | |
| scale error of the vertical circle | 2" – 3" |
| scale error of the horizontal circle | 1" – 2" |
| tilting axis error | 1" – 2" |
| index error of the vertical circle | 0.5" – 1.5" |
| line-of-sight error | 0.5" – 1.5" |
| crosshair alignment and perpendicularity | |
| influence of focussing | |
| checking the readings of the environmental sensors | |
| divergence test of automatic targeting | |

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