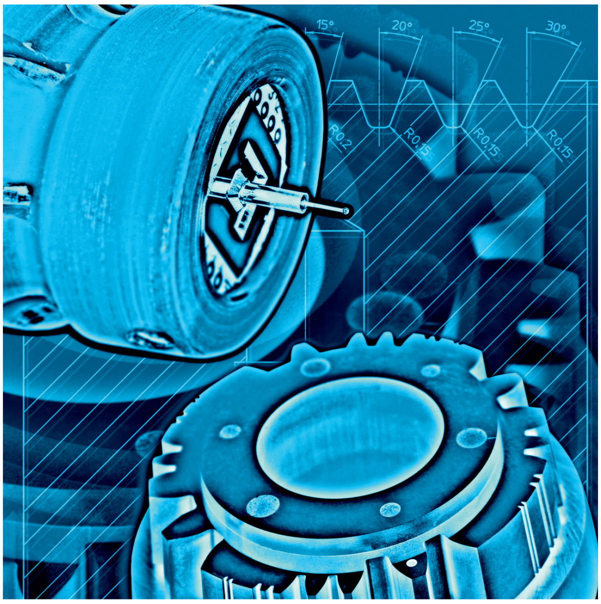
Division 5
Precision Engineering



The *Precision Engineering* Division carries out research and development activities with the aim of covering, as best as possible, the current and – in particular – the future needs of industry, society and science for metrological traceability of dimensional quantities with the measurement uncertainty required for the individual application. Based on the results of this research and development work, new and improved metrological services in the fields *calibration of standards*, *validation of metrological procedures*, and *testing of special evaluation algorithms* are offered and carried out. The type and design examinations for length measuring machines and devices in accordance with the European Measuring Instruments Directive (MID) as well as the testing and the national approval for verification of dimensional measuring instruments complete the spectrum of tasks of the *Precision Engineering* Division. Furthermore, employees of the Division also work as technical and system experts for the German Accreditation Body (DAkkS) and participate in peer reviews of other metrology institutes.

The technical tasks of the Division are dealt with in the Departments *"Surface Metrology"*, *"Dimensional Nanometrology"*, *"Coordinate Metrology"* and *"Interferometry on Material Measures"*. The Division's *"Scientific Instrumentation Department"* supports all divisions of PTB with high-quality services in the design, manufacture and assembly of prototype measuring devices and standards.

Progress in metrology requires an exact understanding of the relevant quantities which influence the measurement process applied. The establishment of the uncertainty budget is, in principle, also possible without this knowledge. It is, however, associated with an increased measurement uncertainty. In accordance with the GUM (Guide to the expression of uncertainty in measurement), all relevant influence quantities must be taken into account and correctly determined in the model equation for the measurement process. The measurement process is, however, often rather complex, and the model equation can only be established with great effort (or it cannot be realized at all). Already at the end of the 1990s, PTB's *Coordinate Metrology* Department developed the procedure of the *virtual coordinate measuring machine* for the determination of task-specific measurement uncertainties on complex specimens, which allows task-specific measurement uncertainties to be calculated with simulation procedures based on Monte Carlo methods. Another field of application in which simulations in metrology are used is nanometrology. Here, special challenges arise due to the dimensions of the nanostructures to be characterized, which are small – compared to the measuring probes of the different measuring instruments. In this case, the achievement of small measurement uncertainties requires modelling of the interaction between the probe and the specimen in order to describe and interpret the signal contrast indicated by the measuring instrument on the nanostructure with sufficient accuracy.

Cover picture:

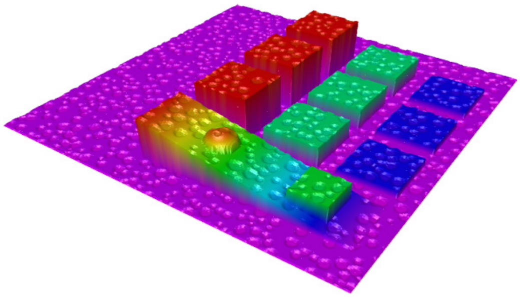
New developments in coordinate metrology: Microgear standard with sub-millimetre transverse modules and adapted microprobe.

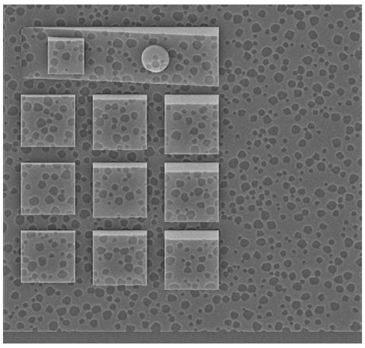
This year, the report of the Division is focussed, on the one hand, on the discussion of this mutual dependence of the progress made in the modelling of metrologically relevant properties of measuring instruments or essential components in interaction with the objects and standards to be calibrated. On the other hand, it is focussed on the profound knowledge of the measurement process being made possible by this, which considerably contributes to reducing the calibration uncertainties of standards and to optimizing measuring instruments (and possibly also manufacturing equipment).

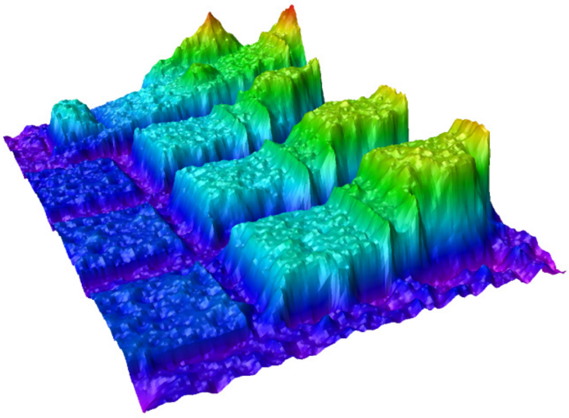
Modelling procedures for modern production measurement

Examples from the field of nanometrology

In nanometrology, modern scanning electron microscopes have become an indispensable tool. They allow sample surfaces to be scanned with a very fine electron beam (only approx. 1 nm in width) which is moved across the surface following a raster scan. The primary electrons are, however, subject to different interaction processes in the solid state sample material to be investigated – such as, for example, elastic and inelastic scattering – so that the low-energy secondary electrons (SEs) which are generated in the area of the sample close to the surface and which are frequently used for detection originate from a larger area around the point of entry of the primary electrons. The expansion of this SE emission range depends on different conditions such as, for example, the material and the topography of the sample, but also on the primary energy of the electrons. In addition, the measured SE intensity signal also depends on the angle- and energy-dependent efficiency of the electron detection of the SE detector used.







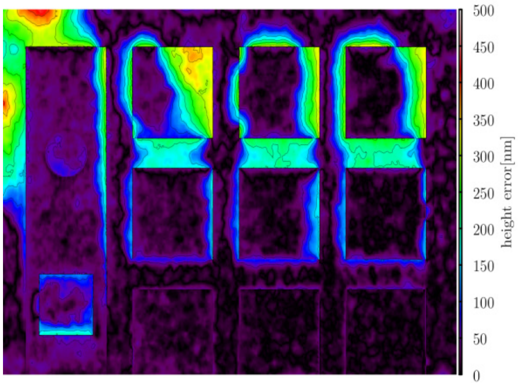


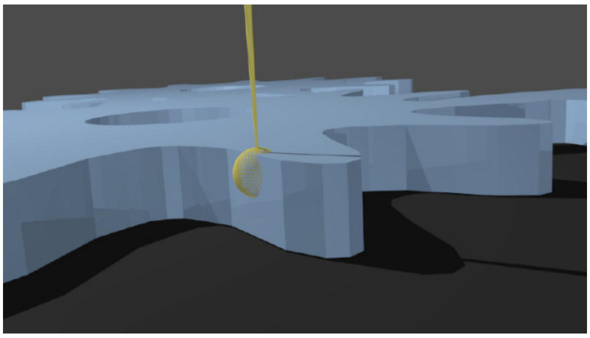
Figure 1: a) 3D test structure, composed of several simple geometry elements and a superposed texture; 1b) simulated SEM image of the test structure tilted by 10°; 1c) result of the reconstruction from the simulated SEM images of the tilted sample; 1d) analysis of the deviations of the reconstructed 3D topography from the assumed 3D topography.

To live up to this complexity of the formation of the imaging signal in the electron microscope, the simulation software MCSEM was developed which allows, among other things, the scattering processes of the electrons in the solid state to be simulated by means of Monte Carlo methods. SEM images simulated by means of MCSEM on well-defined samples (known materials and topographies) can be used to check algorithms applied for SE image evaluation, for example for algorithms – the so-called "edge detection algorithms" – to determine the width or the position of nanostructures in the SEM image.

To measure the topography of technical surfaces, they are imaged in the SEM at different angles. By means of the so-called *"SEM photogrammetry method"*, the resulting image sequences are analyzed by special programmes, and the surface topography on which they are based is reconstructed. To check the achievable accuracy and the limitations of SEM photogrammetry (which must be taken into account) in the case of surfaces with nanoscale topography, again SEM images simulated by means of MCSEM were used.

Figure 1a shows a simulated test structure, composed of several simple geometry elements with a maximum height of 300 nm, complemented in addition by a texture to create favourable preconditions for the correlation algorithms (which are used as a basis for the reconstruction during SEM photogrammetry) over the whole image field. Figure 1b shows an SEM image of the test structure simulated by means of MCSEM, which has been recorded in a position tilted by 10°. The SEM images of the well-defined test structures simulated in this way were used to investigate the achievable accuracies of commercially available SEM photogrammetry reconstructions within the scope of the European joint research project JRP MADES. The mean deviations between the reconstructed topography and the model topography of approx. 40 nm, which are obtained for the example, demonstrate the limits of the method's applicability to nanometrology.

To considerably accelerate the calculation of SEM images, a simplified simulation procedure has been developed which is only based on a geometrical



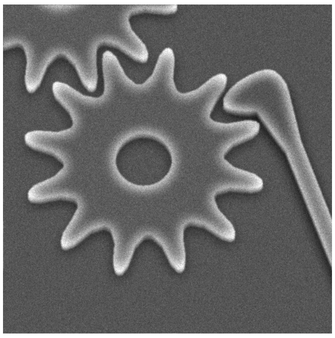


Figure 2: a) Visualization of the principle of the fast computation method for SEM signals; 2b) SEM image of a micro gear wheel, simulated by the fast computation method.

analysis of the surface topography and on an assumed spherical scattering volume of the electron beam – i.e. which does without the computationally intensive Monte Carlo method for the calculation of scattering processes, but shows a smaller accuracy. Figure 2 illustrates the geometrical principle of the fast simulation used as a basis, as well as an SEM image of a micro gear wheel simulated in this way.

The MCSEM simulation software was also used within the scope of another project to optimize the exposure processes in electron beam lithography facilities, see "Headlines".

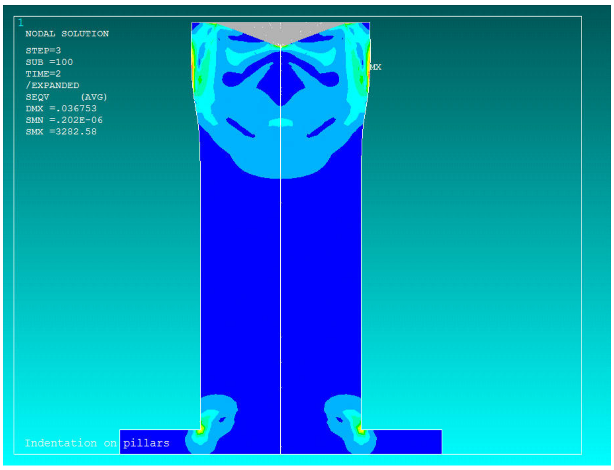
The investigation of the characteristics of nanoscale objects is associated with special challenges. This shall be shown here by the example of the determination of the mechanical properties of nano-objects by means of nano-indentation. Conventional data analysis models for the indentation test in the nanometer range are not able to correctly interpret measurement results on nano-objects. Therefore, the experimentally determined results of nano-indentation measurements on cylindrical silicon nano-columns (500 nm in height) were supported in addition by simulations by means of the Finite Element Method (FEM). Figure 3a) shows the result of an FEM simulation of the deformation of a Si nano-column for a central indentation by a rounded indenter (Berkovich indenter). In the case of real indentation tests, it is often not possible to indent exactly in the centre of the nano-columns. This leads to even larger strains at the base and, thus, frequently to dislocations (see the black curve in Figure 3b), or even to the destruction of the columns.

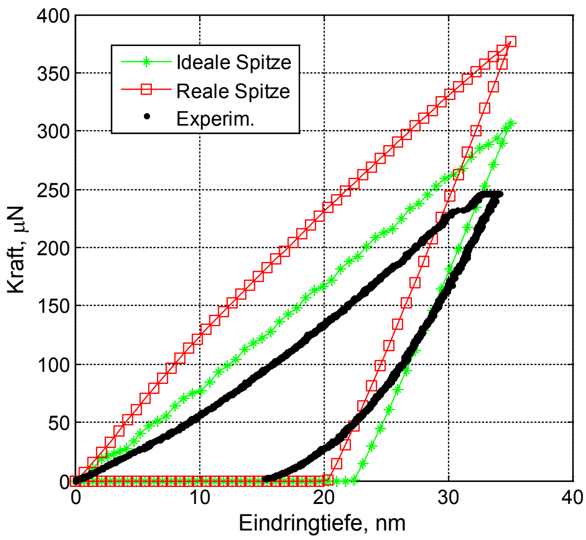
The comparison of the simulated force indenter curves of an ideal and a real Berkovich indenter in Figure 3b with an experimental curve shows even larger deviations. This indicates that the relatively simple two-dimensional simulations with a centric indentation of the nano-columns are not sufficient to describe the experiments with sufficient accuracy. For the future it is, therefore, intended to perform also three-dimensional simulations with excentric indentation.

Figure 3: FEM simulation of the nano-indentation measurement of silicon nano-columns.

a) Numeric 2D simulation of the strain distribution of a nano-column during a nano-indentation measurement with a rounded Berkovich indenter (r_{tip} = 30 nm)

b) Comparison between the simulation results and the indentation measurement on a silicon column (diameter: 386 nm)





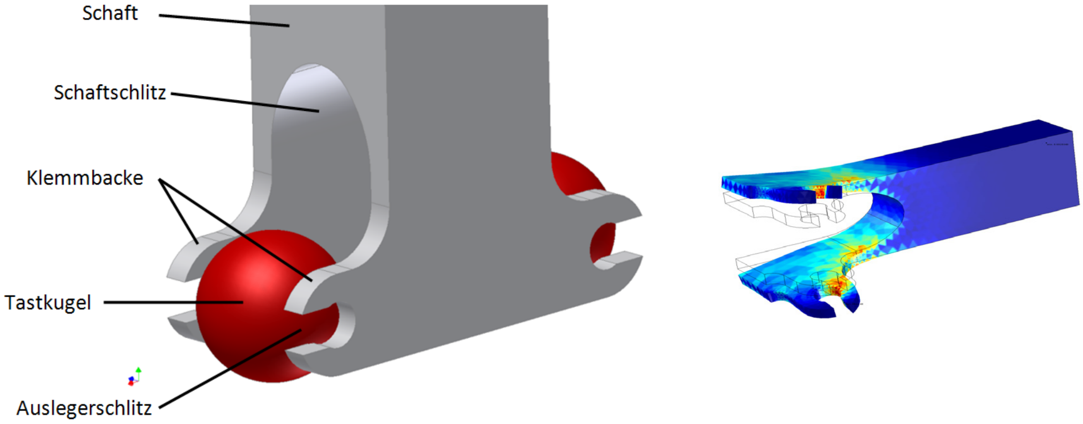


Figure 4: a) Schematic representation of the T-shaped microprobe developed for internal microthreads; b) results of an FEM simulation of the deformations occurring on the clamping device of the T-shaped microprobe. The figure shows both the unloaded body (thin black framing lines) and the deformed body with the representation of the von Mises voltages in false colours. The deformations are represented in an amplified way and do not correspond to the actual deflections of up to 10 µm.

Example from micrometrology

The measurement of microstructure components often still represents a special challenge to dimensional metrology. Probes adapted to internal microthreads (e.g. M0.7 x 0.175) have, so far, not been available in the sufficient quality and with the required dimensions. Within the scope of an MSTQ project, a microprobe has been developed which is – due to its special T-shaped geometry – optimal for measurement tasks on internal microthreads. In the case of this probe, commercially available ruby microspheres with sphere diameters down to 110 µm, which are fixed to a T-shaped probe stylus made of hard metal, are used as the probing elements. Whereas for microprobes, the assembly of small probing balls has so far often been realized by bonding, another concept – in the case of which the spheres are fixed by a clamping device integrated into the probe stylus – has been followed here. The geometric parameters of the design of the fixation, which are important for the functioning of the clamping device, had in advance been investigated and optimized by FEM calculations (see Figure 4). In the simulations carried out, the length of the slit along the shaft was systematically varied at a defined spreading of the probe's clamping jaws. The criterion for the assessment of the optimum slit length was the maximally occurring mechanical stresses in the probe. These stresses had to lie as close as possible to the breaking stress of the material used to achieve sufficiently high clamping forces without, however, exceeding the breaking stress. FEM calculations allowed the number of probe styli to be manufactured and the time required for the development to be minimized. A patent application has meanwhile been filed for the developed T-shaped microprobe which will soon be available on the market as a commercial product.

The static and – if necessary – also the dynamic FEM analysis are part of the design and constructive optimization of the function-relevant properties of the components of measuring equipment prototypes which are manufactured at PTB. Insofar, the example represented here shows the importance of simulations for the constructive design of a large number of prototypes of special measuring instruments and components manufactured at PTB.

Example of the further development of virtual measuring instruments

Virtual measuring instruments are simulation procedures which allow the task-specific measurement uncertainties of complex measuring instruments to be calculated. The method was developed in the 90s for the so-called *virtual coordinate measuring machine* (VCMM) and successfully transferred to industry. The basis of this method is the consideration of both the basic components of the measuring instrument (movement axes, probing systems, etc.) – including their systematic measurement deviations assumed to be known – and also their systematic unknown and random measurement deviations which are caused, for example, by the assumed variations of the ambient parameters such as temperature or air pressure. For the variation of all input parameters, distributions close to reality are assumed. The distribution of the measurement values of the virtual measuring instrument is simulated in the computer for any measurement task on the basis of these changing input data with the aid of the Monte Carlo method. From the distribution of the simulat-

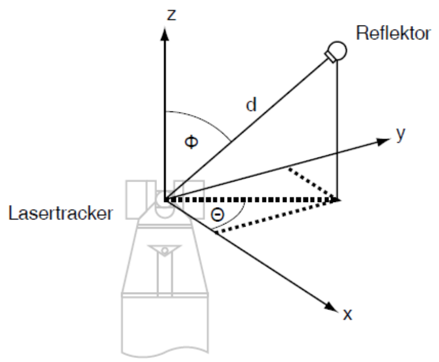


Figure 5: a) Schematic representation of a laser tracker b) PTB's reference wall for testing the metrological characteristics of mobile 3D coordinate measuring machines such as, for example, laser trackers.

ed measurement values, the resulting measurement uncertainty is easier to estimate.

Since 2008, this computation method for the measurement uncertainty – in particular of complex measurement tasks – on the basis of the Monte Carlo method has also been described in the supplement to the GUM (Evaluation of measurement data — Supplement 1 to the "Guide to the expression of uncertainty in measurement — Propagation of distributions using a Monte Carlo method"). The procedure of the virtual measuring instrument has meanwhile been applied to different measuring instrument classes (for example, in the field of precision engineering on gear measuring instruments, surface measuring instruments, interferometers as well as scanning probe and scanning electron microscopes).

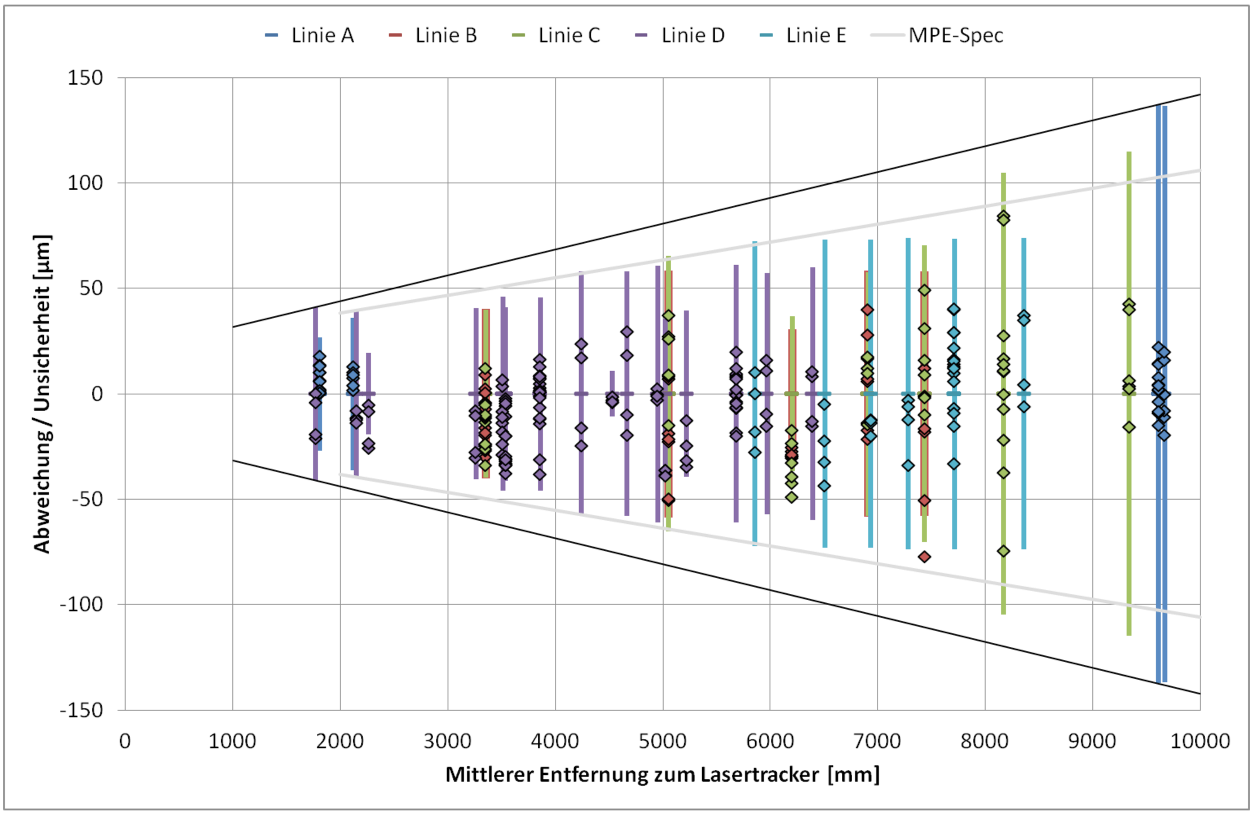
Laser trackers are mobile 3D coordinate measuring machines which determine the position of a reflector in the 3D space by a distance measurement and two angle measurements in a polar coordinate system and which usually indicate the result to the user in a Cartesian coordinate system. Figure 5 a) shows the principle of these measuring instruments. The measurement deviation of such laser trackers is influenced by different factors. The laser-interferometric distance measurement depends on the refractive index of the air which, in turn, depends on the ambient parameters *air temperature*, *air pressure* and *air humidity* in the beam path. The angle measurement depends on the measurement deviations of the angle measuring systems used, and the resulting 3D space coordinates, ultimately, also depend on the orientation of the measuring systems to each other.

For the experimental determination of the measurement deviations of mobile 3D coordinate measuring machines, a reference wall composed of a thermally stable network realized by reflector measurement points reinforced by glass-fibre plastic bars, was installed at PTB in a larger measurement room (see Figure 5 b). Here, laser trackers can be tested in accordance with the requirements formulated in Directive VDI/VDE 2617, sheet 10.

To determine task-specific measurement uncertainties of laser trackers on large components, the so-called "*virtual laser tracker*" (VLT) has been developed within the scope of a research project funded by the AiF (*Arbeitsgemeinschaft industrieller Forschungsvereinigungen*). For this purpose, the basic modules of a virtual measuring instrument, which have been described before, were used. They were, however, adapted to the specific influence quantities of the measuring instrument class "laser trackers". Figure 6 shows the results of the measurement uncertainties of a laser tracker, determined by means of the VLT, compared to the measurement uncertainties determined by experiment on the reference wall of PTB for different positions of the laser tracker in the room, i.e. also for different distances of up to 10 m. The results plotted show that the variations of the measurement results along several measurement lines which have been determined by experiment can – in the majority of the realized positions of the laser tracker investigated – be well described by the measurement uncertainties simulated by means of the VLT.

Final remark

This year's report of the Division illustrated the special importance of simulation calculations for precision engineering on the basis of some examples. Applications of simulations in nanometrology, in micrometrology and in the construction and cal-



culation of task-specific measurement uncertainties were represented for different instrument classes. In future, and with increasing complexity, these procedures will have to be further developed and integrated.

Figure 6: Length measurement deviations determined by experiment (symbols) and uncertainties of the length measurement simulated with the VLT (vertical line marks) in accordance with VDI/VDE 2617 sheet 10, based on the individual residual geometry errors of a laser tracker measuring head. In addition, the maximum measurement deviations specified by the manufacturer of the laser tracker investigated (MPE-Spec) have been plotted.

Headlines: News from the Division

Fundamentals of Metrology

New method for the testing of Newton's gravitational law at small distances

Modelling infrastructure for electron beam lithography

High-precision determination of form deviations of spherical material measures with an improved reconstruction algorithm

Kourogi comb for absolute length measurements

Assessment and optimization of a procedure for the use of a multimode-step index fiber as an interferometer light source

Interferometer probing on both sides for the absolute length measurement of prismatic bodies without wringing

Development of a BlueRay laser exposure facility for 3D microstructuring

Metrology for the Economy

Improved procedure for the non-destructive determination of the bending stiffness of scanning force microscope cantilevers

Roughness measurements in micro-nozzles with the profile scanner

TEM measurements for traceability of the linewidth of nanostructures

Ultra-precise position control by means of interferometric position detection and moving coil drive

Upgrade of the nanometer comparator for measuring the straightness on scale graduations

FPGA-based assessment of interferograms for tilting and displacement measurements

Traceable and robust calibration procedures for internal microstructures

3D microprobe for the measurement of microgearings

Diamond-coated probes for coordinate and form measurements

Realization and calibration of air gap standards for the traceability of coaxial interferential layer thickness measurement

International Affairs

International comparison measurement on ball plates concluded