PTB news
Scientific Newsletter
2
2015

Three times a year, PTB News provides topical information from the varied spectrum of activities of the Physikalisch-Technische Bundesanstalt (PTB) consisting of fundamental research, legal metrology and PTB's various activities in the service of the economy.

SCIENTIFIC NEWS

TECHNOLOGY TRANSFER

MISCELLANEOUS

The fundamental constants are still constant

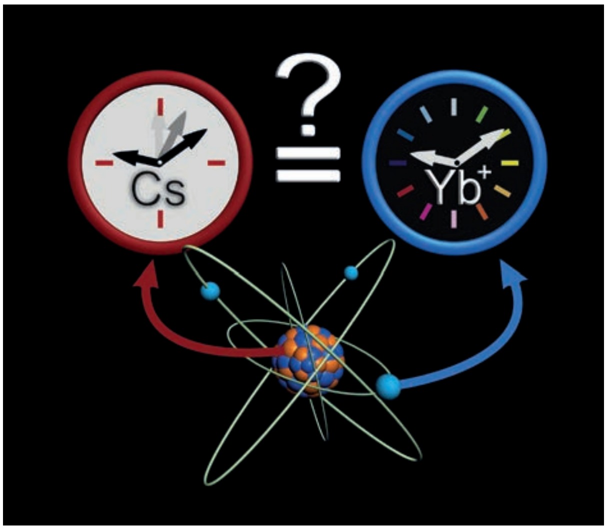
Atomic clocks prove the stability of the mass ratio of protons to electrons

Especially interesting for
• fundamental research

Are the fundamental constants really constant? Recent investigations carried out at PTB have shown that one essential fundamental constant – namely the mass ratio of protons to electrons – can have changed only by a maximum of one part in a million over the age of our solar system (i.e. extrapolated over approx. 5 billion years). Previously, scientists deemed the possible changes to be twice as high. To obtain this result, physicists from PTB compared cesium and ytterbium atomic clocks with each other for 7 years.

The Universe is expanding. After this finding in the 1930s, physicists started to speculate whether in such a dynamic universe, constant quantities could exist at all. Maybe even the so-called "fundamental constants" are subject to temporal changes which could give us key information on the structure and the development of the Universe? Since then, astrophysicists and geophysicists have sought to find evidence of changes undergone by fundamental constants over cosmologic periods of billions of years. The results allowed somewhat contradictory conclusions. In the past few years, laboratory experiments with atomic clocks have attained such accuracy that it is already possible to contribute to the answer to this question by studying a period of just a few years. If certain fundamental constants changed, then two atomic clocks which are based on different elements would deviate from each other in a predictable manner over time. This method was used at PTB to check the constancy of an essential physical quantity – the mass ratio of protons to electrons – by comparing an optical clock with a trapped ytterbium ion and cesium atomic clocks and taking the results of other research groups into account.

A proton is approx. 1836 times heavier than an electron and, in addition to being subject to the electromagnetic force, it is also subject to the so-called "strong interaction", which is responsible for the structure and the cohesion of atomic



Comparisons between atomic clocks with cesium and ytterbium, respectively, confirm the constancy of the mass ratio of protons to electrons. (Photo: PTB)

nuclei. Variable fundamental constants would lead to changes in the relative strength of these forces, which, in turn, would have an influence on the masses of the particles involved.

The mass of the electron determines

the frequency of the optical atomic clocks; the mass of the protons shows in the frequency of the cesium clock (via the properties of the atomic nucleus). When developing the atomic clocks, the cesium clock has repeatedly been compared with the ytterbium clock at PTB over the past few years – with increasing accuracy. These are currently among the most accurate atomic clocks in the microwave and the optical frequency range, respectively. Similar experiments were carried out in parallel at the British metrology institute NPL. From these data, it was now possible to conclude that the mass ratio of protons to electrons shows no detectable change up to a relative uncertainty of only a few parts per 10^{-16} per year. Thus, even when extrapolating across the age of our solar system (i.e. approx. 5 billion years), this means a change in this fundamental constant of less than one part in a million, so that it can still be considered a universal and stable quantity. ▪

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Scientific publication:
N. Huntemann, B. Lipphardt, Chr. Tamm, V. Gerginov, S. Weyers, E. Peik: Improved limit on a temporal variation of m_p/m_e from comparisons of Yb^+ and Cs atomic clocks. Phys. Rev. Lett. 113, 210802 (2014)

Polymer films on invisible substrate

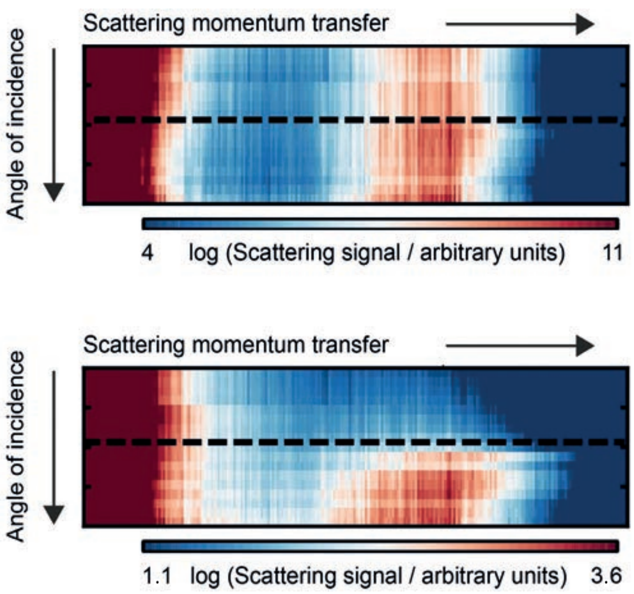
Novel X-ray detector enables contrast variation in scattering experiments

Especially interesting for
- nano- and thin-film technologies
- surface science

The inner structure of technologically relevant polymer films in the nanometer range can, in principle, be easily investigated with scattering of synchrotron radiation in the X-ray range at wavelengths below 1 nm. The sensitivity of this method is, however, often considerably limited by additional scattering occurring at the boundary between the film and the substrate. In the PTB laboratory at the synchrotron radiation source BESSY II, this effect has now been clearly reduced by means of contrast variation at appropriate wavelengths or photon energies. Hereby, the use of a novel detector for scattered X-rays has been decisive in achieving the corresponding – mostly low – photon energies.

X-ray small-angle scattering under grazing incidence (GISAXS: Grazing Incidence Small Angle X-ray Scattering) is an established method for the contact-free determination of the size of vertical and lateral surface structures in the range from a few nanometers up to several micrometers. In current research activities on self-organized nanostructured polymer films as organic photovoltaic systems or on functionalized surfaces for applications in medicine as well as in micro- and/or nano-electronics, GISAXS is sometimes the only method available when it comes to characterizing structures in the nanometer range. Due to the high scattering contrast at the boundary between the polymer film and the substrate, a high share of substrate scattering may occur which may overlap the – mostly weak – scattering observed on the nanostructures within the polymer film in such a way that the data can no longer be analyzed.

With the new in-vacuum hybrid-pixel detector PILATUS 1M, which was developed by PTB in collaboration with Dectris Ltd., high-precision GISAXS measurements on thin-film polymers on a silicon substrate have been made possible for the first time at very low X-ray energies, namely at the silicon-K edge at 1.84 keV. By adjusting the contrast, the silicon substrate can be made practically "invisible" to X-rays. This allowed structure changes inside thin-film polymers to be observed with vertical (in-depth) resolution, before and after thermal processing. In both cases, the surface of the thermally processed sample displayed a strong decrease in the order within the first approx. 30 nm of the 85 nm thick film.



Horizontal cuts through GISAXS images before (top) and after (bottom) thermal processing. Each line represents an intensity profile (blue: low; red: high) at a specific angle of incidence of the X-rays onto the sample (i.e. at different penetration depths). The thermally processed sample shows the lack of signals of the surface-sensitive scattering at small angles of incidence, which suggests a loss of structure order at the surface. The order at larger angles of incidence, i.e. in the presence of scattering also coming from deeper layers close to the boundary with the substrate, remains unchanged.

The results make a considerable contribution to a deeper understanding of the restructuring processes in self-organized polymer films. This is important for the precise control of the structure in technological applications. At the same time, this has shown very clearly that the in-vacuum PILATUS detector has allowed an extension of the measurement capabilities at PTB's four-crystal monochromator beamline of the electron storage ring BESSY II. ■

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Scientific publication:
J. Wernecke, H. Okuda, H. Ogawa, F. Siewert, M. Krumrey: Depth-dependent structural changes in PS-b-P2VP thin films induced by annealing. Macromolecules 47, 5719–5727 (2014)

Graphene for quantum capacitance standards

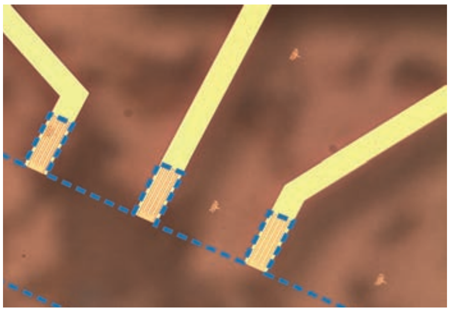
First-time AC precision measurements confirm the material's potential as a standard for the unit of capacitance.

Especially interesting for
- metrology institutes
- calibration laboratories

The particular properties of the two-dimensional conductor material graphene can also be exploited in the case of the quantum Hall effect on which extremely precise calibrations of the electric DC resistance are based worldwide. Graphene is, in many aspects, superior to all previously used materials. Now PTB has shown that graphene exhibits excellent properties also in the case of AC applications. Developing a quantum standard for AC resistance (impedance) – and, thus, also for capacitance – therefore seems realistic.

From applications with DC current, it is already known that the quantized resistance values of quantum Hall structures made of graphene do not – not even at maximum measurement accuracy – differ from those of conventional semiconductor materials (e.g. GaAs heterostructures). Graphene, however, offers further advantages: to realize the quantum Hall effect (QHE), the magnetic fields do not need to be as high and the temperatures do not need to be as low. It is expected that in the next few years, this will make considerably more practicable calibration facilities possible.

Precise AC measurements of the quantum Hall effect of graphene have been carried out at PTB for the first time. Hereby, high-quality graphene material was used which had been grown epitaxially on a SiC substrate. Contrary to the DC QHE, in the case of AC measurements, parasitic effects caused by stray capacitance between the electron system of graphene and the ambient environment play a role. Dissipation processes resulting from these effects cause deformations of the ideally flat QHE resistance plateau and, thus, deviations from the quantized resistance values. These effects must therefore be sufficiently reduced or even suppressed to allow applications as a quantum standard for AC resistance. In the case of the usual GaAs-based quantum Hall structures, this has, so far, only been achieved at PTB to such an extent that the AC QHE could be successfully used to derive the unit of capacitance, the farad. The relative uncertainty achieved hereby is $1 \cdot 10^{-8}$, which is clearly lower than that of all conventional calibration methods for the electric capacitance.



As graphene is highly transparent, apart from the eight gold supply lines, it can hardly be differentiated under an optical microscope from the also transparent SiC substrate. Therefore, the quantum Hall structure is marked with a blue line. Contrary to the previous article, here, only the substrate is visible, the film itself is invisible.

The AC measurements carried out on graphene at PTB at frequencies in the kHz range have now shown that graphene, compared to GaAs structures, exhibits particularly beneficial properties. Due to the geometry, parasitic dissipation effects are, even without special compensation measures, already so small that the QHE plateaus remain practically flat. Remaining stray capacitances between the contacts of the structure cause, at a frequency of 1 kHz, only a very small relative deviation from the quantized resistance value of approx. $1 \cdot 10^{-7}$. The researchers are currently working on reducing this influence by optimizing the structure geometry of graphene QHE samples. The results achieved so far allow us to expect that graphene-based impedance standards will soon be widely used by national metrology institutes as well as by industrial calibration laboratories. ■

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Scientific publication:
C.-C. Kalmbach, J. Schurr, F. J. Ahlers, A. Müller, S. Novikov, N. Lebedeva, A. Satrapinski: Towards a graphene-based quantum impedance standard. Applied Physics Letters 105, 073511 (2014)

Highly exciting interferometry

PTB interferometer for precise length measurements has been specially upgraded to measure the length change in functional materials.

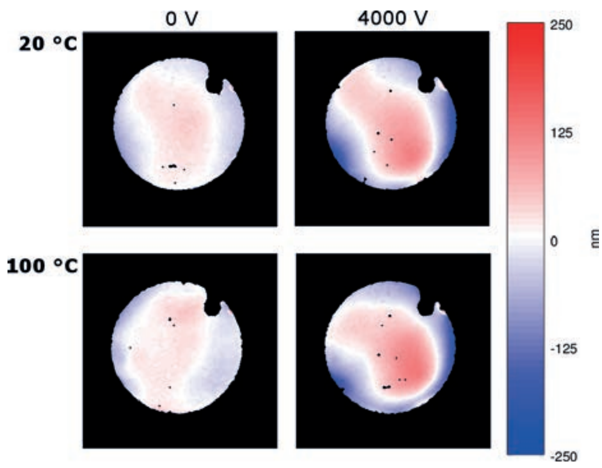
Especially interesting for
- manufacturers of functional materials
- the automotive industry
- aeronautical engineering
- metrology

The piezoelectrically induced length change in functional materials has been measured at PTB for the first time at high temperatures and with lateral resolution. For this purpose, a new sample environment was created which can be integrated into the existing interferometer for precise length measurements.

Functional materials such as, e.g., piezoceramics, are used in numerous application fields, among other things in the automotive industry, in aeronautical engineering, in metrology, in energy production and in process monitoring. Use at high temperatures is increasingly aimed at. Developing such new materials, together with the corresponding metrological infrastructure, is the aim of the European cooperation project METCO. Concretely, the activities revolve around the ability to measure the coupling between mechanical, electrical and thermal properties in a wide temperature range. PTB's task hereby consists in measuring changes in length interferometrically, at high temperatures (currently up to 200 °C) and with an electric field applied (from -2 kV/mm to +2 kV/mm). To this end, a special sample environment was developed at PTB and tested with a commercially available lead zirconate titanate (PZT) ceramic at various temperatures.

From the measured piezoelectrically induced length change, the piezoelectric coefficient was determined at 20 °C as well as at 100 °C. The results are in agreement with measurements which were carried out by partners with commercially available measuring systems; they could also be reproduced on other samples under investigation. The advantage of PTB's interferometer resides in the fact that it is an imaging system, so that not only point-by-point length measurements, but also spatially resolved length variations (length topography) of the entire surface of the sample are possible. This provides additional information, e.g., on inhomogeneities or edge effects.

After initial tests have been successfully completed, the next step will consist of investigating high-temperature piezo-materials which have been newly developed by our project partner, the University of Leeds (UK). ■



Height topography of the PZT sample (diameter: 15 mm, thickness: 2 mm) at 20 °C and 100 °C, with and without applied voltage.

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Scientific publication:
T. Stevenson, T. Quast, G. Bartl, T. Schmitz-Kempen, P. Weaver: Surface mapping of field-induced piezoelectric strain at elevated temperature employing full-field interferometry. IEEE Trans Ultrason Ferroelectr Freq Control 62, 88–96 (2015)

Diamond-coated probes

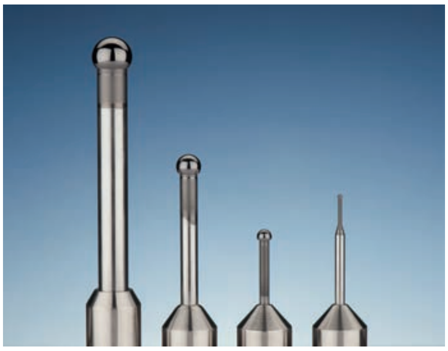
A good alternative to probing spheres made of pure diamond

Especially interesting for
- manufacturers and users of coordinate measuring machines, and of form and contour measuring instruments

At PTB, the properties of diamond-coated probing spheres have been investigated for use with coordinate measuring machines (CMMs). The results show that using such probing spheres in CMMs, form measuring machines and also in contour measuring machines allows a considerable increase in the service life of the probing spheres as well as a reduction in the uncertainty of the measurements.

In coordinate metrology, geometrical measurements are mostly carried out by means of tactile probing, e.g., with ruby spheres. Mechanical wear or material deposition onto the probing sphere (e.g. when measuring aluminum surfaces) reduce the accuracy of the measurements as well as the service life of the probe stylus. As an alternative to expensive and relatively irregular (non-circular) probing spheres made of pure diamond, the properties of diamond-coated probing spheres with diameters from 0.3 mm up to 8 mm were investigated at PTB.

The investigations were carried out within the scope of a cooperation project between PTB and Zeiss IMT. The probe styli are manufactured by the Dutch company DiamondProductSolutions. They consist of a spherical segment of approx. 240° and a stylus shaft. Both elements are one unit of hard metal. Since



Probe style with sphere diameters from 8 mm to 1 mm for coordinate measuring machines

there is no glued joint, cleaning with harsh solvents is, in principle, possible. The probing spheres are coated with polycrystalline, synthetic diamond and are then polished.

Compared to other spheres made of aluminum oxide, zirconium oxide, ruby, hard metal and silicon nitride, which were also investigated, the diamond-coated spheres investigated exhibited the smoothest surfaces, with roughness in the order of 2 nm. The form errors lay in the range from 200 nm down to 20 nm and are, hence, comparable to, or even smaller than, those of commercial ruby probing spheres. Wear was tested on a special steel ring with embedded abrasive particles at measuring forces of 20 mN. At a probed distance of approx. 11 m in length in total, the diamond-coated surface did not exhibit any wear. The abrasion on a ruby probing sphere, however, amounted to approx. 1 µm. When scanning smooth aluminum surfaces with a roughness smaller than 5 nm, no material deposition was detected on the diamond-coated probing spheres. On rougher aluminum surfaces, material deposition from 5 µm to 15 µm was detected, depending on the measuring force. In contrast, with ruby probing spheres, material deposition ranged from a few micrometers to 40 µm. ■

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Scientific publication:
M. Neugebauer, S. Bütefisch, T. Dziomba, S. Koslowski, H. Reimann: High-resolution investigation and application of diamond coated probing spheres for CMM- and form measurement technique. Proceedings of the 13th international conference of euspen, 1, 75–78 (2013)

PTB chopper-stabilized amplifier

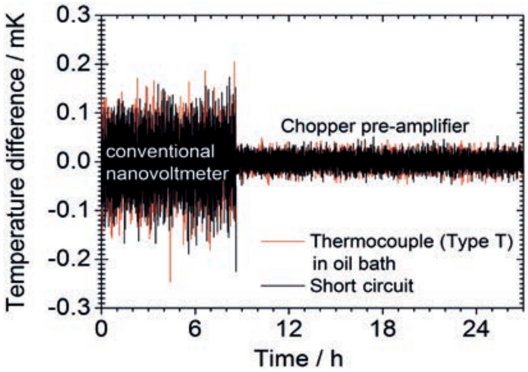
Used to improve measurements on thermocouples within the scope of the Avogadro Project

Especially interesting for
- metrology institutes, fundamental research
- calibration laboratories
- manufacturers of high-precision electronics

A chopper-stabilized amplifier with excellent properties has been developed at PTB and is used in a measurement setup for the Avogadro Project to measure voltage on thermocouples. This has led to a reduction in noise amplitude by a factor of 4.

To measure small DC voltages, PTB has developed a chopper-stabilized amplifier with excellent properties. The amplifier exhibits very fast settling and an extremely low voltage noise of only 0.73 nV/√Hz down to frequencies of a few millihertz. At the typical chopping frequency of 570 Hz, a current noise of 40 fA/√Hz with a 1/f corner frequency of 3 mHz is achieved. This amplifier had originally been designed as a null detector for the cryogenic current comparators developed by PTB, but the instrument is also very well suited for other demanding metrological applications such as high-precision voltage measurements on thermocouples.

For the redefinition of the Avogadro constant, the ratio of the volume of a silicon sphere to the volume of the unit cell of the silicon crystal must be determined. Special interferometers are used in vacuum to measure each of these two geometrical quantities with relative uncertainties lower than 10^{-9}. Due to the low thermal expansion coefficient of approx. $2.5 \cdot 10^{-6}\ K^{-1}$, the temperature of the silicon sphere must be measured accurately to a millikelvin or better. For this purpose, thermocouples – in combination with a platinum resistance thermometer – are used which, due to their small dimensions, can be mounted very flexibly on the test sample and, in addition, exhibit no self-heating. With approx. 40 µV/K, such thermocouples, however, have very poor sensitivity, which represents a considerable challenge when



Measurement of the thermoelectric voltage difference across both junctions of a thermocouple, represented as the corresponding temperature difference (red curve). At a constant temperature difference, the result expected would be similar to the measurement of a short circuit (plotted here as a black curve for comparison purposes). Using the chopper-stabilized pre-amplifier (in the diagram after 8.5 hours) causes the noise amplitude to decrease by a factor of approx. 4, down to effectively 0.1 mK (peak to peak).

measuring the thermoelectric voltages. In this measurement set-up, the chopper-stabilized amplifier has now been used as a low-noise pre-amplifier – compared with the previously used commercial nanovoltmeter. The figure shows the results of a measurement series where the difference in the thermoelectric voltages has been measured in the two junctions of the thermocouple. According to these results, using the chopper-stabilized amplifier reduces the noise amplitude by a factor of 4. Aiming for the same measurement uncertainty, the chopper-stabilized amplifier thus enables the measuring time to be reduced by at a factor of 16, alternatively. At the same measuring time, the measurement uncertainty achieved is four times smaller. ■

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Scientific publication:
D. Drung, J.-H. Storm: Ultra-low noise chopper amplifier with low input charge injection. IEEE Trans. Instrum. Meas. 60, 2347-2352 (2011)

Analyzing inconsistent measurement data

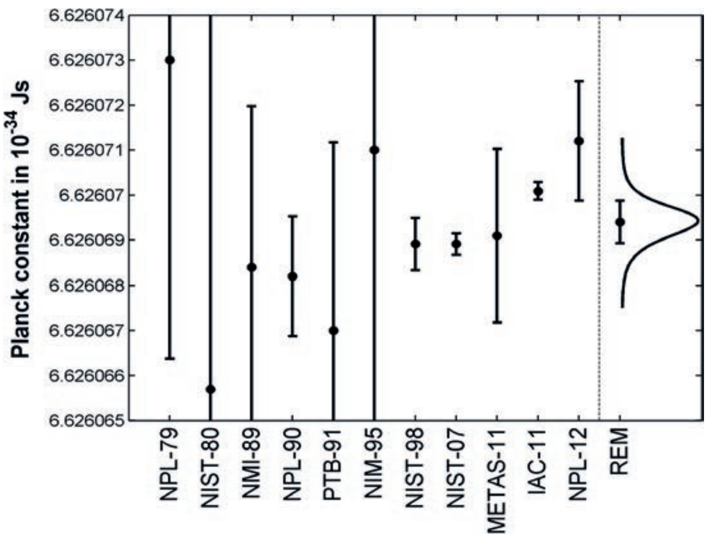
New procedure provides improved, more robust results with more reliable uncertainties

Especially interesting for
- metrology
- statistics

At PTB, a new statistical method has been developed to adjust inconsistent measurement data. Its advantages: more reliable results and a more realistic evaluation of the associated uncertainties. The procedure can, for example, be applied to determine fundamental constants.

Adjusting inconsistent measurement data plays an important role in metrology, for example, to determine reference values when analyzing interlaboratory comparison measurements or when determining values for fundamental constants. The figure shows the example of current values measured for the Planck constant. The data are inconsistent with respect to the quoted uncertainties. Simple application of the weighted mean of the measured values would not be advisable, since this could lead to unreliable results. In such cases, metrology often resorts to the so-called "Birge ratio" method, in which all measurement uncertainties are enlarged in the same way so that consistency of the measurement data is achieved. This procedure is, however, only admissible on the basis of a very specific statistical model. If this – very restrictive – assumption is, however, violated, the Birge ratio method might yield unreliable results.

A new procedure based on Bayesian statistics has been developed at PTB; it allows inconsistent measurement data to be adjusted under considerably weaker assumptions about the underlying statistical model. The procedure is based on a more general class of statistical models, the so-called elliptically contoured distributions. It was possible to demonstrate that the results obtained with the new procedure are better and more robust than those obtained with alternative procedures and, especially, that the uncertainties determined by the new method are more reliable. The figure illustrates the application of the method. The result obtained is a probability distribution for the value of the Planck constant, from which an estimate and its associated uncertainty can be determined. ■



Data measured for the Planck constant (left of the dashed line). The error bars show standard uncertainties. As a result of the new adjustment method, the probability distribution for the value of the Planck constant is shown, together with the derived estimate and the corresponding standard uncertainty (right of the dashed line).

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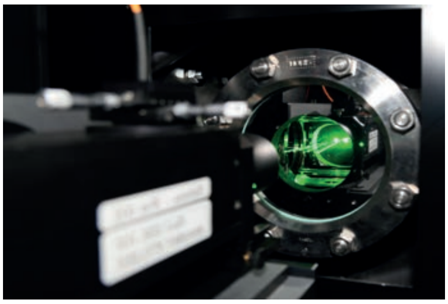
Scientific publication:
O. Bodnar, A. Link, C. Elster: Objective Bayesian inference for a generalized marginal random effects model. Bayesian Analysis, doi: 10.1214/14-BA933 (2015)

LDA flow sensors

Especially interesting for
- manufacturers of laser Doppler anemometers
- power plant operators

Laser Doppler Anemometry (LDA) measures the velocity in liquids optically – i.e. contact-free. A procedure developed at PTB to determine the position of the measuring volume considerably reduces the uncertainty of volume flow determination when calibrating flow sensors by means of LDA. From the power of the backscattered laser light, the path of the interfering beams is reconstructed and the interference fringe interval, the position and the size of the measuring volume are determined. LDA enables the calibration of flow sensors, for example in power plants, at temperatures up to 230 °C and at a pressure up to 40 bars. (Technology Offer #0375) ■

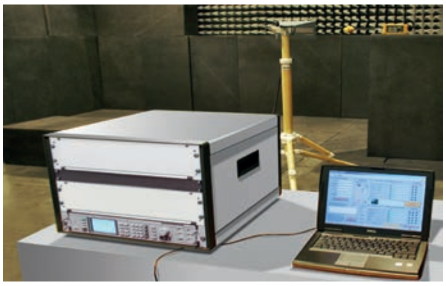


Flow velocity measurement in a pipe (left: LDA probe; right: optical access)

Advantages
- determining the position of the LDA measuring volume with high precision
- reducing the measurement uncertainty
- calibrating at high temperatures and high pressures

In situ EMC test equipment

Especially interesting for
- verification authorities
- EMC labs



Test equipment developed at PTB allows, for the first time, components and systems to be tested with regard to their electromagnetic compatibility (EMC) without needing a special stationary laboratory. The main characteristics of this equipment are its simple operation and short measuring times. Diverse carrier frequencies enable the simulation of practically all relevant emitters of electromagnetic disturbance. Via various antennae, the susceptibility to disturbances in connection with high-frequency fields is tested in situ in short measuring intervals. As the system is particularly operator-friendly, the test can even be carried out without the operator having to be specially trained on it. (Technology Offer #0189) ■

Advantages
- mobile EMC measurement
- simple operation
- 27 MHz to 6 GHz
- short measuring times (approx. 1 minute)
- software with protocol function

Gap measurement standard

Especially interesting for
- manufacturers of coordinate measuring machines
- calibration and test laboratories

Lengths on screw threads, toothed gears or other components exhibiting gaps are often measured in double-flank contact. The gap measurement standard developed at PTB detects and corrects influences which are due to self-centering probing or to double-point contact and are frequently neglected. On a thermally invariant base plate, at least four precision spheres are placed which were calibrated against each other in this position. For maximum measurement accuracy, the geometry as well as the probing conditions of the gap measurement standard and of the component to be tested should correspond to each other. (Technology Offer #0365 ■

Example of a gap measurement standard with 3 selected sets of 4 spheres

Advantages
- calibration of probe stylus configurations
- optimized measurements in double-flank contact
- same measurement strategy for both calibration and application

Contact person for questions about technology transfer
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Awards

Ulrich Johannsmeyer

The Head of Department 3.6 "Intrinsic Safety and Safety of Systems" has won the international IEC 1906 award. The International Electrotechnical Commission (IEC) has decorated the standardization expert for his knowledge and his great commitment.

Ian Leroux

The guest researcher at the QUEST Institute of PTB was awarded the Heraeus Poster Prize for his poster presentation entitled "Building a portable $^{27}Al^{+}$ Frequency Standard" at the 576th Heraeus Seminar "Designed Quantum States of Matter".

Beatrix Pollakowski

This staff member of Department 7.2 "Cryophysics and Spectrometry" has won the Young Postdoc Award in X-ray Spectrometry of the European X-ray Spectrometry Association (EXSA) for her excellent work in grazing incidence X-ray spectrometry in combination with X-ray absorption spectroscopy for the non-destructive chemical analysis of complex nanostructures.

Cornelia Streeck

This staff member of Department 7.2 "Cryophysics and Spectrometry" won the poster prize at ALTECH 2014 for her presentation on reference-free TXRF analysis for the quantification of functional molecules on surfaces for bioanalysis.

Projects and initiatives

"NanoMag"

At the EuroNanoForum 2015 in Riga, the "NanoMag" Project – Nanometrology Standardization Methods for Magnetic Nanoparticles" which is funded by the EU was selected as one of the Top 10 among more than 1000 EU projects in the field of "Nanotechnologies/New Materials". The project aims to validate and harmonize measurement procedures for magnetic nanoparticles. PTB's "Biosignals" Department coordinates the two central work packages "Analysis of Magnetic Nanoparticles" and "Standardization of Magnetic Nanoparticles".

Fair datasheet

At present, users of optical 3D surface measuring devices experience difficulty comparing different measurement procedures or instruments, since a confusing amount of different terms coexist in the datasheets. This makes direct, objective comparability difficult. An initiative has now presented a "Fair Datasheet" for optical 3D surface measuring devices (http://optassyst.de/faires-datenblatt/ – in German). It consists of three components: the definition of characteristics, reading support and a layout sample. The initiative is supported by manufacturers of measuring instruments (Alicona, NanoFocus, Polytec), users (Audi, Robert Bosch, Daimler) and by the Technische Universität Kaiserslautern, with PTB, ZVEI and VDI considerably contributing to its operation. The "Fair Datasheet" considers itself as a quality label to encourage manufacturers of measuring instruments to provide practice-oriented and comparable specifications.

nuClock

The "nuClock" project, which is coordinated by the TU Wien in Vienna (Austria), has been selected for support by the EU program for "Future and Emerging Technologies FET Open" and began its work on 1 June 2015. With the participation of PTB, a consortium of 7 groups in Austria, Finland and Germany will promote the development of a novel clock over the next 4 years. This clock will, for the first time, be based on a transition in an atom nucleus (Th 229) and will thus exhibit less sensitivity to external disturbances than current atomic clocks. The concept of such a "nuclear clock" was suggested for the first time by PTB in 2003. (Project website: http://www.nuclock.eu/.
EC horizon 2020: http://t1p.de/horizon.

PTB at trade fairs

14 October
MEORGA
Trade fair specializing in process control systems as well as in measurement, adjustment and control technologies. Volkswagen Halle, Braunschweig. Contact: Andreas Barthel (+49 (0)531 592-8307, andreas.barthel@ptb.de)

Further dates

13–18. September 2015
16th Int. Conf. On Small Angle Scattering
TU Berlin.
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12–16 October 2015
8th Symposium on Frequency Standards and Metrology 2015
Seminaris See-Hotel, Potsdam.
Contact: Ingrid Herrmann
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27–29 October 2015
Scientific and Fundamental Aspects of the Galileo Programme
5th International Colloquium. PTB Braunschweig. Contact: Andreas Bauch
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