NEW FRONTIERS IN ANGLE METROLOGY AT THE PTB

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Abstract:
An overview of the current status of angle metrology at the Physikalisch-Technische Bundesanstalt (PTB), the National Metrology Institute of Germany, is provided. Current and future challenges to angle metrology are described. Novel developments at the PTB are outlined. Our research programme is currently strongly influenced by the European Metrology Research Programme (EMRP) SIB 58 Angle Metrology project. We present our novel self-calibration method for the fast and precise in-situ calibration of angle encoders without recourse to external reference standards which relies on a suitable geometric arrangement of multiple heads which read out the radial grating of the encoder at different angular positions. Additional progress has been achieved in this field by adapting an advanced error-separating shearing technique to angle metrology and by testing it experimentally. This technique, by applying defined angle offsets between two angle measuring devices, offers a unique opportunity to cross-calibrate both devices. We also present progress in the development of a novel concept and of a device for the precise and traceable calibration of spatial angles, the Spatial Angle Autocollimator Calibrator (SAAC). We report on the status of the first European Association of National Metrology Institutes (EURAMET) Key Comparison on autocollimator calibration (EURAMET.L-K3.2009).

Keywords: Angle measurement, angle standard, angle encoder, autocollimator, traceability

1. INTRODUCTION

Precision angle measurement is an important enabling technology with a wide range of scientific and industrial applications, e.g., in precision engineering, optics, synchrotron beamline metrology, aerospace, geodesy, navigation, and astronomy. Through research and development in the field of angle measuring techniques and by the calibration of angle measuring systems, PTB creates optimum conditions for the wide use of these systems in industry and research. Our spectrum of diverse and varied tasks covers the application-oriented experimental characterization and precise calibration of angle measuring systems, basic research on new measurement procedures and mathematic algorithms, as well as the improvement of the design of angle measuring instruments. Through this balance of activities, the frontiers of angle metrology can be advanced effectively by reacting flexibly to demands from industry and science and by providing necessary calibration methods and facilities in time.

2. ANGLE ENCODERS

2.1 Primary angle standard WMT 220

PTB uses the high-precision angle comparator WMT 220, manufactured by Johannes Heidenhain, Germany, as its primary standard for angle metrology (see Figure 1). It is installed in a clean-room facility and thus operates under favourable environmental conditions, such as a highly stable ambient temperature (ΔT < 0.05 K), low vibration, and a stable laminar air flow.

Its main component is a precision air bearing rotary table equipped with a radial phase grating and an interferential measuring system that uses eight photoelectric scanning heads which are distributed in 45° intervals and eight auxiliary heads which are arranged in pairs (diametrically opposite to each other) to form angle intervals of $360°/2^n$ with $1 \geq n \geq 7$, whereby the smallest interval is 2.81°. The radial phase grating consists of 2^{17} = 131072 graduation lines in 360° with angular intervals between adjacent lines of 9.89 arcsec. Each scanning head furnishes sinusoidal signals with twice the graduation frequency, i.e., 2^{18} intervals in 360°, corresponding to angular intervals of 4.94 arcsec. These intervals are further subdivided by the reading heads' electronics and software by a factor of 2^{12} to obtain 2^{30} intervals in 360° (see [1] for technical details).

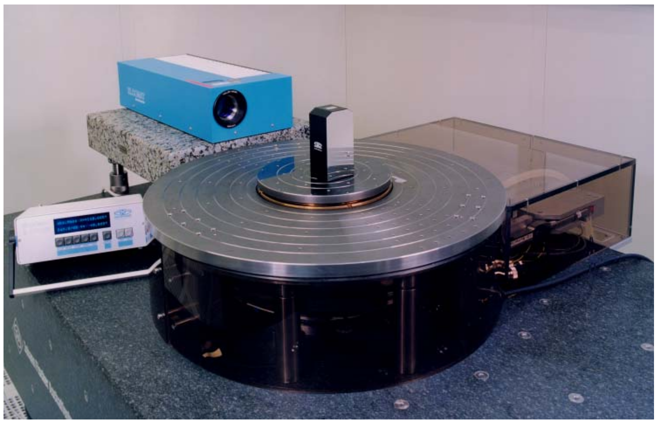

Figure 1: The WMT 220 angle comparator of PTB is the primary national standard of the plane angle in Germany. Its calibration uncertainty is u = 0.001 arcsec (5 nrad).

The graduation errors of the radial grating can be determined by two independent methods: cross-calibration by use of a built-in or external secondary angle encoder and self-calibration by use of the geometric arrangement of the multiple reading heads. At PTB, a self-calibration method was developed which is capable of the fast and precise in situ calibration of the WMT 220 independent of auxiliary devices and external reference standards [2] which is described in Section 2.2 in detail. With it, a standard uncertainty of the self-calibration of the WMT 220 of the order of 0.001 arcsec (5 nrad) has been achieved. It has been verified by various internal comparisons (of cross- and self-calibration results) and by comparisons with independent, external partners [3] which all demonstrate consistency at a level below one milliarcsec root mean square (rms).

2.2 In situ self-calibration

Angle encoders are essential components of a wide range of rotating precision devices, such as industrial robots in manufacturing. Usually, their angle deviations need to be calibrated by comparing the encoders with reference encoders provided by, e.g., a National Metrology Institute (NMI). For industrial applications, however, a fast and precise method for the in-situ calibration of encoders is preferable. Extensive research on the self-calibration of angle encoders has been carried out at PTB which offers a solution to this problem.

Our novel self-calibration method relies on a suitable geometric arrangement of multiple reading heads which are located on the circumference of a circle and read out a radial grating which rotates beneath them. They detect the same graduation errors of the grating, albeit with a phase shift which depends on their location on the circumference [2, 4]. The self-calibration analysis is performed most naturally in the frequency domain. Using the Fourier shift-theorem to account for the phase-shift, the graduation errors can be reconstructed by analysing measurement differences between pairs of reading heads.

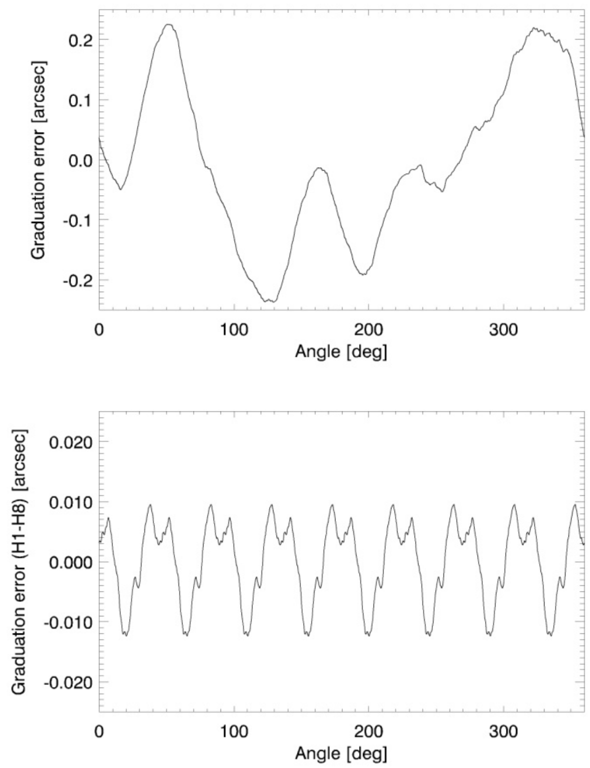

Figure 2: Results of the in situ self-calibration of the WMT 220. Graduation errors of the radial grating registered by a single reading head (upper graph) and after averaging over the eight primary reading heads (lower graph).

We successfully included the evaluation and correction of error influences due to lateral shifts of the centre of the encoder's grating during its rotation (including its eccentricity) in the self calibration analysis [2]. To this purpose, after self-calibration, the measurement data by the reading heads are corrected for the graduation errors of the encoder's grating. Modelling of the resulting residuals allows deriving the grating's lateral shift by fitting the model to the data, see Figure 3.

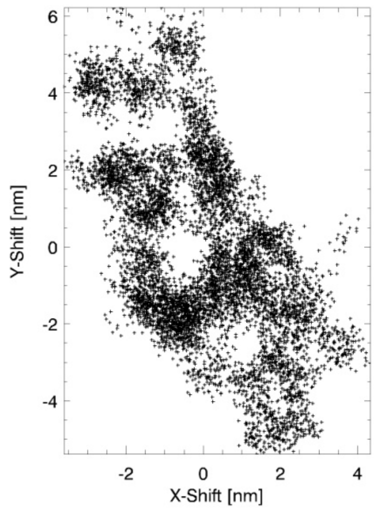

Figure 3: Lateral shifting of the encoder's grating during its rotation for the angle comparator WMT 220.

Our method proved to be capable of the fast and precise in situ calibration of angle encoders, independent of any external standards. It is one of those techniques which have been developed for the self-calibration [2, 4, 5-10] and cross-calibration [11-14] of angle encoders. They, in turn, are part of a wider class of reversal techniques in which measurements are set up in such a way as to provide redundant data sets which allow them to separate and eliminate errors [15].

Self-calibration offers a number of advantages, foremost that it is independent of auxiliary devices (such as, e.g., a secondary angle encoder or a polygon). As part of the family of circle division methods, self-calibration is based on the subdivision of the full circle and makes use of circle closure, expressing the fact that the sum of the angles of a divided circle in a plane equals 2π rad. The full circle therefore represents the fundamental, error-free angular standard and thus provides independence from external reference standards. This makes self-calibration ideally suited for primary angle standards. Furthermore, in comparison to cross-calibration, it is fast and therefore ideally suited for industrial applications.

2.3 Interpolation errors

Our self-calibration method successfully evaluates the graduation errors of the encoder's grating at regularly sampled points over 2π rad. At much smaller angular scales of the order of a few arcsec, interpolation errors become relevant. Interpolation errors result from the subdivision of the angular intervals between the grating's graduation lines by the reading heads' electronics to obtain a larger effective resolution (in the case of the WMT 220, by a factor of 2^{12}). Progress has been achieved in this field as we have adapted an advanced error-separating shearing technique [16-18] to angle metrology and tested it experimentally [19]. It proved to be ideally suited for the calibration of interpolation errors of the devices at small angular scales which are difficult to characterise with other methods.

This technique, by comparing the angle readings of an autocollimator and an angle encoder in different relative angular orientations, offers a unique opportunity to separate the errors of the two angle-measuring systems and, therefore, to calibrate both systems without recourse to any external standard. The non-linear errors of the two devices can be recovered, up to their linear components, from a set of three comparisons. In the case that the linear components of the errors are needed, too, only two angle differences, which correspond to the changes in the relative angular orientations of the devices, need to be traced back to an external standard. In [19], we demonstrate error-separation with a standard measurement uncertainty at a level of 1 milliarcsec (5 nrad) which beats uncertainties reachable by conventional calibration methods for autocollimators by a factor of two to three.

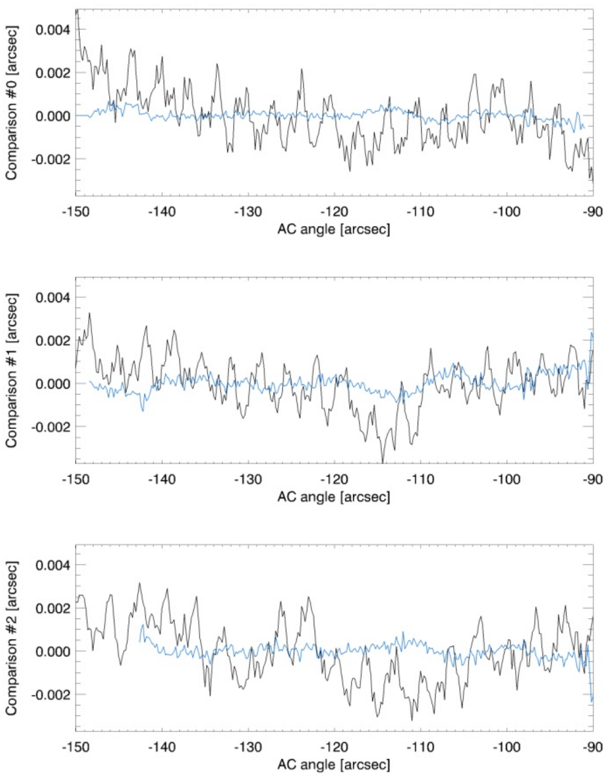

Figure 4: Data sets used for the shearing analysis (black lines) and residuals after correcting them for the reconstructed measurement errors of the autocollimator and of the WMT 220 (blue lines). Each panel shows the comparison of the autocollimator to the WMT 220 performed in a different relative angular orientation of both devices.

Figures 4-5 present the results of such a shearing analysis. The angle measuring devices consisted of the high-precision angle comparator WMT 220 and an autocollimator type Elcomat HR, Möller-Wedel Optical. The measurement errors of the encoder (Figure 5, lower graph) are of the order of 1 milliarcsec rms and are dominated by residual interpolation errors. Interpolation errors result from the subdivision of the angular intervals between the grating's graduation lines by the reading heads' electronics to obtain a larger effective resolution.

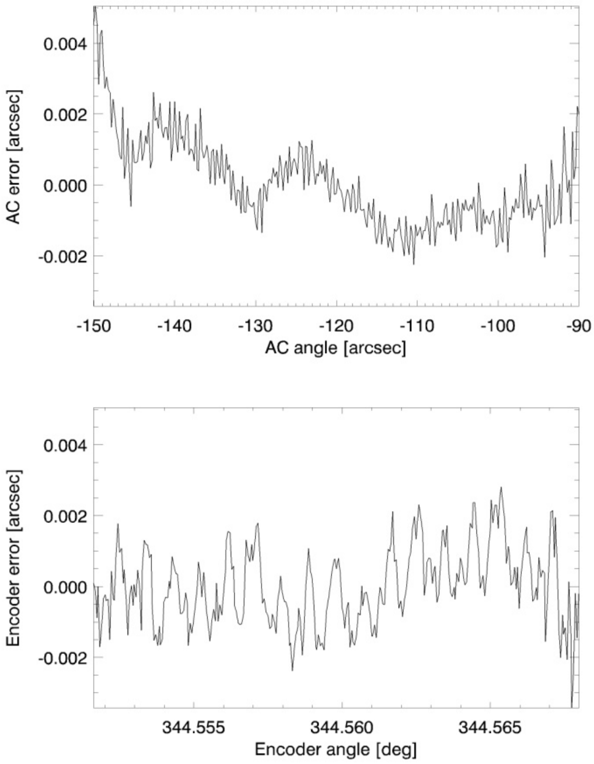

Figure 5: Reconstructed measurement errors of the autocollimator (upper graph) and of the encoder (lower graph) obtained by the shearing analysis of the data presented in Figure 4 (black lines).

3. AUTOCOLLIMATORS

3.1 Autocollimator calibration – plane angle

In Figure 1, the measurement set-up for the calibration of an electronic autocollimator against the primary angle reference of the PTB, the angle comparator WMT 220 is presented. The calibration can be realised against coated or uncoated mirrors and by using the full autocollimator aperture or an aperture stop. The position and the size of the aperture stop are variable. The calibration can be carried out in a limited range of fixed distances (250 mm – 550 mm) between autocollimator and mirror.

Typically, a calibration consists of measurements in forward and backward direction (to eliminate possible linear drifts) and repeat measurements in three different relative positions between the autocollimator and the WMT 220 (to eliminate residual angle deviations of the WMT 220), all realised under automatic computer control. The air path between the autocollimator and the plane mirror does not need to be specially shielded as the constant ambient temperature and the laminar air flow at the clean room facility do not exert any significant disturbing influences.

For more information on autocollimator calibration at the PTB, see [20].

Using highly stable autocollimators, calibrations with standard measurement uncertainties of u = 0.003 arcsec (15 nrad) have been achieved. Note that, in addition to the uncertainty contribution by the WMT 220, the uncertainty of the autocollimator calibration includes components which depend on the type of autocollimator and the calibration parameters. The later contributions usually dominate the final uncertainty budget and may result in an uncertainty for the autocollimator calibration larger than the value stated above. In contrast, the uncertainty contribution of the primary angle standard WMT 220 is of subordinate importance.

3.2 Influences of measuring conditions

In order to make full use of the autocollimator's calibration values for correcting its angle measuring deviations, the autocollimator must operate in the experimental set-up under the same measurement conditions under which it was calibrated. Ultimately, the calibration is only valid if the calibration and measurement conditions are identical. Any deviation between both leads to additional errors in the autocollimator's angle response which need to be characterised by additional calibrations or raytrace modelling. As the need for a high lateral resolution in deflectometric profilometry is driving the autocollimator apertures towards ever smaller diameters, issues such as the limits of the validity of the calibration and proper specifications for the adjustment of the optical components in deflectometric set-ups become ever more significant.

The current limitations of angle metrology with autocollimators originate from four main source clusters [21]:

1. From the autocollimator itself, specifically its design and manufacturing tolerances. Its operation at small apertures is especially problematic as commercial autocollimators have generally not been designed for use with small apertures.
2. From changing measuring conditions.
3. From characteristics of the reflecting surface under test (SUT).
4. From limits posed by currently available calibration facilities.

The factors influencing the angle response / calibration of an autocollimator can be sub-divided into two broad categories: external vs. internal. External factors are given by the measuring conditions under which the device is used (and can thus be specified by the user). These include:

- SUT reflectivity
- SUT curvature
- Distance (path length) to the SUT
- Diameter and shape of the aperture stop
- Position of the aperture stop along the autocollimator's optical axis
- Position of the aperture stop perpendicular to the optical axis

Internal factors are specific to the each autocollimator's internal design (and are therefore generally beyond user control):

- Aberrations of the optical components (autocollimator's objective, reticle illumination, beam splitter cubes …)
- Alignment of the components, including the detector
- Non-orthogonality of the measuring axes
- Internal specular reflections and stray light
- Geometrical imperfections of the reticles
- *Inter*-pixel variations of the CCD (geometry, quantum efficiency, dark current …)
- *Intra*-pixel quantum efficiency pattern (across *single* CCD pixels, due to their internal structure)

3.2.1 SUT distance / beam path length

In the case of different distances between the autocollimator and the reflecting SUT, the beam returning to the autocollimator after reflection follows different paths through its optics. In the case of ideal optical elements and their perfect alignment, no errors in the autocollimator's angle response are occurring. However, if aberrations of the optical components and errors in their alignment (and that of the CCD detector) are present, angle measuring deviations are introduced which are a function of the SUT's distance / path length [22]. These deviations become more prominent as the product of the deflection angle and the distance from the SUT increases. (Note that when the SUT is located at a distance equal to the objective's focal length, angle measuring errors due to aberrations and alignment errors are minimised.)

Influences of the path length on the autocollimator's angle response are of special importance to deflectometric profilometers, where the length of the beam to the SUT changes by the entire scanning length (up to 1.2 m) as different points on the optical surface are accessed by a movable pentaprism. The same holds true for applications in precision engineering (e.g., the measurement of machine geometries) where path length changes also occur. In the case of deflectometric profilometers, this effect causes the dominant uncertainty component in the form measurement of extended, highly curved optical surfaces.

We also would like to mention the influence of environmental conditions, e.g., beam refraction by gradients in the air's refractive index, which may lead to angle errors if the distance to the SUT is changing. Temperature and pressure are the most important parameters influencing the refractive index of air.

3.2.2 SUT curvature

Most synchrotron and Free Electron Laser (FEL) beamline optics feature strong and locally varying curvatures of the SUT which affect both the location and the quality of the image of the autocollimator's reticle on the CCD detector. Beamline optics even exhibit different radii of curvature in longitudinal and sagittal directions. Even polygon calibrations, where differences in the topographies of the optical faces are far smaller, are affected by the faces' flatness deviations. Therefore, a systematic effort to characterise the influence of the SUT's curvature is essential for advancing deflectometric form measurement. It was therefore chosen to be part of the European Metrology Research Programme (EMRP) Joint Research Project (JRP) SIB 58 Angle Metrology.

3.2.3 SUT reflectivity

Optical surfaces of different reflectivity (e.g., aluminium-coated and uncoated) are commonly in use. The reflectivity of the SUT and the aperture size influence the autocollimator's angle response by causing, e.g., changes in the signal-to-noise ratio (SNR) of the detected image, internal reflections, and stray light [21] and [23]. Some autocollimators adapt their light output to compensate for differing reflectivity which may mitigate some problems (e.g., SNR changes) while aggravating others (e.g., internal reflections). Generally, due to differing sensitivities to changes in SUT reflectivity and aperture size, different types of errors cannot be minimised simultaneously by a well chosen set of parameters. Ray tracing simulations are difficult as stray light influences cannot be modelled adequately. Therefore, the experimental characterisation of its influence on the autocollimator's angle measurement is part of EMRP SIB 58 Angle Metrology.

3.3 Autocollimator calibration – spatial angle

In most autocollimator applications, e.g., deflectometric profilometers or the measurements of machine geometries (straightness, flatness, and parallelism) in precision engineering, both of the autocollimator's measuring axes are engaged simultaneously, i.e., the autocollimator beam is deflected in two orthogonal angular directions by the SUT. The simultaneous engagement of both axes results in crosstalk between them, i.e., their angle measurements are not independent of each other. Reasons for this include optical aberrations and alignment errors of the autocollimator's internal components, and imperfections of the reticles which are imaged onto the autocollimator's CCD. This influence has not yet been investigated in detail and a systematic effort to characterise this is essential for advancing angle metrology with autocollimators.

The multiple challenges of traceable autocollimator calibration for spatial angles resulted in the development of a novel concept and the realisation of a device for the precise and traceable calibration of spatial angles at PTB, the Spatial Angle Autocollimator Calibrator (SAAC) [24]. It makes use of an innovative Cartesian arrangement of three autocollimators (two reference autocollimators and the autocollimator to be calibrated) facing a reflector cube on a precision tilting stage. Each of the two reference autocollimators, which are used for the precise measurement of the cube's angular orientation, is primarily sensitive to rotations of the cube around one of the two relevant axes. It can thus be calibrated and traced back to PTB's national primary standard for the plane angle in a conventional manner.

3.4 EURAMET.L-K3.2009 Key Comparison

An international Key Comparison on autocollimator calibration, EURAMET.L-K3.2009, was initiated by the European Association of National Metrology Institutes (EURAMET) to provide information on the capabilities and limits of independent calibration methods and devices in this field [25]. It is headed by the PTB and a total of 27 international participants are involved. NMIs both from EURAMET and from the Asia Pacific Metrology Programme (APMP) are represented in this comparison.

The circulation of the standard has already started in December 2009. The standard is an electronic autocollimator type Elcomat 3000 by Möller-Wedel Optical which has been made available for this comparison by the manufacturer. The circulation of the standard is still in progress and scheduled to be finished by the end of 2014. As the pilot laboratory, PTB will analyse the results of the Key Comparison afterwards and will present and publish the results.

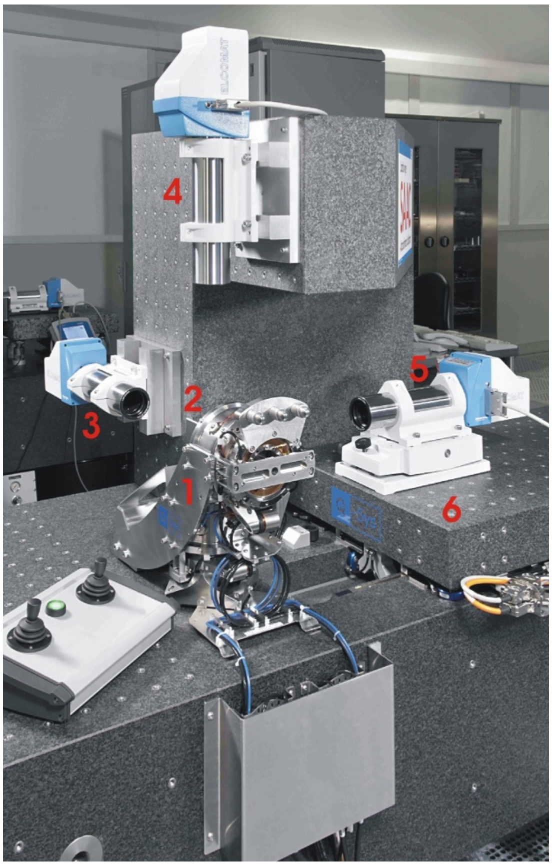

Figure 6: SAAC set-up for spatial angle autocollimator calibration. A precision two-axis tilting unit (1) rotates the reflector cube (2). Two reference autocollimators, a horizontal (3) and a vertical (4) one, are mounted to a granite bridge. The autocollimator to be calibrated (5) is set on a linear stage (6) for the automatic distance adjustment.

4. CONCLUSION

At the PTB, the classical angle metrology tasks (e.g., the flexible calibration of angle artefacts and angle measuring instruments for industry, execution of international comparisons) of an NMI are performed. Additionally, during the last decade, the application of autocollimators in deflectometric profilometers for the form measurement of optical surfaces became an important focus of our research. The improvement of angle metrology with autocollimators in deflectometric set-ups, especially for synchrotron applications, is of strong strategic importance to the community as the form measurement of beam-shaping optical surfaces currently limits their manufacturing. These applications are major drivers of the demand for lower uncertainty in angle measurement, and the PTB has been able, due to its competencies and capabilities, to advance this field. PTB has been reacting to these challenges flexibly through research and the development of several novel calibration methods and devices. This includes our activities in EMRP SIB 58 Angle Metrology.

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