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1 Executive Summary

Introduction

Angle metrology is a key enabling technology for scientific and industrial areas of high value in which the EU is globally competitive. Precise angle measuring devices – such as angle encoders, angle interferometers, small angle generators and autocollimators – are extensively used in various applications where high precision is demanded. This project has made a significant contribution towards traceable angle metrology targeted at nanoradian uncertainty for the evermore stringent demands of advanced scientific and industrial application. The project has provided novel methods, tools, instruments, guides and knowledge that will help to ensure that current and future metrological demands which to date have not been sufficiently catered to are supported by the necessary level of precision angle metrology.

The Problem

Angle measurement-generation, and the control of angle tilting units at the nanoradian uncertainty level are essential to numerous applications ranging from astrometry, space missions, and scientific experiments to industrial applications. Meeting the demand for traceable angle measurement-generation at sub-nrad sensitivity is very challenging and has not yet been addressed adequately.

Autocollimator-based slope measuring profilers represent the state of the art for the inspection of ultra-precise X-ray optical components of today. However the inspection of ultra-precise X-ray and EUV (Extreme Ultra Violet) optical components particularly for applications in the next generation of synchrotron radiation (SR) and Free Electron Laser (FEL) light sources using angle measurement-based profilometers is highly challenging and requires urgent solutions in order for manufacturing capability to meet both design as well as regulatory demands. As an example, the focusing optics proposed at the European XFEL under construction in Hamburg, now requires 20 nrad rms residual slope deviation (1 nm pv figure error). Additionally, optical angle measurement devices, using autocollimators require two-axis (2D) calibration (i.e. spatial angle calibration). This has never been achieved before due both to lack of demand for such detailed investigation and precision and thelimited knowledge on the performance of autocollimators used for form measurement of highly curved optical surfaces and for application in surface measuring profilers. In the case of form measurement with autocollimator-based profilometers, measurement limits are defined by the limits of the angle measurement with the autocollimator. Ultimately, these limits define the manufacturing potential of beam-shaping optics by advanced surface modification technologies.

The Solution

In response to this problem, the project set out to develop novel methods, tools, instruments, guides and greater understanding of angle measurement devices by accomplishing the following objectives:

- Perform investigations for reaching fundamental metrological limits in the autocollimator-based form measurement of curved optics (e.g. X-ray optics)
- Develop new tools-methods for enhancement of precise angle metrology devices such as autocollimators, angle encoders and small angle generators

Calibration of autocollimators with state of the art uncertainties down to 0.001" (arcsec) or 5 nrad using developed novel methods, sub-nrad sensitivity angle measurements with newly developed devices, guides and new measurement capabilities, model for highly accurate new generation industrial angle encoders, most importantly a milestone; first spatial (2D) autocollimator calibrations are now available.

Impact

The results obtained have significantly advanced the current state of the art knowledge on precise angle measuring devices such as autocollimators, angle encoders and small angle generators for nanoradian angle metrology applications. Novel methods, tools and knowledge produced in the project enable NMIs to be able perform calibrations of angle measuring devices with uncertainties less than 50 nrad. Besides, new prototype devices for the realisation of the SI angle unit 'radian' with an expanded uncertainty less than 0.01" (50 nrad) will answer the demands of particularly SR and FEL centers. The project has generated eighteen high impact publications in key journals, fifteen proceedings, one chapter as contribution to book and one master thesis. Additionally, the project contributed fifty six presentations to conferences and input to numerous relevant standards committees. For example, the knowledge produced in the project is being used for revision of VDI/VDE 5575 - Blatt 4 / Part 4, "X-ray optical systems - X-ray mirrors - Total reflection mirrors and multilayer mirrors".

Early impact included the development of new 2D autocollimator calibration devices available in PTB and VTT. These are the first devices for the traceable realisation and dissemination of spatial angles worldwide. They greatly extend the frontiers of angle metrology, ending its former limitation to plane angles. The first spatial angle (2D) calibration of an autocollimator was achieved with these devices promising substantial information for the first time for autocollimators when used for form measurement of highly curved optical surfaces. The service for two-axis (2D) calibration of autocollimator will be available in PTB and VTTfollowing the quality management process. Additionally an Aperture Centring Device (ACenD), useful alignment tool to centre an aperture up to 0.1 mm to the optical axis of the autocollimator, was developed in the project is now commercially available to end users. Furthermore the capabilities at partner institutes and NMIs have been improved. DLS gained the ability for analysis of shear results by utilising documentation and reference data sets created in the project. CMI is now using their new large range small angle generator for calibration of autocollimators. All NMIs improved their services for calibration of angle measurement standards. Most of them are making preparations for task specific calibration of autocollimators that will be available to customers. Unfunded project partners FAGOR established a new angle comparator together with IK4-TEKNIKER on their premises and a new portable device (Large Range Small Angle Generator) for precise calibration of autocollimators developed in the project will be used in TUBITAK for their services.

The research work carried out for the use of autocollimators for the inspection of ultra-precise X-ray optical components will allow the production of more precise beam shaping optics resulting in improved photon flux, coherence and resolution (i.e. better images) in the research carried out by SR and FEL sources. The knowledge generated through the project has already been used for the inspection of world's best quality optics delivered to European XFEL in 2016. Such focusing optics will be used e.g. to focus photons at the Single Particles, Clusters and Biomolucules (SPB) experimental station at the European XFEL under construction in Hamburg (Germany).

2 Project context, rationale and objectives

2.1 Context

Enhancement of X-ray technologies in science and technology is progressing rapidly. The use of synchrotron radiation (SR) and Free Electron Laser (FEL) sources increases with the new demands of advanced application industries. Intense and brilliant hard X-ray sources in SR and FELs centers functions like a 'super-microscope', which 'films' the position and motion of atoms in condensed and living matter, and reveals the structure of matter in all its complexity. For example, synchrotron radiation is used increasingly as a response to industrial challenges related to the life cycle of materials: development, manufacturing, operation, aging, wear-and-tear, preservation, restoration, recycling, evaluation, and more. Observing, characterising and understanding the structure of matter are at the heart of these challenges for industry. The main applications of such technology cover many fields, including pharmaceuticals and biotechnology, magnetism, chemistry and catalysis, cosmetics, food products, construction and transport engineering, nanotechnologies, semi-conductors, energy, environment, metallurgy, and advanced materials. The SR and FEL sources are used to probe matter and analyze a host of physical, chemical, geological, and biological processes. Information obtained by scientists can be used to help design new drugs, examine the structure of surfaces to develop more effective motor oils (solar fuels), build smaller, more powerful computer chips, develop new materials for safer medical implants, and help with the clean-up of mining wastes, to name just a few applications.

Optical elements are used to guide infrared, ultraviolet, and X-rays along very large distances from SR/FEL source to a dedicated focal point, i.e. application point where researchers choose the desired wavelength to study their samples. The quality of the optical components is one of the limiting issues for the performance of SR beamlines at storage rings as well as in FELs. Thus the precise characterisation of such components is a critical task to preserve the quality of SR-light in terms of coherence, spectral purity and time structure. Slope/surface (i.e. deflectometric) measuring profilers are used to inspect the quality of these optical elements and today angle measurement device-autocollimator based surface measuring profilers offer the state of the art capability for the inspection/form measurement of ultra-precise X-ray and EUV optical components.

The need for advanced angle metrology is continually increasing at synchrotron radiation beamlines and FEL centres. Due to the stringent demands on the form measurement of highly curved optical surfaces, synchrotron / FEL metrology laboratories worldwide have been developing a new generation of highly accurate angle-based surface profilometers. Currently, the measurement of form measurement limits the fabrication of these optical surfaces. Therefore, the development of X-ray and EUV optics for the next generation of synchrotrons and FEL light sources necessitates the further improvement of the angle metrology with autocollimators in the profilometer set-up (target for FEL optics: 0.01" rms / 50 nrad rms slope deviation, corresponding to 0.5 nm rms form deviation). Additionally, a 20 nrad rms residual slope deviation (up to a length of 1000 mm corresponding to 1 nm peak to valley figure error) for elliptical-cylinder shaped focusing optics is required to focus photons at the Single Particles, Clusters and Biomolucules (SPB) experimental station at the European XFEL under construction in Hamburg (Germany).

Apart from use of angle metrology in form measurement, angle measurements at nrad uncertainty level are essential to numerous applications; e.g., to monitor the angles of telescope mirrors in astrometry (0.1 nrad sensitivity), to tune the angle between a pair of silicon crystals in gamma ray spectroscopy (0.1 nrad resolution), to calibrate accelerometers for space missions (20 nrad accuracy), to determine the constant of gravitation *G* by a torsion balance (less than 5 nrad accuracy).

Most measurement equipment used in geodesy, long distance measurement, and large volume metrology (e.g. laser trackers, theodolites) is fitted with angle measuring devices such as angular encoders; the same holds true for robots and machine tools used in industry. The accuracy of these devices depends on the capabilities of their in-built angle encoders and they are subsequently determining manufacturing accuracy. Increasing demands on manufacturing accuracy from production industry raise the need for improvements in angle encoders and their calibration.

2.2 Objectives

The project 'Angle Metrology' aimed to provide significant advancement on the current state of the art knowledge on precise angle measuring devices of autocollimators, angle encoders and small angle generators. It also aimed to answer the challenge of the aforementioned issues which have never been addressed before by developing novel tools, methods, devices, techniques, new services, guides and knowledge in order to provide a wide range of scientific and industrial community with improved angle measurements for their needs in high precision angle metrology applications. The improvement of angle metrology for synchrotron application is of strong strategic importance to the community as the angle measurement based form measurement of beam shaping optical surfaces currently limits their manufacturing.

The project focused on a number of key objectives grouped in four titles:

- Performing extensive research for 'Metrological characterisation of autocollimators'
  - To improve autocollimator performance at small apertures (beam diameters) by means of novel reticules and by the improvement of the algorithms for the sub-pixel image location on the CCD detector
  - To develop facilities and methods for the two-axis (2D) calibration of autocollimators to address influences of the sagittal beam deflection by the optical
  - To develop ray tracing modelling of autocollimators to connect experimental data to opto mechanical causes
  - To characterise the influence of the distance between the autocollimator and the optical surface, i.e., the optical path length of the autocollimator beam, on its angular response when used with small apertures at various distance to the target
  - To understand the behaviour of autocollimators when used with small apertures and in various distances to the target
- Performing investigations on 'Application of autocollimators in profilometry'
  - To perform investigations on new generation autocollimators which are specially designed for high precision profilometers

- To characterise the influence of the locally changing curvature of the surface under test on the angle response of autocollimators

- Performing investigations on ‘Precise angle encoders’
  - To improve the accuracy of angle measurements by performing investigations on various independent angle measurement methods and various angle measuring devices
  - To produce guidelines for the calibration of autocollimators
  - To develop accurate facilities for the calibration of angle encoders
- Performing extensive research for improvement of ‘Small angle generators and hybrid devices'
  - To produce portable and cost effective small angle generators (3 different types) with an expanded uncertainty less than 0.01” (50 nrad) and a calibration range of about 3600” (17 mrad)
  - To develop hybrid angle calibrators
  - To perform investigations for nrad and sub-nrad level angle metrology according to demands of synchrotron beamlines at storage rings, FELs and XFELOs

Angle measurements at nrad uncertainty level are essential to numerous applications. In particular, non-contact angle measurement at the nrad scale is of interest. Autocollimators (ACs) with a resolution of 1 mas (5 nrad) are utilised to this purpose. Autocollimators, versatile optical devices, for the contactless measurement of the angular tilt of reflecting surfaces, are also used in slope measuring profilers for the inspection of ultra-precise X-ray optical components. Another example of the precise measurement of angular deflections with autocollimators is in scientific experiments, such as the improved determination of the constant of gravitation *G*. The BIPM measurement of *G* heavily relies on the precise determination of angular deflections. Extensive research for ‘*Metrological characterisation of autocollimators*’ was required for reaching fundamental metrological limits in the autocollimator-based form measurement of curved optics and nanoradian angle metrology applications. In order to achieve this, theoretical and experimental research work had to be carried out to improve autocollimator performance at small apertures (beam diameters), to develop facilities and methods for the two-axis (2D) calibration of autocollimators, to develop ray tracing modelling of autocollimators, and to characterise the influence of the distance between the autocollimator and the optical surface under test (SUT).

Autocollimators have recently become very popular since autocollimator-based slope measuring profilers have proven to be capable of characterising ultra-precise X-ray and EUV optical components of today; particularly for applications in Synchrotron Radiation (SR) and Free Electron Lasers (FELs). Use of autocollimators for the ultra-precise measurement of optical surfaces using scanning techniques (such as inspecting the quality of SR optics) requires further investigations and more detailed calibration to obtain better accuracies (than those stated by the manufacturers). This is only possible after individual calibration of the devices customised to the specific measuring tasks. Therefore, the autocollimators must be calibrated to detect and correct any systematic error and determine the uncertainty associated to their readings, making their measurements traceable to the SI plane angle unit. Another important issue is the correct use of the autocollimator’s calibration values. For this, the autocollimator must operate in the experimental set-up under the same measurement conditions when calibrated. In case of different conditions (e.g. optical profilometry), additional errors in the autocollimator’s angle response occur and they need to be characterised by additional calibration, or in-situ calibration, or ray trace modelling. This required further extensive research to be undertaken to reach lower uncertainties. From this point of view, investigations on ‘*Application of autocollimators in profilometry*’ was needed to characterise the influence of the locally changing curvature of the surface under test on the angle response of autocollimators, to perform investigations on new generation autocollimators designed for high precision profilometers and to understand the behaviour of autocollimators when used with small apertures and at various distances to the target.

The calibration of autocollimators is conveniently carried out by rotary tables fitted with angle encoders. The best standard measurement uncertainty for calibration of the autocollimators is around 0.005" (25 nrad) and this is limited with the unique and very special angle encoder which is not commercially available. Other rotary tables fitted with commercially available angle encoders can offer standard measurement uncertainty of about 0.03" as the best. This needs further improvements to answer the challenging demands for calibration of autocollimators using angle encoders. Another important issue is the calibration of angle encoders and the enhanced performance required for industrial applications, e.g., the measurement of long distances by theodolites, precision distance measurements by laser trackers, and rotary tables used in machine tools for the manufacturing of parts (e.g. gear wheels). Angle encoders are employed in these devices and the devices' precision heavily depends on the performance of the built-in encoders. The built-in angle encoders are calibrated with various methods but these suffer from coupling and alignment problems resulting in enormous errors that compromise the actual performance of angle encoders. No proper solutions existed in the literature for preventing such problems. Therefore the project aimed to perform investigations on '*Precise angle encoders*' to improve the accuracy of angle measurements, to develop accurate facilities for the calibration of angle encoders and to produce guidelines for the calibration of angle encoders and also for autocollimators. Acquiring substantial information for understanding the parameters affecting the encoder performance were aimed to produce work beyond the current state of the art.

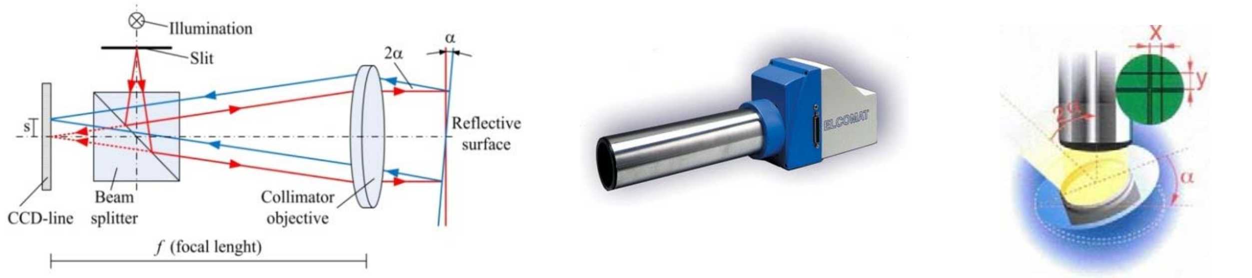
Regular in-situ checks of the performance of autocollimators when used in high precision applications such as deflectometric profilometry become more and more important. Such in-situ checks are able to uncover differences in the angle response of autocollimators between the calibration at a laboratory/NMI and their subsequent application in deflectometric profilometers. Apart from subtle changes in the autocollimator's measuring conditions, shocks, particularly during their transportation, may affect the previous calibration values. The calibration of autocollimators is also conveniently carried out by small angle generators (SAGs) utilizing sine or tangent arm principle. However, achievable uncertainty values were not satisfactory for the measurement ranges needed for full scale calibration of autocollimators. Achievement of required uncertainties for larger measurement ranges requires highly sophisticated, specially designed, state of the art angular measurement devices. Such devices are not commercially available; they need to be custom-built and, therefore, their costs are fairly high. Increasing numbers of synchrotron radiation and FEL centres require portable and precise small angle generators for regular in-situ checks of their autocollimators. Such portable low cost devices do not exist at the moment. Most metrology departments in SR&FEL centres are seeking solutions to get traceability to the SI angle unit 'radian' with low uncertainties and high resolutions. Improving applied angle metrology (and therefore the traceability of angle measurements) necessitates in-situ calibrations with low uncertainties. Therefore, SR&FEL centres (more than 50 worldwide) require the availability of portable and precise small angle generators. Besides, the motion errors of metrology stages need to be measured with increasing demands for accuracy both for measurement and high precision production. These errors consist, besides translational errors, also of rotational errors, such as pitch, yaw and roll errors. Their characterisation requires improved angle measuring devices, seeking traceability to SI angle unit 'radian'. Therefore, the project aimed to perform extensive research for improvement of '*Small angle generators and hybrid devices*' to produce portable and cost effective small angle generators (3 different types) with an expanded uncertainty less than 0.01" (50 nrad) and a calibration range of about 3600" (17 nrad). A further objective was to perform experimental research to generate-measure ultra-small angles in nrad accuracy and sub-nrad sensitivity.

3 Research results

The results are presented on the basis of grouped objectives as indicated and defined in section 2.2.

3.1 Metrological characterisation of autocollimators

The level of precision now required for angle measurements carried out by autocollimators is increasing for scientific and industrial applications of high value and extensive research for 'Metrological characterisation of autocollimators' is required in order to address these more stringent demands in the general use of autocollimators (including profilometry). A review of the state of the art of autocollimator application, performance, and calibration has been prepared in the project and can be accessed via the project website. **Figure 1** illustrates basic information on autocollimators and **figure 2** shows the application examples for nrad angle metrology using autocollimators. A photo of an autocollimator-based slope measuring profiler in HZB is illustrated in **Figure 3** and measuring conditions for an autocollimator when used in profilometry are given in **Figure 4**.



(a) (b) (c)

Figure 1. Electronic autocollimator (a) schematic diagram of working principle (b) Elcomat 3000 autocollimator device (c) 2D Angular tilt and measurement by autocollimator

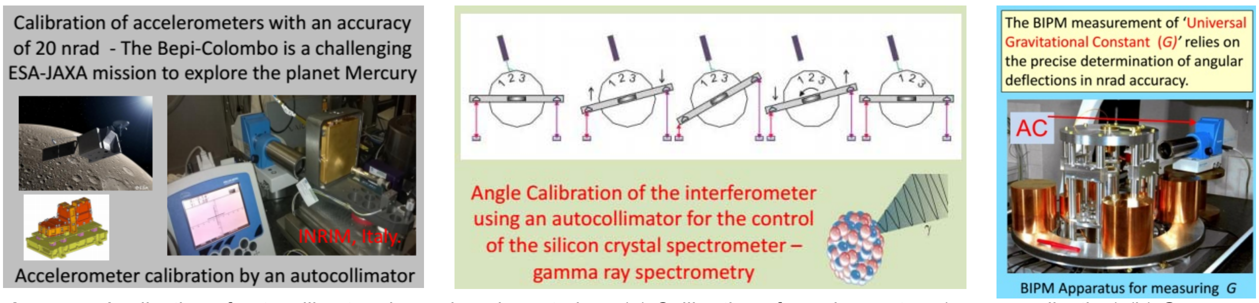


Figure 2. Application of autocollimators in nrad angle metrology (a) Calibration of accelerometers (space application) (b) Gama ray spectrometry (Material Science) (c) Measurement of universal gravitational constant (*G*) in BIPM - big scientific experiments for universal constants (CODATA).

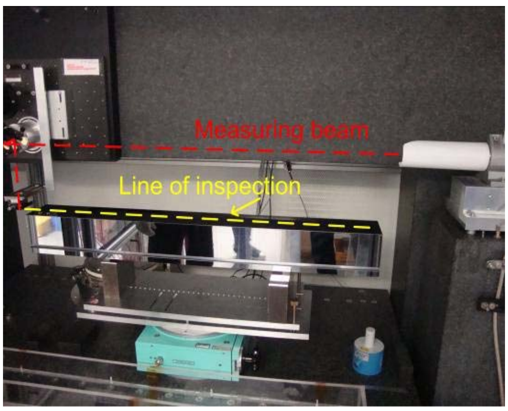


Figure 3. Autocollimator based slope (deflectometric) measuring profiler - HZB

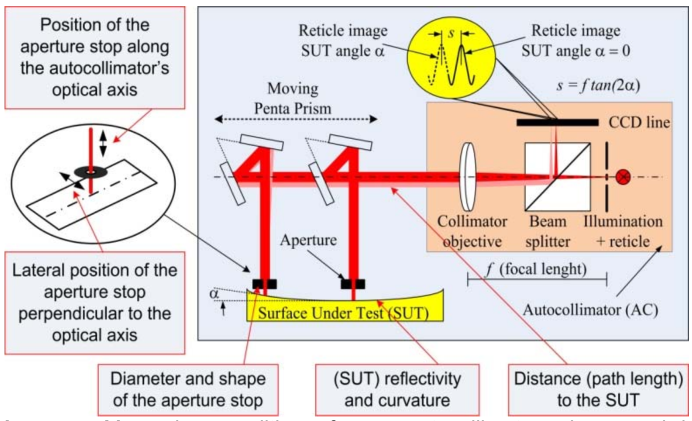


Figure 4. Measuring conditions for an autocollimator when used in profilometry (challenging demands for autocollimators)

Through this project's extensive research the performance of autocollimators was significantly improved by advancing the available knowledge on the following topics :

- Investigation of influences of variable beam path lengths on the autocollimator's angle measurement
- Two axis (2D) calibration of autocollimators
- Investigation and improvement of autocollimator performance at small apertures

3.1.1 *Investigation of influences of variable beam path lengths on the autocollimator's angle measurement*

Variation in the optical path length of the autocollimator beam (i.e. the distance between the autocollimator and the optical surface) has influence on the autocollimator's angular response. Investigations are essential for angular error (pitch and yaw) measurement of precision guides and also for deflectometric profilometers as the optical path length changes in both cases. During such measurements, the reflected beam follows different geometrical paths through the autocollimators' optics and, in conjunction with aberrations and alignment errors of the optical components, path-length-dependent angle measurement deviations are induced (See **Figure 5**).

The project has advanced our knowledge on distance-dependent angle measuring errors of autocollimators. To this purpose, PTB, TUBITAK, VTT, IPQ, CEM, AIST-NMIJ and MWO delivered a total of 27 calibration data sets obtained at distances between the autocollimator and the reflecting surface between 90 mm to 1800 mm (mostly used by the synchrotron community) (**Table 1**). Results were obtained with new generation autocollimators (Elcomat 3000, Elcomat HR, and Elcomat HR-500, from Möller Wedel Optical). Ray tracing simulations of an autocollimator to investigate the effect of variable path lengths was performed by PTB accessing to confidential design data on autocollimators with permission of MWO.

Figure 6 illustrates the calibration results of the autocollimator by TUBITAK obtained at two different optical lengths (*D*=300 and 600 mm) and their differences. **Figure 7** illustrates differences between the angle deviations by PTB for *D*=300 mm (reference) and *D*=675, 1050, 1425, and 1800 mm, respectively. Experimental results and theoretical results calculated using Best-fit polynominals determined using autocollimator parameters (ray tracing simulations) are also shown.

This collaborative work profited heavily from the synergy between the experimental results and the raytracing simulations which demonstrate excellent agreement. It will help autocollimator users and manufacturers to minimise measurement errors due to distance-dependent effects.

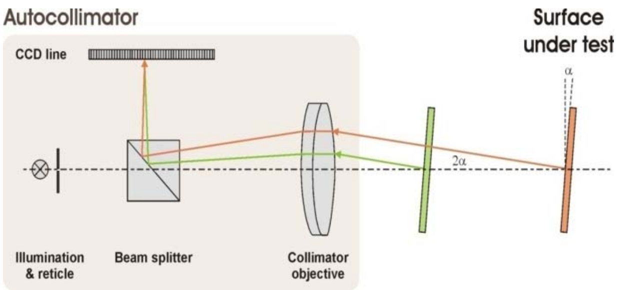


Figure 5. The reflected beam follows different geometrical paths through the autocollimators' optics due to the varying optical path length and angular error exists because of non-perfect optics and non-proper alignments.

Table 1. Participants with parameters of calibrations

Participant	Autocollimator	Distances/mm (reference in **bold**)	Remarks
PTB	Elcomat 3000	**300**, 320, 340, 360, 380 **300**, 675, 1050, 1425, 1800	
TUBITAK	Elcomat 3000/8 Elcomat 3000/4	**300**, 600 **300**, 600	Y-axis has been examined. X-axis has been examined.
CEM	Elcomat HR	120, **300**, 500, 1000	
IPQ	Elcomat HR	**300**, 1100, 1500	
MWO	Elcomat HR-500	90, **300**, 600, 900, 1200	
AIST-NMIJ	Elcomat 3000	**160**, 500	
VTT-MIKES	Elcomat 3000	100, **300**, 720	Two aperture diameters have been examined.

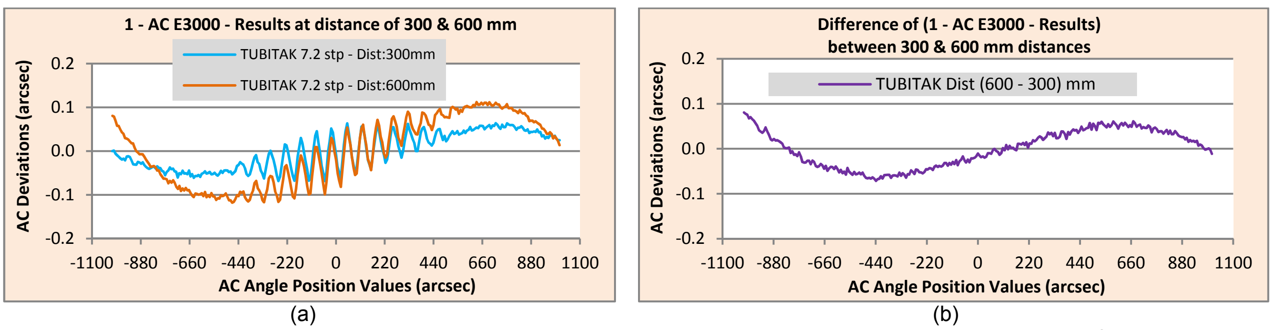
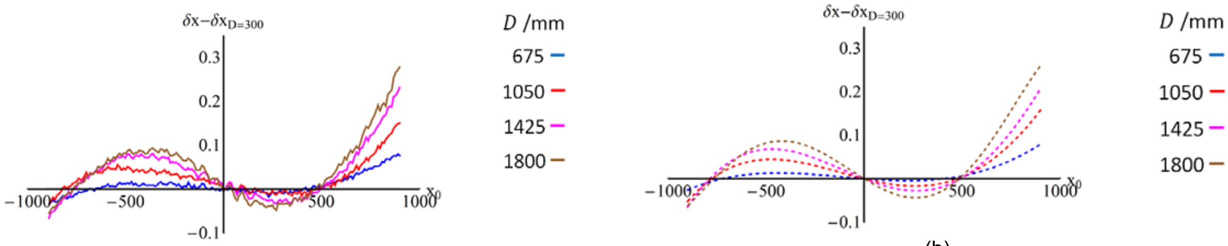


Figure 6. Autocollimator angle deviations by TUBITAK at various optical lengths (a) Angle deviations at Distances of *D*=300 mm and *D*=600 mm between AC and SUT (b) Differences between the angle deviations for *D*=300 mm (reference) and *D*=600 mm



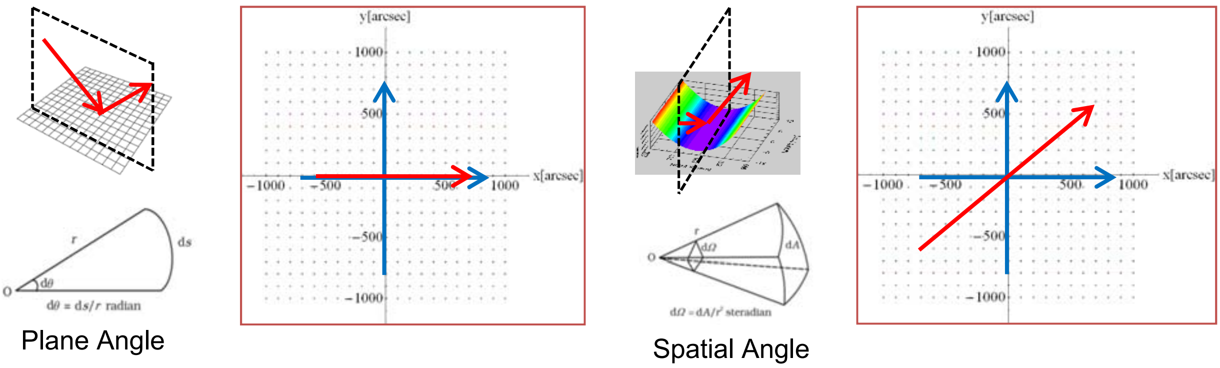
(a) (b)

Figure 7. Differences between the angle deviations by PTB for D=300 mm (reference) and D=675, 1050, 1425, and 1800 mm, respectively (a) Experimental data (b) Best-fit polynominals determined using ray tracing simulations.

3.1.2 *Two-axis (2D) calibration of autocollimators*

A milestone in the calibration of autocollimators was achieved by advancing autocollimator calibration from plane to spatial angles. Two-axis (2D) calibration of autocollimators was carried out first time in the world. This is essential when the autocollimators are used for precise inspection of curved optical surfaces (e.g. inspection of elliptical-cylinder shaped focusing optics proposed at the European XFEL or at Diffraction Limited Storage Rings (DLSR)).

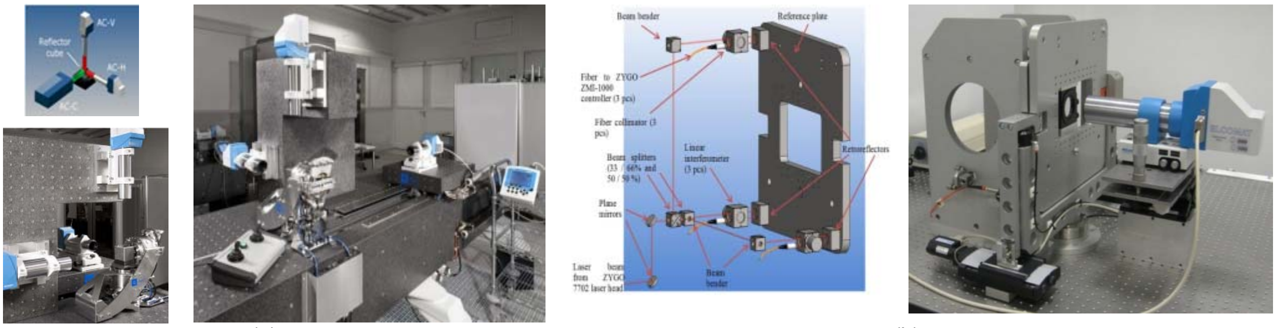
The autocollimator beam is deflected in two orthogonal angular directions by a reference mirror / the SUT in most autocollimator applications resulting in the crosstalk effect due to simultaneous engagement of both measuring axes (**Figure 8**). In other words, their angle measurements are not independent of each other due to alignment errors and optical aberrations of the autocollimator's internal components, and imperfections of the reticles which are imaged onto the autocollimator's CCD. It is essential to determine these errors for precise application of autocollimators where both measurement axes are engaged, to address the influences of the sagittal beam deflection by the optical surface and to perform investigations on applications of autocollimators in challenging conditions of profilometry.



(a) (b)

Figure 8. Autcollimator axis engagements depending on the reflected surfaces (SUTs) (a) Engagement of one measuring axis (b) simultaneous engagement of both measuring axes: Measurement of plane angle by x- axis and spatial angle by x- and y axes.

Two different innovative set-ups for 2D calibrations of autocollimators were accomplished. They are a Spatial Angle Autocollimator Calibrator by PTB and an interferometer-based 2D autocollimator calibration set-up by VTT (**Figure 9**). These are the first devices for the traceable realisation and dissemination of spatial angles worldwide. They greatly extend the frontiers of angle metrology, ending its former limitation to plane angles. The first spatial angle (2D) calibration of an autocollimator was achieved with these devices promising substantial information first time for autocollimators when used for form measurement of highly curved optical surfaces. The service for two-axis (2D) calibration of autocollimator will be available in PTB and VTT following the quality management process.

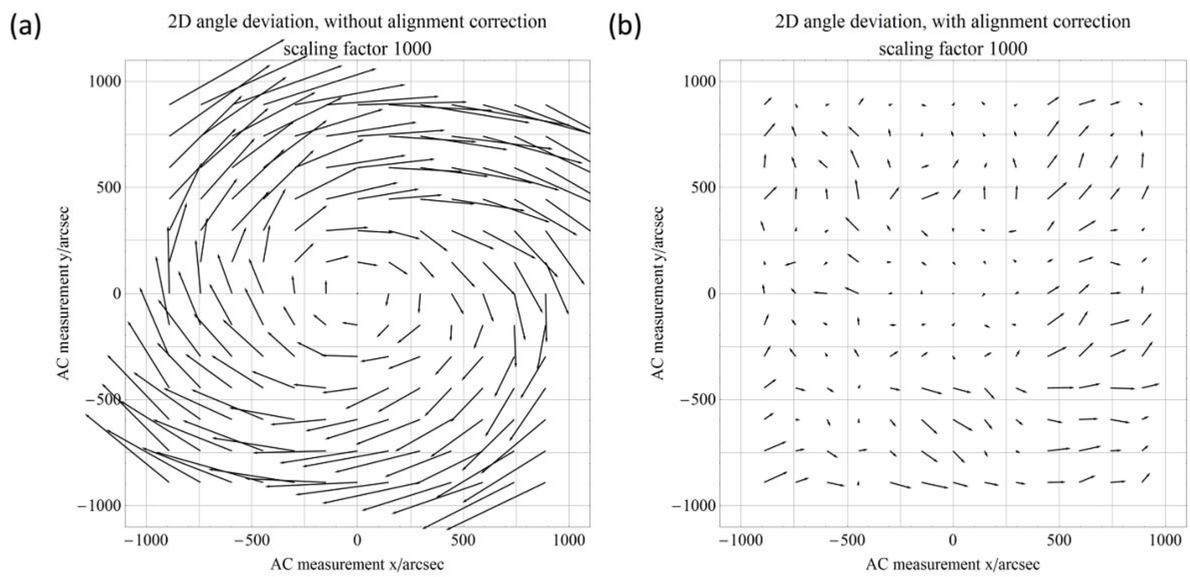


(a) (b)

Figure 9. Two different innovative set-ups for 2D calibrations of autocollimators (a) Spatial Angle Autocollimator Calibrator by PTB (b) interferometer-based 2D autocollimator calibration set-up by VTT

Figure 10 illustrates the first results of the 2D calibration of an autocollimator. The angle deviations of the autocollimator's x- and y measurement axes at the respective measurement values of the autocollimator are illustrated by arrows. With the help of 2D data, alignment error of x- and y measurement axes were determined and then corrected. Results with and without correction are illustrated in **Figure 10**.

A comparison between the angle deviations of the 2D calibration which correspond to the measurements along the x-axis with a plane-angle calibration of the examined autocollimator show a good agreement and corroborate the calibration process and the applied methods.



Figures 10. Results of the 2D calibration of an autocollimator: (a) shows the angle deviations of the autocollimator without applying the alignment correction, (b) shows the angle deviations with all corrections considered. The arrows illustrate the angle deviations of the autocollimator's x- and y measurement axes at the respective measurement values of the autocollimator.

Intercomparison measurement for 2D calibrations of autocollimators, for the first time in the world was also carried out in the project. PTB performed spatial angle calibrations of an autocollimator type Elcomat 3000 (MWO) with its SAAC set-up and VTT with its interferometer based set-up. Two data sets were obtained: One grid with a measurement range of (±900")^2 and a grid sampling of 60", another one with a range of (±45")^2 and a sampling of 3". The two ranges and samplings were chosen to cover different types of systematic errors of the autocollimator on different angular scales. VTT performed a comparative analysis of the data sets with help from PTB and both partners created a report. This work promotes the validation of the calibration set-ups at PTB and VTT which were created as part of this project.

The extended characterisation of autocollimators will enable autocollimator manufacturers to improve their products. Autocollimator users, especially users of deflectometric profilometers at synchrotrons, FEL, and NMIs, will be able to benefit from the new calibration capabilities. Through these users, the traceable calibration of interferometers by use of optical flatness standards (at NMI) and the manufacturing of beam-shaping optics for synchrotrons and FEL applications can be improved.

3.1.3 *Investigation and improvement of autocollimator performance at small apertures*

The improvement of autocollimator performance at small apertures is of special importance for achieving improved lateral resolution with autocollimator-based deflectometric profilometers as well as angular displacement measurement of reflecting surfaces in very small sizes. For example, it is required to inspect surface figure of optical surfaces with higher lateral resolution (i.e. obtaining more information from the surface) in order to determine and remove surface irregularities more precisely. At small apertures, diffraction and interference distort the autocollimator's reticle image on its CCD detector and angle measurement errors with a period which corresponds to the CCD pixel size occur. This is hard to characterise as the autocollimator calibration needs to be performed with high angular resolution across the entire measurement range.

The improvement of autocollimator performance at small apertures was collaboratively achieved in the project. PTB developed a novel reticle design for autocollimators which markedly reduces measuring errors. The old and two new patterns were realised on a single substrate and integrated into the autocollimator by project partner MWO. PTB performed extensive calibrations to evaluate the comparative performance of the reticle patterns at variable aperture diameters and their interaction with different algorithms for locating the pattern on the CCD with respect to several outcome variables. The focus was on interpolation errors, i.e., errors on the angular scale which corresponds to the pixel size of the CCD, which are a dominant error source at small autocollimator apertures. The goal was to achieve the state-of-the-art level of interpolation errors at an autocollimator aperture of 7 mm (without design improvements) at a substantially reduced aperture of 5.5 mm (with improvements). This goal has even been surpassed. Over the tested aperture range (5 mm – 50 mm), the interpolator errors fell below the threshold of detectability. PTB has initiated a patenting the novel reticle pattern design.

Application in commercial products is expected particularly to increase the performance of autocollimators when used with small apertures (< 2.5 mm diameter) for inspection of future X-ray and EUV optics. This will result in development of new generation autocollimators in the near future.

3.1.4 *Summary*

The project has advanced the available knowledge on distance-dependent angle measuring errors of autocollimators with small and full aperture sizes. The influence of the distance between the autocollimator and the optical surface was characterised with experimental data sets of the project partners. The work profited heavily from the synergy between the experimental results and the raytracing simulations which demonstrate excellent agreement. It will help autocollimator users (particularly the synchrotron community) and manufacturers to minimise measurement errors due to distance-dependent effects. A novel reticle design with improved algorithms (for the sub-pixel image location on the CCD detector) was developed for autocollimators which markedly reduces measuring errors (i.e., interpolation errors), and formed the basis of for the submission of a patent. Its application in commercial products is expected particularly to increase the performance of autocollimators when used with small apertures (< 2.5 mm diameter) for inspection of future X-ray and EUV optics. This will result in the development of a new generation of autocollimators in the near future. New facilities and methods for the two-axis (2D) calibration of autocollimators addressing the influences of the sagittal beam deflection by the optical parts were developed. They are a Spatial Angle Autocollimator Calibrator (SAAC) of PTB and an interferometer-based 2D autocollimator calibration set-up of VTT. These are the first devices for the traceable realisation and dissemination of spatial angles worldwide. They greatly extend the frontiers of angle metrology, ending its former limitation to plane angles. Two-axis (2D) calibration of autocollimators was carried out first time in the world and now available as a new calibration service in PTB and VTT. All the scientific and technical objectives were achieved.

3.2 Application of autocollimators in profilometry

The aim of this work is to produce significant advances in the form measurement of optics for synchrotron beamlines and FELs which relies on autocollimator-based surface profilometers. The size (up to 1.5 m) and extremely stringent shape tolerances (2 nm pv in form, 50 nrad rms in slope) of the beam-guiding and shaping optical surfaces for these applications have led to equally stringent demands on the calibration and performance of autocollimators which far surpasses the demands of industrial autocollimator applications in precision engineering. Form measurement uncertainty and traceability depends directly on the calibration and performance of the autocollimators. The limits of the angle measurement with the autocollimator directly define the limits of the ultra-precise form measurement. Ultimately, these limits define the manufacturing limits of beam-shaping optics by advanced surface modification technologies. In addition, the mounting of such optics needs to be controlled by dedicated metrology instrumentation with the requirement to inspect the final state of the optics and mechanics under the condition of final application (e.g. in face-side or face-up state). **Figure 11** gives information about the World's most precise mirror to be used in European XFEL in Hamburg and **Figure 12** illustrates measured parameters used during inspection of SR/FEL optics as background information.

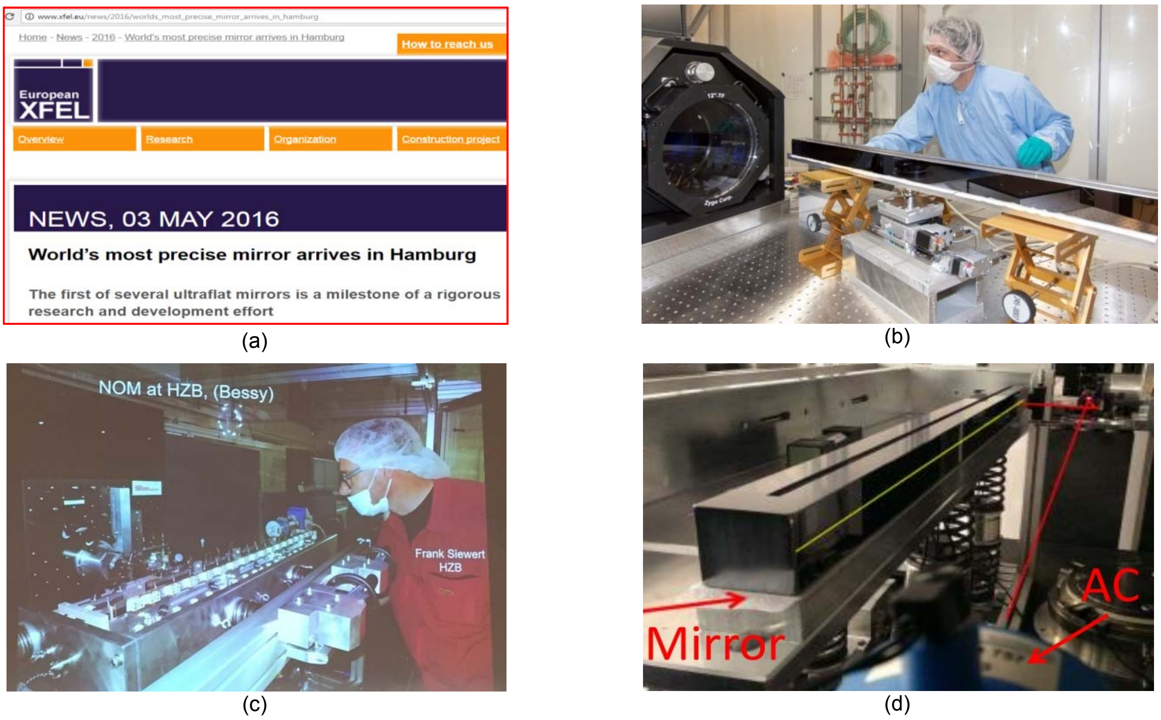


Figure 11. Information about the highest precision mirror in the world (a) News on the website of European XFEL about arriving of the World's most precise mirror (b) first inspection of the mirror using flatness interferometer (c) slope measurement of the mirror by autocollimator-based slope measuring profiler (NOM) in HZB by our project's Research Excellent Grant (REG) researcher, REG(HZB), Frank Siewert and (d) detailed view for measurement of the mirror in horizontal orientation using the autocollimator.

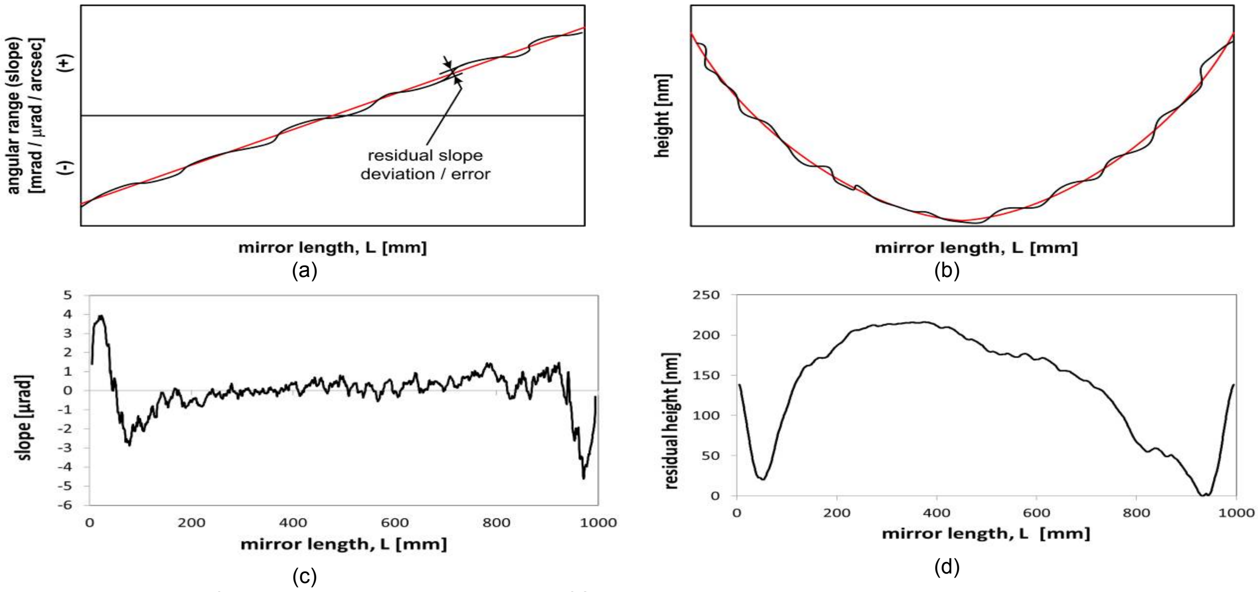


Figure 12. Illustration of parameters used during inspection of SR/FEL optics: (a) the angular data and (b) corresponding height values as an example (c) the profiles of residual slope, (d) the profiles of height on a toroidal mirror to collimate synchrotron light at a beamline at the BESSY-II storage ring, the aperture section is from mirror position x 200 -800 mm.

A special – but not exclusive – focus was set on the form measurement of beam-guiding and -shaping optics for synchrotron and FEL beamlines which relies on autocollimator-based profilometers. The reason for this is that these applications are the most challenging ones due to the size, strong curvature, and stringent shape tolerances of the measured optics. The investigations on the influences of properties of the SUT, primarily its curvature and reflectivity (on the angle response of autocollimators) and on the highly reproducible positioning of the aperture which, in profilometers, defines the beam footprint on the SUT are being carried out. A review of the state-of-the-art of angle-based precise form measurement of optical surfaces with deflectometric profilometers has been prepared under the project and can be accessed via the project website. Investigations on 'Application of autocollimators in profilometry' was performed to characterise the influence of the locally changing curvature of the surface under test on the angle response of autocollimators, to perform investigations on new generation autocollimators designed for high precision profilometers and to understand the behaviour of autocollimators when used with small apertures and in various distances to the target by focusing on the following topics:

- Investigation of influences of surface under test properties on the autocollimator's angle measurement
- Development of devices for reproducible positioning of the aperture relative to the autocollimator's optical axis

3.2.1 *Investigation of influences of surface under test properties on the autocollimator's angle measurement*

Most optics in synchrotron and FEL beamlines pose strong and locally varying curvatures affecting both the location and the quality of the image of the autocollimator's reticle on the CCD detector. They even exhibit different radii of curvature in longitudinal and sagittal directions. A systematic effort to characterise the influences of these surface characteristics is essential for advancing deflectometric form measurement.

PTB performed the first systematic investigation of the influence of the curvature of optical surfaces (provided by REG(HZB)) on the angle response of an autocollimator (**Table 2**). Extensive calibrations of different autocollimators at different SUT reflectivity were also performed by PTB resulting in new knowledge particularly for synchrotron metrology, autocollimator application and design (**Table 3**). It was found that autocollimators show different behaviours (even individual exemplars of the same type). In this case, ray tracing simulations are not sufficient as stray light influences cannot be modelled adequately. **Figure 13** shows a ZEMAX model of the simulated autocollimator for ray tracing simulations.

Table 2. Autocollimator calibrations with different radii of curvature performed at PTB.

Calib. #	SUT radius [m]	Aperture diameter [mm]	SUT reflectivity [%]	Calibration range / steps [arcsec]	Std. dev. mean calibration [arcsec]	Std. dev. difference calibrations [arcsec]
1	∞	5	4	±1000 / 10	0.0025	0.0337
2	44	5	4	± 1000 / 10	0.0019	
3	∞	2.5	27	± 1000 / 10	0.0018	0.0524
4	9.3	2.5	27	± 1000 / 10	0.0067	

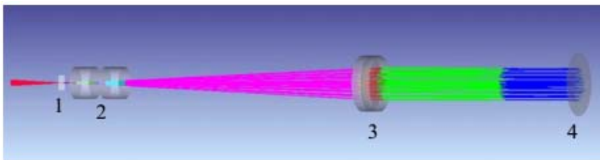


Figure 13. Simplified ZEMAX model of the simulated autocollimator. 1: detector; 2: two plane-parallel plates; 3: objective and source; 4: aperture stop and mirror, 5 mm apart

Table 3. Autocollimator calibrations with different surface reflectivity performed at PTB.

Figure No.	AC type	Distance [mm]	Aperture diameter [mm]	SUT reflectivity [%]	Calibration range / steps [arcsec]	Std. meas. uncertainty calibration (low refl.) [arcsec]	Std. meas. uncertainty calibration (high refl.) [arcsec]	Std. dev. difference calibrations [arcsec]
1	A	300	5	4 & (>85)	±1000 / 10	n. a.	n. a.	0.020
2	A	300	5	4 & (>85)	± 1100 / 10	0.0055	0.0045	0.011
3	A	560	18	4 & (>85)	± 1000 / 20	0.004	0.004	0.028
4	A	300	2.5	4 & (>85)	± 1000 / 10	0.007	0.007	0.088
5	A	300	32	4 & (>85)	± 1000 / 10	0.005	0.005	0.003
6	A	300	32	4 & (>85)	± 1000 / 10	0.005	0.005	0.018
7	B	300	25	4 & (>85)	± 160 / 1	0.005	0.005	0.011
8	B	300	25	4 & (>85)	± 160 / 1	0.005	0.005	0.003
9	C	300	32	4 & (>85)	± 545 / 5	0.009	0.009	0.018

Collaborative work of PTB and REG(HZB) created a report which addresses the influences of the reflectivity and curvature of optical surfaces on the angle response of autocollimators from an experimental point of view (by means of extended autocollimator calibrations) and a theoretical one (by raytrace modelling). These investigations are crucial for reaching fundamental metrological limits in the autocollimator-based form measurement of curved optics (e.g., beam-shaping optics for synchrotrons and FEL applications).

3.2.2 *Development of devices for reproducible positioning of the aperture relative to the autocollimator's optical axis*

Small aperture size is used to obtain higher lateral resolution for inspection of optics in autocollimator-based profiliometers. The reproducible centring of the circular aperture axis (used to restrict the beam footprint on the SUT in deflectometric profilometers) relative to autocollimator's optical axis is a crucial task since autocollimator angle response depends sensitively on its measuring conditions (e.g. the aperture's positioning). The non-repeatable centring during calibration and experimental set-up (i.e. in profilometry) will restrict the use of autocollimator calibration values. Ray tracing simulations of an autocollimator with variable aperture positions were completed in the project and the results proved that *'a device and standardised procedure for the highly reproducible (<0.1 mm) positioning of small (1.5 – 2.5 mm in diameters) apertures near the SUT relative to the autocollimator's optical axis during autocollimator use and calibration'* is required (**Figure 14**).

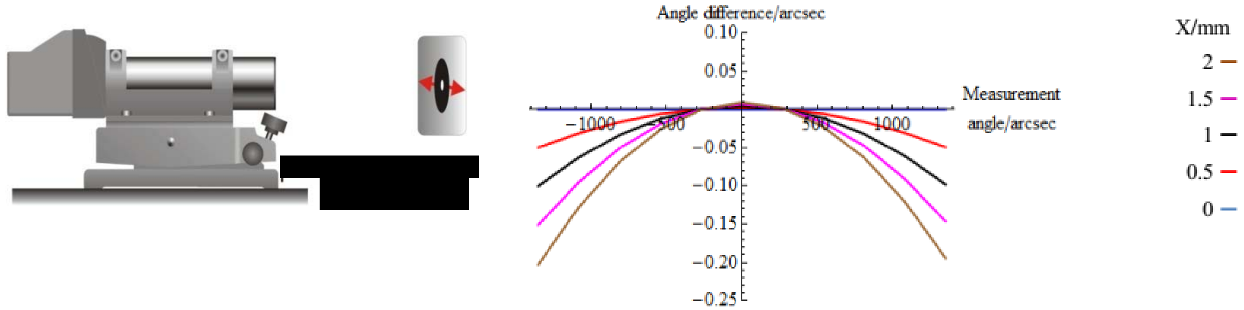


Figure 14. Ray tracing simulations of an autocollimator with variable aperture positions (a) Drawing showing the process (b) Angle differences between the reference simulation and simulations with variable lateral X/mm positions of the aperture. Distance to Mirror D=300 mm.

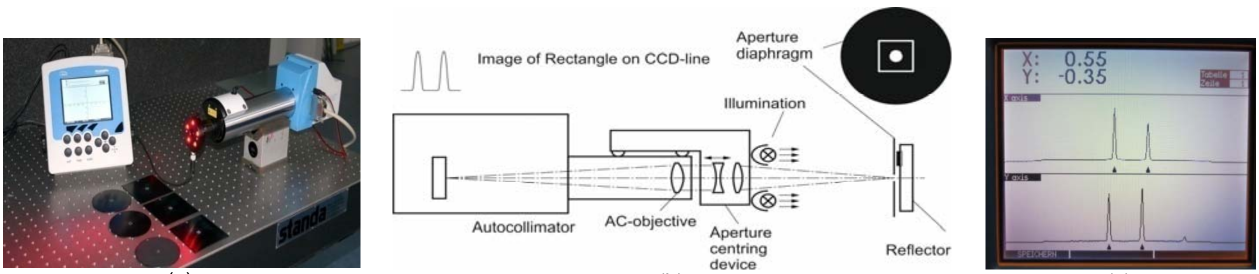
A novel aperture centring device, ACenD (with reproducibility < 0.1 mm) was developed, for the first time, for efficient use of autocollimators in deflectometric profilometry. This was indeed a challenging job and in fact it had been tried several times before the project but no success had been achieved.

MWO created an Aperture Centring Device (ACenD) which can be attached to their Elcomat 3000 series of autocollimators (**Figure 15**). MWO has applied a utility model and also submitted a European patent for this device through the patenting process. PTB initiated and coordinated its experimental testing according to developed procedure in the project. PTB, TUBITAK, IPQ, GUM, CEM, and VTT used the ACenD to perform autocollimator calibrations at a fixed distance (500 mm) between the autocollimator and the reflector at an aperture of 2.5 mm. Each participant performed repeat calibrations between which the set-up was disassembled and reassembled. **Figure 16(a)** shows the set-up in TUBITAK. PTB analysed the data with respect to the reproducibility of the calibrations within each participant's data set and differences of the average calibrations between participants by use of E_N criteria. It can be verified that the ACenD is capable of achieving a reproducible aperture alignment < 0.1 mm (the targeted value). The device produced significant improvement when compared to available laser target devices.

- positioning of aperture was improved better by a factor of 10 (deviation in repeat tests 0.02 mm, much better than the targeted value of 0.1 mm)
- standard uncertainty of autocollimator calibration was reduced by a factor of 3 (standard uncertainty 0.0046" in repeated calibration of autocollimators was achieved when ACenD is used)

More importantly, ACenD provided a 'measurable, documentable, transferable aperture positioning' facility which did not previously exist.

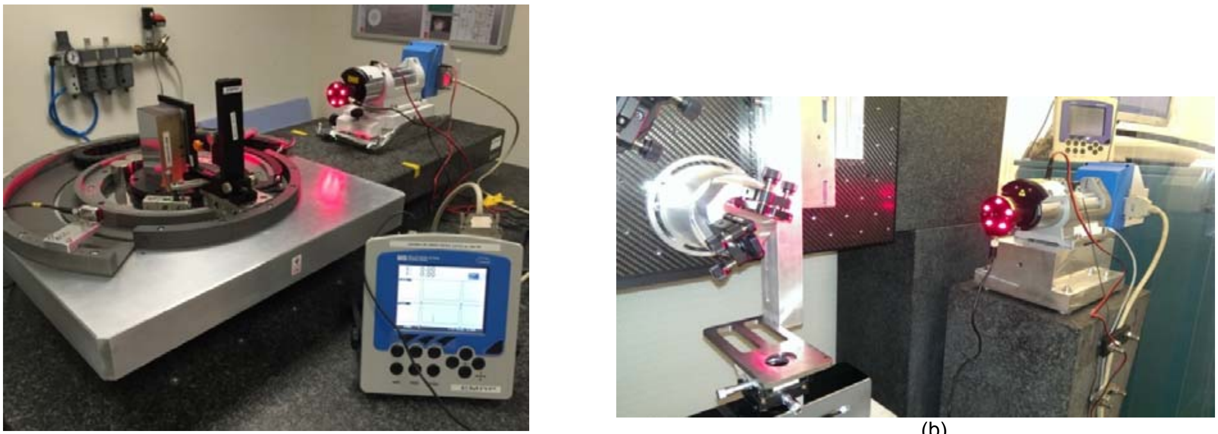
It should also be noted here that correction of autocollimator errors due to pressure variations in the environment was first applied to repeated results by PTB in order to determine the performance of ACenD more precisely.



(a) (b) (c)

Figure 15. A novel aperture centring device (ACenD) by MWO (a) Parts of ACenD (b) working principle (c) monitoring screen showing precise adjustment aperture in horizontal (X) and vertical (Y) direction with a resolution of 0.01 mm.

REG(HZB) applied the ACenD in an profilometer for the first time in the world (**Figure 16(b)**). The ACenD is now available by MWO as a commercial product. This success advances traceable angle metrology with autocollimators as their angle response depends sensitively on their measuring conditions, including the aperture's position. The device will be of use to precision engineering in general and especially to users of autocollimators in deflectometric profilometers for the precise form measurement and the fabrication of future optical surfaces, such as NMIs, synchrotron and FEL metrology labs. It was reported by MWO that six units of this device were sold at the time this report was prepared.



(a) (b)

Figure 16. Evaluation of Aperture Centring Device (a) Testing of ACenD during calibration of an autocollimator in TUBITAK (b) Testing of ACenD in slope measuring profilometer by HZB

3.2.3 *Summary*

Investigations were performed on new generation autocollimators which are specially designed for high precision profilometers. Also the influence of the locally changing curvature of the surface under test on the angle response of autocollimators was characterised. A report which addresses the influences of the reflectivity and curvature of optical surfaces on the angle response of autocollimators from an experimental point of view (by means of extended autocollimator calibrations) and a theoretical one (by raytrace modelling) was created. It was found that autocollimators show different behaviours (even individual exemplars of the same type). In this case, ray tracing simulations are not sufficient as stray light influences cannot be modelled adequately. These investigations are important for reaching fundamental metrological limits in the autocollimator-based form measurement of curved optics (e.g., beam-shaping optics for synchrotrons and FEL applications). A novel aperture centring device, ACenD (with reproducibility < 0.1 mm) was developed for the first time for efficient use of autocollimators in deflectometric profilometry. Further progress has been achieved with respect to the precise centring of small apertures when used with autocollimators. It was verified that the ACenD is capable of achieving a reproducible aperture alignment < 0.1 mm (the targeted value). The device demonstrated significant improvements when compared to available laser target devices. e.g. better standard uncertainty of autocollimator calibration by a factor of three in repeated set-ups. More importantly, ACenD provided a 'measurable, documentable, transferable aperture positioning' facility which did not exist before. It should also be noted here that correction of autocollimator errors due to pressure variations in the environment was first applied to repeated results by PTB in order to determine the performance of ACenD more precisely. As a result of these activities, the device is now available as a commercial product from MWO and is expected to provide solutions for form measurement and then fabrication of future synchrotron optics. All the scientific and technical objectives were achieved.

3.3 Precise angle encoders

In order to provide traceability during investigations and enhancement of autocollimators' performance under extremely challenging measuring conditions (e.g. use of autocollimators in profilometry with small apertures at varying measurement beam path for form measurement of curved optical surfaces with 50 nrad rms precision) small angle measurements are required at very low uncertainty values, e.g. less than 0.01" (50 nrad) with k=2. Precise angle encoders fitted to the high precision rotary tables (RTs) are utilised for small angle generation as well as large angle generations. Angle encoders are also essential components of a wide range of rotating precision devices, such as industrial robots in manufacturing or under UHV-condition for high resolution synchrotron radiation monochromators. Their angle deviations need to be calibrated by comparing encoders with the reference encoders provided by e.g. NMIs. For industrial applications, however, fast and precise method for the situ calibration of encoders is preferable. During the project, first a review of the state of the art of angle encoder application, performance, and calibration has been prepared and can be accessed via the project website. Later the above mentioned challenges were tackled for improvements on the performance of precise angle encoders by focusing the following topics:

- Realisation of a novel RT based on a rotating encoder using a pair of reading heads; one fixed and one moving
- Investigations on calibration of rotary tables fitted with multiple reading head angle encoder used for generation of angles using subdivision of 2π rad
- Novel methods for calibration of rotary tables (RTs) fitted with one reading head angle encoders used for generation of angles using subdivision of 2π rad
- Novel calibration methods for autocollimators by use of rotary tables fitted with angle encoders
- Investigations on practical calibration of one reading head encoders using other encoders
- New methods for better signal interpolations in angle encoders

In addition to new devices, tools, novel methods and research papers, the extensive investigations completed for calibration of angle encoders and autocollimators produced two EURAMET calibration guides and also recommendations to DG3 CCL Discussion Group in Angle standards under Consultative Committee for Length (DG3 CCL) of CIPM (International Committee for Weights and Measures) for use of angle encoders in CCL-K3 intercomparisons.

3.3.1 *Realisation of a novel RT based on a rotating encoder using a pair of reading heads; one fixed and one moving*

Alternative concepts for construction of angle rotary tables to realise SI unit radian are valuable in angle metrology. A new angle reference standard called RES (also REAC) was established in INRIM reducing the non-uniformity and interpolation errors. The device applies a concept of using a pair of heads, one fixed and a second rotating with the measurement drum (**Figure 17**). The angle measurement is based on the phase difference between the fixed head signal (used as a reference) and the rotating head. The phase measurement is intrinsically free from nonlinearities and the encoder errors are cancelled by the average made each complete revolution of the encoder. With this concept, it became possible to produce small angles free from interpolation error which is one of the most important errors that affect the use of angle encoders in precise angle metrology applications.

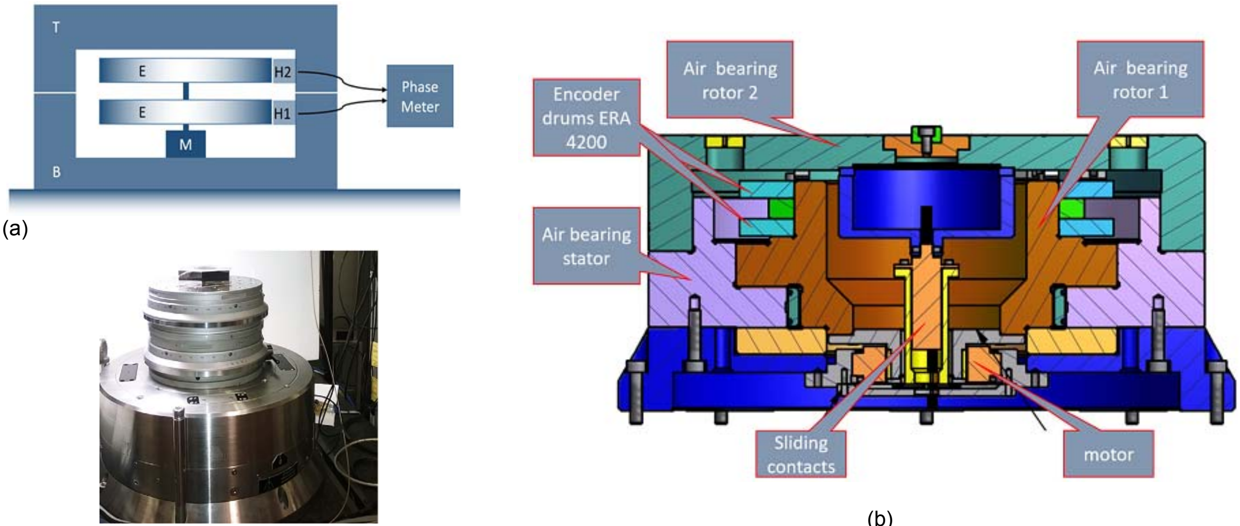


Figure 17. A new angle reference standard called RES (also REAC) by INRIM (a) working principle (b) vertical cross section (c) photo

3.3.2 *Investigations on calibration of rotary tables fitted with multiple reading head angle encoders used for generation of angles using subdivision of 2π rad*

Multiple readings head angle encoders are becoming commercially available. They possess the advantage of applying the full closure principle during operation i.e., SI unit ‘radian’ can be realised using the subdivision of a full circle, representing an error-free natural standard: 2π rad = 360º without requiring further auxiliary devices and references.

Investigations on the calibration of rotary tables fitted with ‘multiple reading head’ angle encoders were carried out (**Figure 18**). A self-calibration method for the fast and precise in-situ calibration of multiple head angle encoders without recourse to external reference standards has been developed in PTB. The method relies on a suitable geometric arrangement of multiple reading heads, which read out the radial grating of the angle encoder at different angular positions. The measurement differences of pairs of heads are analysed using Fourier-based algorithms to recover the graduation error of the grating. The evaluation and correction of error influences due to lateral shifts of the centre of the encoder’s grating during its rotation have been achieved and detailed results were published. Optimal reading head arrangements for the fast in-situ self-calibration of angle encoders without reference to external standards were investigated. The outcome of this work will be the use of a minimal number of reading heads for self-calibration angle encoders in cost-effective industrial applications. This was also followed by uptake activity. Vermont Photonics, US, will realise a geometrical read head arrangement which will be optimised based on the knowledge gained in this project.

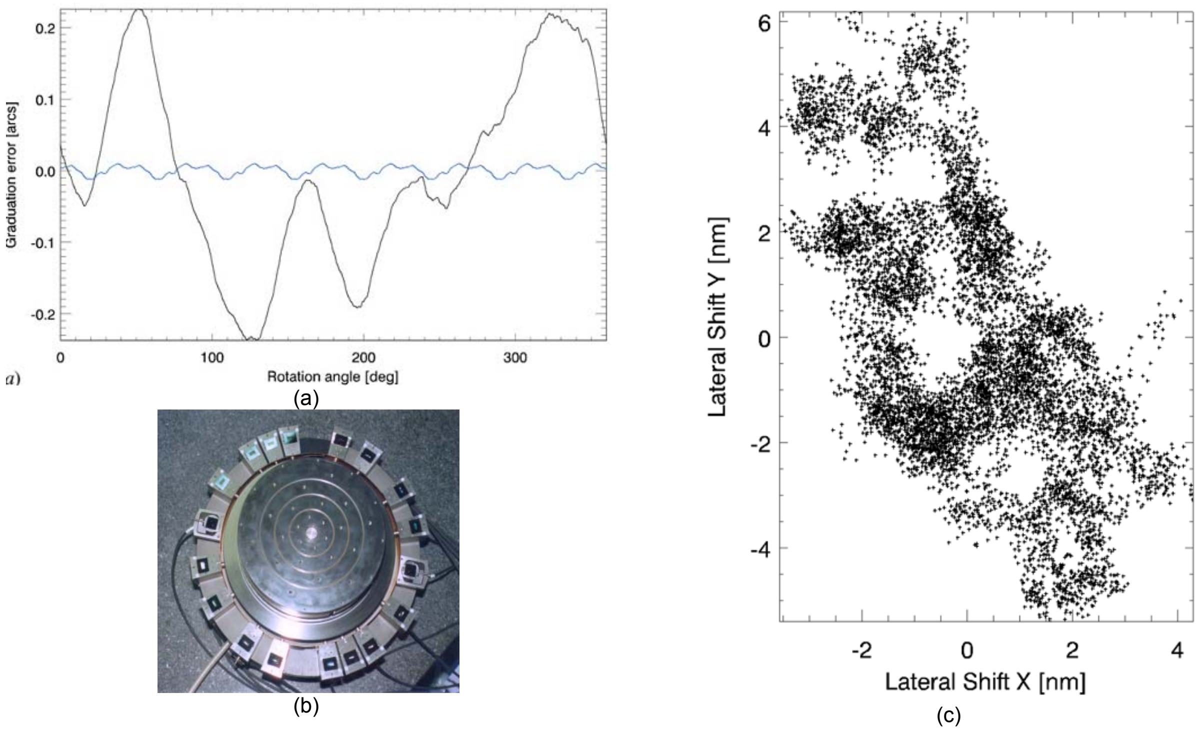


Figure 18. Investigations on calibration of rotary tables fitted with ‘multiple reading head’ angle encoders (a) Graduation errors of the encoder’s: black line -measured by a single reading head, blue line - after averaging over the eight primary reading heads (b) Photo for multiple reading head angle encoder (c) Determination of the lateral shifting of the encoder’s grating (eccentricity removed) during its rotation using angle measurement values from multiple reading heads.

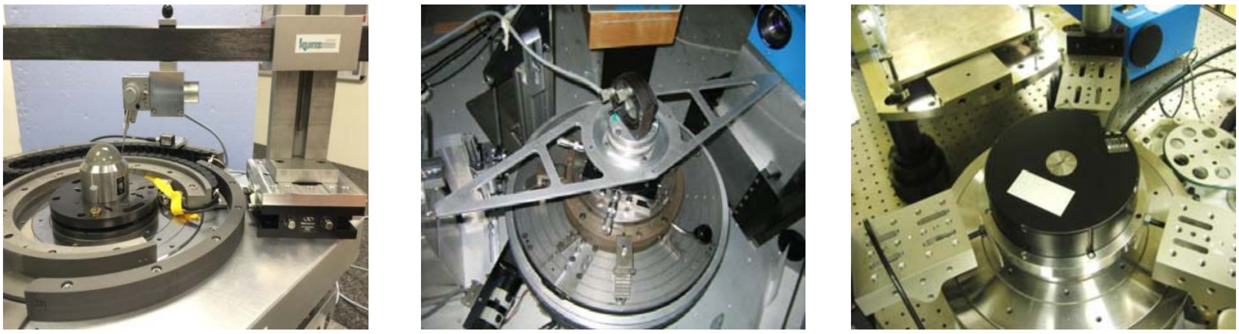
3.3.3 *Novel methods for calibration of rotary tables (RTs) fitted with one reading head angle encoder used for generation of angles using subdivision of 2π rad*

Commercial high precision angle encoders are mostly available with one reading head. Unlike multiple reading head angle encoders, acquisition of angle data from one reading head does not take into account the rotational errors e.g. forms errors of rotary table (RT) which heavily affects the performance of angle encoder. This provides difficulties for the compensation of angle errors when the SI unit radian is realised using the subdivision of a full circle and required uncertainties less than 0.01” cannot be achieved for calibration of high resolution electronic autocollimators.

Investigations on alignment/form effects for performance of angle encoders with one reading head were completed by collaborative work of TUBITAK, CEM, FAGOR, GUM, AIST and LNE. The approaches included investigation of form errors against errors of angle encoder and their effects, calibration of angle encoders using available methods but further correcting with supplementary correction data (**Figure 19(a)**), investigations in encoder calibration using another encoder with controlled and measured alignment methods using a special set developed as in **Figure 19(b)**, and investigations on calibration of encoders using self-calibration and comparison versus a second commercially available encoder taken as a standard (**Figure 19(c)**).

In conjunction, practical calibration of one reading head angle encoder using another encoder was also investigated. New tool utilising flexures and micrometer actuators was developed by IK4-TEKNIKER and FAGOR for measuring encoders on the angle comparators (e.g. Rotary Tables fitted with one reading head angle encoder).

This work provided valuable knowledge for understanding the error sources influencing the angle encoder performance and guidance for the development of future angle encoders to improve the accuracy of angle measurements.



(a) (b) (c)

Figure 19. Investigations on alignment/form effects for performance of angle encoders with one reading head (a) Set-up for investigation of form errors against errors of angle and their effects in TUBITAK (b) Investigations on encoder calibration using another encoder with controlled and measured alignment methods using special set developed by LNE (c) Investigations on calibration of encoders using self-calibration and comparison versus a second commercially available encoder taken as a standard in CEM.

3.3.4 *Novel calibration methods for autocollimators by use of rotary tables fitted with angle encoders*

Rotary tables fitted with angle encoders require prior calibration fin order to provide traceability in the autocollimator calibrations by use of various methods (e.g., self- and cross-calibration). This limits the lower uncertainty values which can be achieved in autocollimator calibration. However, it is possible to separate the errors of the autocollimator and of the angle encoder applying defined angle offsets between both systems (i.e. adapting the shearing method). In this way, simultaneous access to the angle deviations of the autocollimator and to those of the angle encoder in the rotary table is achieved and thus the uncertainty of the angle measurement with both systems is reduced.

The first adaptation of advanced error-separating shearing techniques to the precise calibration of autocollimators with angle encoders has been accomplished and demonstrated experimentally by project partners PTB, TUBITAK, INRIM, MG, CEM, LNE, AIST and IPQ. Autocollimator and angle encoder errors were separated with very small residuals demonstrating systematic error influences at a level below 2 nrad (0.0004”). This achievement is impressive and provides a solid base for improvement of the classical autocollimator calibration methods to reach substantially lower calibration uncertainties.

Two uncertainty models for the novel shearing technique were developed for the first time. One is a Monte Carlo approach by PTB and the other is analytical approach by TUBITAK giving about 0.001" (5 nrad) uncertainty level for separation of autocollimator and angle encoder errors. Compared to uncertainties reachable by conventional calibration methods for autocollimators, this represents an improvement by a factor of two to three.

Shearing techniques offer a unique opportunity to separate the errors of the test and reference measurement system and therefore are able to calibrate both systems without recourse to any external standard. During application, three sets of calibration data (obtained by applying defined angle offsets between autocollimator and the angle encoder) are taken. These three sets of data are used in the shearing algorithm providing re-constructed errors of angle encoder and autocollimator. The description of the shearing method is given in **Figure 20** illustrating the concept for determination of both device's error.

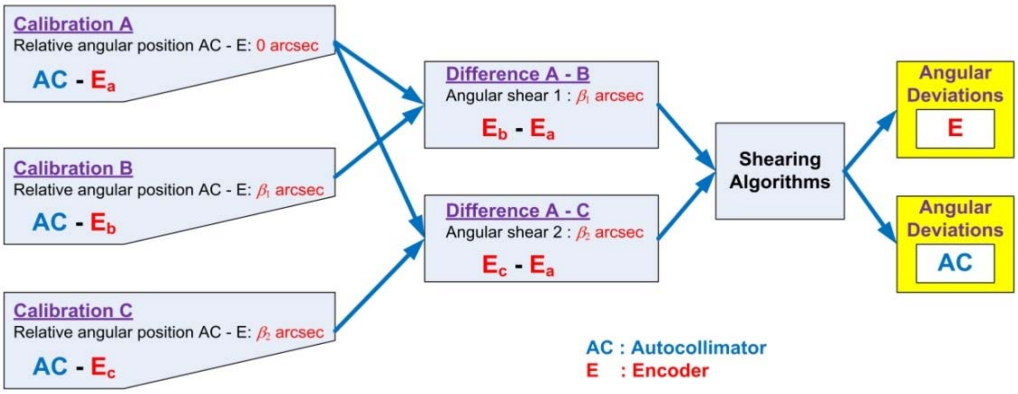


Figure 20. Schematic description of the shearing method.

Application of the shearing method requires very reproducible environment conditions and very reproducible reference angle measurement devices. Participation of a large number of project partners with various devices and environmental conditions contributed well for evaluation of shearing methods during application. Participants applying the shearing method with the equipment details are given in **Table 4**.

Table 4 Participant list and their devices used for shearing application in short.

Participant	Autocollimator	Angle Encoder	Remarks
IPQ	Elcomat HR	RON 905 by Heidenhain	Single head encoder fitted to air bearing RT (axial and radial) made by IK4-TEKNIKER
CEM	Elcomat HR	RON 905 by Heidenhain	Single head encoder fitted to air bearing RT (axial and radial) made by IK4-TEKNIKER
GUM	Elcomat HR	RON 905 by Heidenhain	Single head encoder fitted to air bearing RT (axial and radial) made by KUGLER
INRIM	Elcomat 3000	ERA 4200 by Heidenhain	Double air bearing RT by INRIM
LNE	Elcomat HR	RON 905 by Heidenhain	Double encoder system (2 * RON905) multiple reading heads
AIST	Elcomat 3000	X-1M	Multiple head encoder fitted to air bearing RT (axial and radial) made by AIST-NMIJ
TUBITAK	Elcomat HR and Elcomat 3000	ERP 880 by Heidenhain	Single head encoder fitted to air bearing RT (axial and radial vacuum air bearings) made by KUNZ
PTB	Elcomat HR	WMT 220	Multiple head encoder fitted to air bearing contactless electromagnetic tangential drive system by Heidenhain

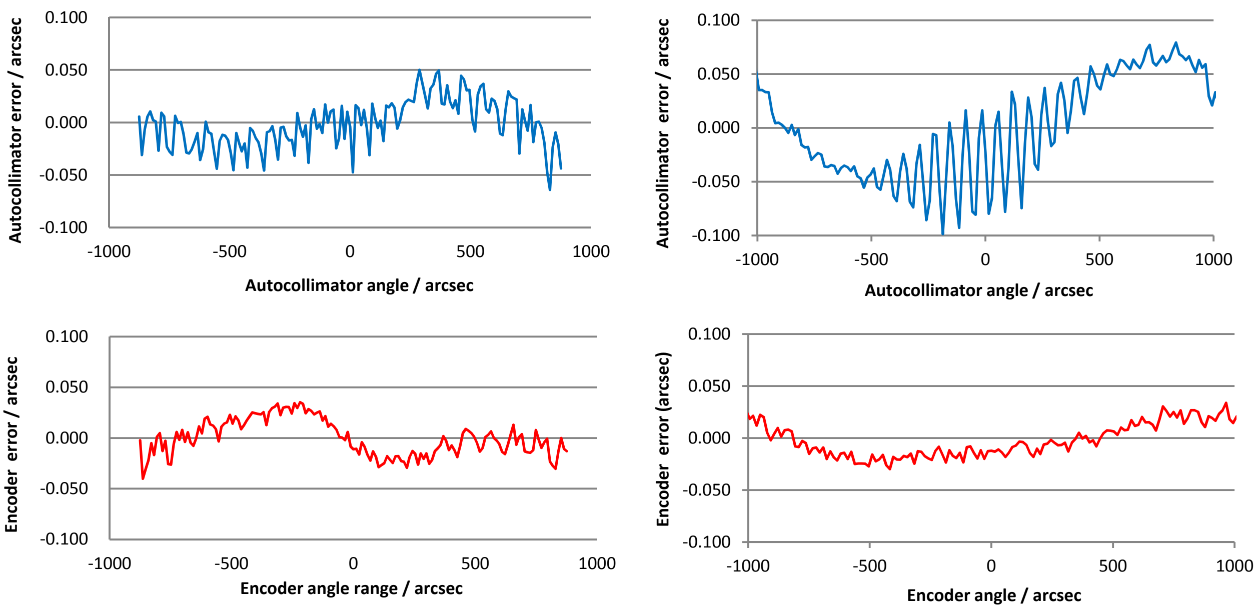
Figure 21 illustrates the results of AIST and TUBITAK for investigation of their angle encoder-rotary table using the shearing method. The aim was to evaluate the performance of the angle encoder in the large range for calibration of autocollimators particularly considering the other error sources than interpolation errors. For

this, sampling points were selected as multiples steps of basic encoder resolution to minimise errors due to interpolation. In this way, encoder errors other than interpolation causes were investigated. Separated errors of angle encoder and autocollimator from the test results are seen on the graphs of **Figure 21**.

Figure 22 illustrates the investigations of high resolution autocollimator errors using shearing methods in PTB. Error sources of the autocollimator are clearly seen. There are various error influences on the angle measurement with autocollimators. At small angular scales, nonlinearities in their angle response are predominant, such as interpolation errors that stem from the subdivision of the intervals between the pixels of the CCD detector by software algorithms in the autocollimator's electronics. This interpolation is necessary to determine the shift of the image of a reticle on the detector, and therefore the associated angle, with sub-pixel resolution. Another error source are internal reflections which depend on the AC's internal makeup and the properties of the reflector. Since their amplitude is usually small but significant at the level of nrad accuracy, more precise methods such as shearing methods are required for their evaluation.

These investigation will help to understand error sources e.g. in the scientific experiments, such as the improved determination of the constant of gravitation *G* that heavily depends on the precise measurement of angular deflections with autocollimators. For example, the angle measurement in this experiment is one of the principle uncertainty sources and uncertainty of the angular value of 0.0015" has contributed about 47 ppm to the standard uncertainty of 56 ppm (for the determination of *G* by the Cavendish method).

Investigations for the calibration of autocollimators using novel methods were used for drafting of EURAMET Calibration guide: Calibration of autocollimators (EURAMET Calibration Guide 22).



(a) (b)

Figure 21. Investigations using the shearing method for performance of angle encoders with associated rotary table in the large measurement range. Reconstructed (separated) errors of the autocollimator (graphs at top as blue line) and of the angle encoder (graphs at bottom as red lines) (a) results of AIST Rotary Table and (b) results of TUBITAK Rotary Table.
Note 1: Sampling points were selected as multiples steps of basic encoder resolution to minimise errors due to interpolation.
Note 2: Different angle encoders and autocollimators were used.

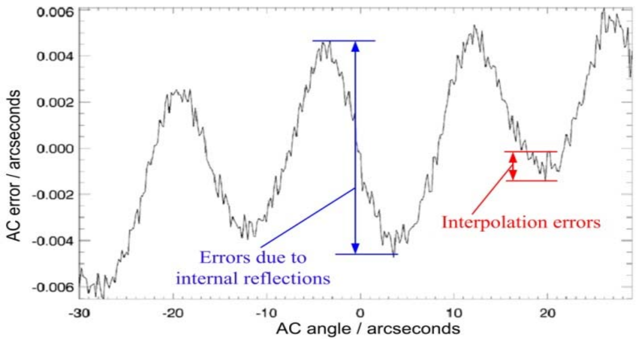


Figure 22. Measurement errors of a high resolution autocollimator (Elcomat HR) as determined by the shearing method with a standard uncertainty of 1 mas (5 nrad) in PTB.

3.3.5 *Investigations on practical calibration of one reading head encoders using other encoders*

Currently, commercial encoders are delivered with one reading head and suffer from rolling defects on their rotary guiding. Problems arise during coupling of the test encoder with a reference encoder when performing calibration by direct comparison method. In the event of non-parallelism of the measurement planes between test and reference encoder with a lateral run-out (i.e. angle between axes of rotation), systematic error effects occur. Another systematic error results in the event of eccentricity between two angle encoders during the coupling process. Effort is made to eliminate such effects performing calibrations at relative positions between test and reference encoders for instance two relative positions 180º apart or three 120º apart as recommended in VDI/VDE 2648 Part 1 (2009). However, this requires that the same metrological outlay is invested at each of the defined positions. This depends on the calibration set-up and repeatability of the same conditions, in addition to requirements for concentric and coaxial position axes of rotation, backlash effects in fixing and requirements for rigid coupling have important effects on calibration of encoders as well as influence of angular velocity and applied torque.

Influencing parameters have been studied and investigated by looking at existing literature and by performing extensive experimental characterisation and calibration of angle encoders using different set-ups. A tool was developed by IK4-TEKNIKER for setting up the test angle encoders during their calibration process with cooperation of FAGOR and CEM (**Figure 22**). The tool operates with micrometer actuators acting on flexures to correctly adjust the encoder position and different mechanical parameters (centring, displacements, etc.). Set-up is made on a rotary table of CEM (operating with an angle encoder) and several tests were performed. GUM prepared the uncertainty evaluations of the system with cooperation of CEM, LNE, FAGOR and TUBITAK.

This work on angle encoders provided valuable knowledge for understanding the error sources influencing the angle encoder performance and guidance for the development of future angle encoders to improve the accuracy of angle measurements. Investigations for calibration of angle encoders were used for drafting of EURAMET Calibration guide: Calibration of angle encoders (EURAMET Calibration Guide 23) and also for giving recommendations to DG3 CCL Discussion Group in Angle standards under Consultative Committee for Length (DG3 CCL) of CIPM (International Committee for Weights and Measures) for use of angle encoders in CCL-K3 intercomparisons.

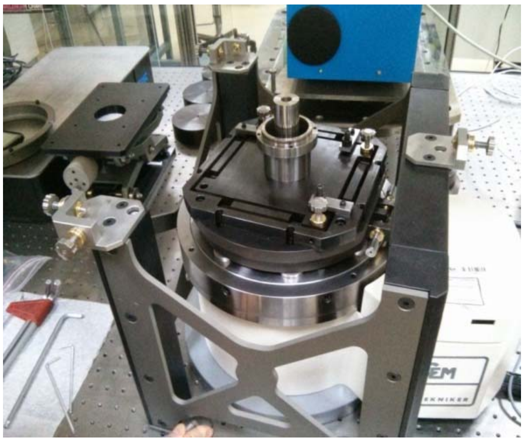



Figure 22. Photos of new tool developed by IK4-TEKNIKER and FAGOR for measuring encoders on the CEM Rotary table

3.3.6 *New methods for better signal interpolations in angle encoders*

The basic resolution of an angle encoder is determined by the number of lines around the encoder's circular disc. The signals obtained from such lines are interpolated to achieve higher resolution. During this interpolation process, systematic errors arise which are repeating themselves within every basic resolution step of the encoder. This is a typical problem of basic commercial systems resulting in angle error of 1 % of the basic resolution (e.g. a typical value for most precision angle encoders is 0.36" for 36000 lines on the encoder's circular disc). Such errors are not conducive to achieving uncertainties of the order of 0.01". Therefore, they are further compensated using signal conditioning techniques. The aim of this work is to measure interpolation errors and evaluate the performance of interpolators used in angle encoders in order to obtain better effective resolution (compared to basic resolution of grating's graduation lines).

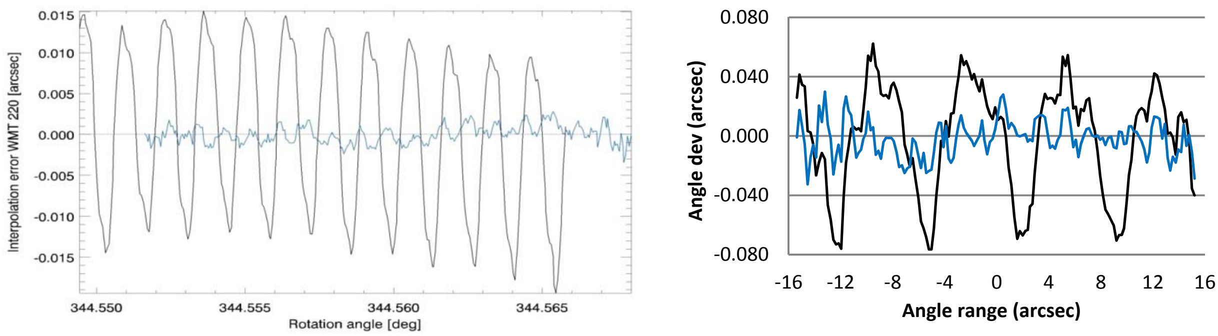
Performance of autocollimators, angle encoders and interpolators were studied without recourse to external standards using the shearing method. The work was carried out with help of various angle encoders and interpolators. TUBITAK, INRIM, MG, CEM, LNE and IPQ used angle encoders with single reading heads, PTB and AIST used angle encoders utilising multiple reading heads. Participants investigating the interpolation errors using the shearing method with the details of interpolators and devices are given in **Table 5**. PTB and TUBITAK has taken the results performed when the compensation mechanism of interpolators is on and off (**Figure 23**). The results showed that the shearing method is ideally suited for the calibration of interpolation errors of the devices at small angular scales which are difficult to characterise with other methods.

KRISS completed the development of a new type reading head for encoders. This new type reading head applies a special algorithm to reduce nonlinearity errors. KRISS tested the new reading head when applied to linear encoders.

Angle encoder interpolation error was also measured using a capacitive sensor and correction of the encoder errors was demonstrated at INRIM. Investigations for testing of interpolation errors were made at SMD using the hybrid set-up (Angle encoder in Rotary Table supported by an angular laser interferometer). Additional investigations for determination of interpolation errors were carried out in TUBITAK using an inductive probe. The outcome of these works will provide new knowledge for evaluation and improvements of the interpolators and will provide traceability with the desired uncertainty levels to tackle the challenging problems in high level scientific work.

Table 5. List of participants and details for application of shearing method during investigation of interpolation errors.

Remarks	IPQ	CEM	GUM	INRIM	LNE	AIST	TUBITAK	PTB
Number of data sets	1	1	3	1	1	3	5	1
Number of encoder reading heads	Single	Single	Single	Multiple (rotating encoder)	Multiple (4 by encoder)	Multiple	Single	Multiple (Eight)
Encoder name	RON905	RON905	RON905	REAC (rotating ERA 4200)	RON905	X-1M	ERP 880	WMT 220
Signal periods per revolution	36000	36000	36000	40000	36000	225000	180 000	262144
Basic resolution (before interpolation)	36"	36"	36"	32.4"	36"	5.76"	7.2"	5"
Final resolution (after interpolation)	0.035" (after AW1024 interpolation unit)	0.035" (after AW1024 interpolation unit)	0.002"	0.01"	0.0088" (Hendeihain IK220, 12bits interpolation)	0.0014"	0.0009" (with ACS & GEMAC) 0.0018" (with EIB741)	0.0012" (per reading head)
Autocollimator to be used	Elcomat HR	Elcomat HR	Elcomat HR	Elcomat 3000	Elcomat HR	Elcomat HR or Elcomat 3000	Elcomat HR and Elcomat 3000	Elcomat HR
Angular Measurement Range for shearing method application in determination of interpolation error	59"	246"	186" 195" 195"	186"	50"	14" 30.4" 1751"	14" (by HR) 30.4" (by HR) 2016" (by E3000) 2188.8" (by E3000) 100.8" (by HR)	59"
Shear numbers: s_1 & s_2 ($n=s_1*s_2$)	8, 37 (296)	17, 29 (493)	11, 17 (187) 17, 23 (391) 17, 23 (391)	11, 17 (187)	9, 11 (99)	3,5 (15) 9, 17 (153) 9, 17 (153)	3, 5 (15) 9, 17 (153) 3, 5 (15) 9, 17 (153) 3, 5 (15)	8, 37 (296)
Interval (Δ)	0.2"	0.5"	1" 0.5" 0.5"	1"	0.5"	1" 0.2" 11.5"	1" 0.2" 144" 14.4" 7.2"	0.2"
Any interpolation compensation	No compensation at the moment. Performance of current interpolator will be checked.	No compensation at the moment. Performance of current interpolator will be checked.	No compensation at the moment. Performance of current interpolator will be checked.	No compensation (rotating encoder)	Yes with Heidenhain soft tools	With and without compensation of interpolation errors of Primary system	Data taken without compensation (ACS) and with compensation (GEMAC & EIB741) simultaneously	With and without compensation of interpolation errors of WMT 220
Remarks for the RT	Air bearing RT - axial and radial	Air bearing RT - axial and radial	Air bearing RT – radial and axial	Double Air bearing RT	Double encoder system (2 x RON905)	Air bearing RT – radial and axial	Air bearing RT - axial and radial (vacuum air bearings)	Air bearing Contactless electromagnetic tangential drive system



(a) (b)

Figure 23. Measurement of interpolation error of angle encoder using shearing method: (a) Residual interpolation error of the WMT 220 with error correction on (blue) / off (black) in PTB (b) Interpolation error of the TUBITAK RT with regular interpolator (black) / with advanced interpolator employing compensation (blue).

3.3.7 *Summary*

The accuracy of angle measurements was significantly improved by performing investigations on various independent angle measurement methods and various angle measuring devices. Using the novel shearing methods, state of the art uncertainties down to 0.001" (5 nrad) were achieved. This is improvement by a factor of three when compared to uncertainties reachable by conventional calibration methods. Performance of autocollimators, angle encoders and interpolators were studied without recourse to external standards using the shearing method. The results showed that the shearing method is ideally suited for the calibration of interpolation errors of the devices at small angular scales which are difficult to characterise with other methods. A new type of reading head for encoders was developed in KRISS. This new type of reading head applies a special algorithm to reduce nonlinearity errors. The outcome of these works will provide new knowledge for evaluation and improvement of the interpolators and will provide traceability with the desired uncertainty levels to tackle the challenging problems in high level scientific work where angle measuring instruments are used (e.g. use of autocollimators for determination of the constant of gravitation *G*). A new angle reference standard called RES (also REAC) was established in INRIM reducing non-uniformity and interpolation errors. A self-calibration method for the fast and precise in-situ calibration of multiple head angle encoders without recourse to external reference standards was created at PTB, together with a mathematical framework for the optimal in-situ self-calibration of angle encoders (particularly in cost-effective industrial applications). Investigations on alignment-form effects for performance of angle encoders with one reading head were completed by TUBITAK, CEM, FAGOR AUTOMATION, GUM, AIST and LNE. Accurate facilities for the calibration of angle encoders were established. New tools utilising flexures and micrometer actuators were developed for calibrating angle encoders on the Rotary Tables (RTs). Guidelines for the calibration of autocollimators and also for calibration of angle encoders were prepared and submitted for publication. Guide for autocollimators was already published as EURAMET Guide 22. All the scientific and technical objectives were achieved.

3.4 Small angle generators and hybrid devices

Angle measurement-generation, and the control of angle tilting units at the nanoradian uncertainty level are essential to numerous applications ranging from scientific experiments to industrial and space applications e.g. to monitor the angles of telescope mirrors in astrometry. Small angle generators (SAGs) and hybrid devices (SAGs with angle encoders) are widely used in nanoradian angle metrology applications in addition to calibration of autocollimators. There is a demand to improve the application of small angle generating devices for dissemination of the SI unit 'radian' realised as 'ratio of two lengths' to achieve required uncertainties better than 0.01” (50 nrad).

Extensive research work and new developments for improvement of small angle generators and hybrid devices were performed in order to provide generated small angles for extremely challenging values such as nanoradian (nrad) uncertainty and sub-nanoradian sensitivity. A review of the state of the art of Small Angle Generators and Hybrid’s application, performance, and calibration has been prepared in the project and can be accessed via the project website. Investigations on nanoradian uncertainty and sub-nanoradian sensitivity angle generation and measurements using small angle generators were carried out by targeting to following topics:

- High precision small angle generation at the nanoradian and sub-nanoradian level
- Development of portable and cost effective small angle generators in the range of ±3600” with an uncertainty better than 0.01”
- Novel calibration methods for autocollimators using small angle generators
- Hybrid angle calibrators (angular interferometer-encoder)

3.4.1 *High precision small angle generation at the nanoradian and sub-nanoradian level*

Extensive experimental investigations on small angle generation at the nanoradian and sub-nanoradian level were carried out. The first angle measurements in steps of 1 nrad (0.0002”) were achieved in TUBITAK.

Differential Fabry-Perot Interferometer (DFPI) of TUBITAK was applied to detection of very small angles (currently 1 nrad steps using available TUBITAK High Precision Angle Generator - HPSAG) utilising the frequency stabilised lasers as an alternative and outperforming method to conventional angle interferometers. Use of DFPI provided displacement measurements with picometre sensitivity free from linearity errors i.e. provided frequency based angle measurements. Experimental results showed first time that TUBITAK’s High Precision Angle Generator can produce 1 nrad angular steps and it is possible to achieve sub-nrad sensitivity angle measurements (**Figure 24**). It is expected that the knowledge generated will be of benefit to the synchrotron & FEL community, gamma ray spectroscopy applications, fundamental physics, scientific space missions as well as NMIs and angle measurement device manufacturers.

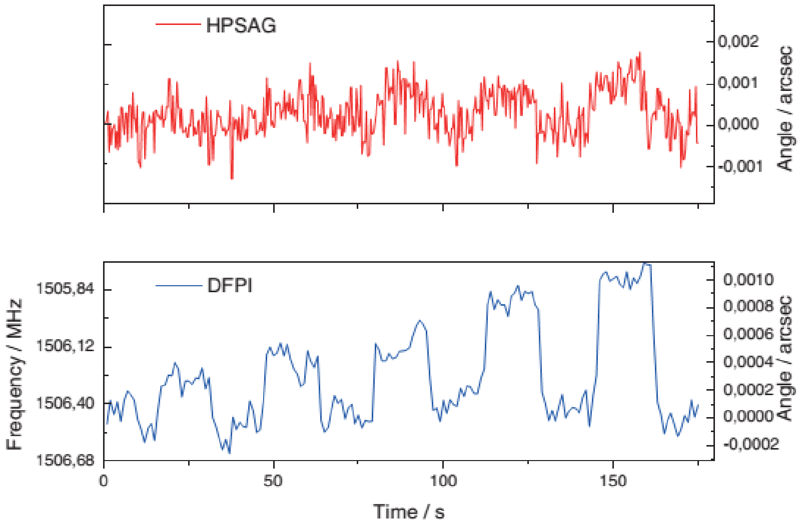


Figure 24. Ultra small angle generation and measurements by DFPI: Comparison of readings taken from the HPSAG and the DFPI with steps of 0.0002" (1 nrad) demonstrating that the HPSAG has a higher step resolution than the raw data implies.

Demands for nanoradian angle metrology motivated us to investigate the autocollimators in detail and to evaluate their capability of achieving angle metrology at the nrad and sub-nrad level. TUBITAK and INRIM used their small angle generators to calibrate autocollimators in small angular steps such as 0.1" and 0.01" while PTB used their rotary table equipped with special angle encoder.

TUBITAK and PTB performed investigations on the capability of electronic autocollimators using various reference devices and newly developed methods within the project. They calibrated high resolution electronic autocollimators in small angular steps such as 0.01" and even further by TUBITAK at 0.001" (5 nrad, at resolution level of the autocollimators). Investigations were also carried out over larger measurement ranges and angular steps with uncertainties down to 0.001" (5 nrad). The performance tests of autocollimators in a short measurement range are illustrated in **Figure 25** and **26**. **Figure 25** shows the results by TUBITAK and PTB for the same autocollimator in a 1 year period of time. TUBITAK also calibrated the same AC by their large range small angle generator (LRSAG developed in the project) in the steps 0.001" (5 nrad) to evaluate its performance with angular increments corresponding to autocollimator resolution (**Figure 26**). The test results provided significant information about the performance of the autocollimators for nanoradian angle metrology.

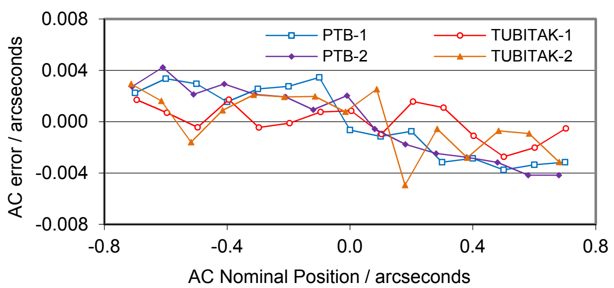


Figure 25. Results of the calibration of an autocollimator (Elcomat 3000) in steps of 0.1" : TUBITAK-1 by use of the LRSAG reference standard, TUBITAK-2 by use of the HPSAG, and PTB-1 and PTB-2 by use of the WMT 220.

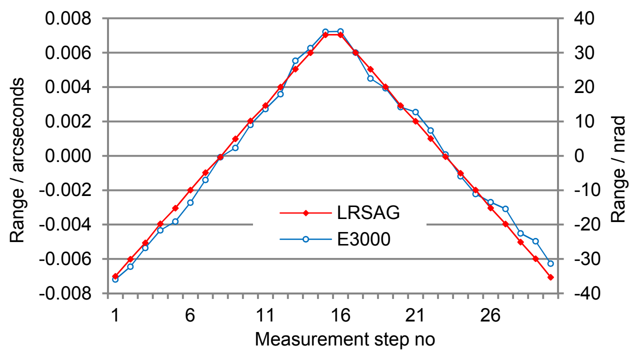


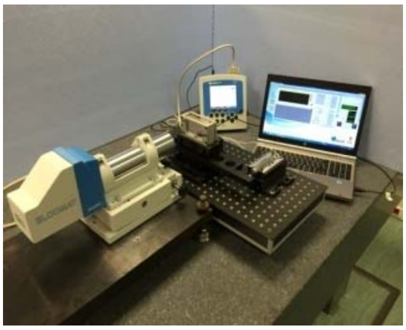
Figure 26. Direct comparison of the angle readings of an autocollimator (Elcomat 3000) and the LRSAG in steps of 0.001" (5 nrad) by TUBITAK UME

3.4.2 *Development of portable and cost effective small angle generators in the range of ±3600” with an uncertainty better than 0.01”*

Autocollimators must be calibrated (sometimes on-site) to detect and correct any systematic error and determine the uncertainty associated to their readings, making their measurements traceable to the SI angle unit radian. Most metrology departments in SR and FEL centres are seeking solutions to obtain traceability for SI angle unit radian with low uncertainties and high resolution not only for the regular checks but also for investigations on the performance of the autocollimators when used in different conditions than the calibrations such as with varying distance to the reflector and different aperture sizes etc. The specific needs of the end users have been determined in detail for calibration of autocollimators used in challenging conditions and a report was created by TUBITAK and REG(HZB) with cooperation of stakeholders e.g. synchrotron community in the project. The report states that there is a need for an on-site calibration tool having the ability to calibrate autocollimators in the expanded uncertainty of better than 50 nrad (0.01”) in the range of ± 10” (±5 μrad) and expanded uncertainty of 0.04” (0.2 μrad) in the ranges of ± 1031” (±5 mrad) for currently available autocollimators and of ± 4125” (± 20 mrad) for future autocollimators.

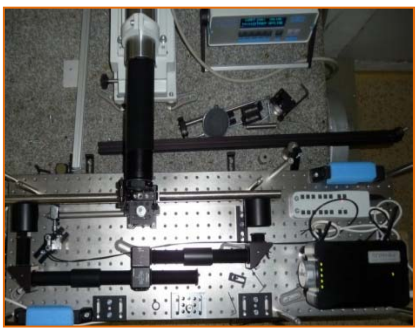
In order to tackle these demands, 3 different novel large range small angle generators (**Figure 27**) were developed by TUBITAK, IK4-TEKNIKER & CEM and CMI for calibration of autocollimators in addition to angle interferometers based on displacement interferometry by CMI and a Fizeau angle interferometer (FAI) by INRIM. The measurement repeatability for the device of CMI was better than 0.01”, for the device of IK4-TEKNIKER & CEM was about 0.018" and of TUBITAK was 0.005". CMI has used the new system for additional measurements in EURAMET.L-K3.2009 comparison measurements with the expanded uncertainty of 0.02". Nevertheless, the main part of the uncertainty is due to the autocollimator that was used as a transfer standard in this comparison. The precision of LRSAG was tested and is better than 0.01". The test results of TUBITAK showed that the error of the system is less than 0.01" for the largest autocollimator range (2300") (**Figure 28 and 29**). The device is ready to be tested for on-site calibration of autocollimators. The autocollimators were tested in very small angular steps by TUBITAK using the newly developed Large Range Small Angle Generator-1 (LRSAG-1). The smallest angular step was used as 0.001" (5 nrad), the resolution of the current state of the art autocollimators (**See Figure 26**). The test results provided significant information about the performance of the autocollimators for nanoradian angle metrology.

During development of these devices, high level cooperative work between the participants existed. An Aangle scale (based on angular interferometer) for the device developed by IK4-TEKNIKER & CEM was made and delivered by CMI. PTB analysed TUBITAK's autocollimator by performing extensive calibration in various conditions such as large and small ranges in various sampling steps. **Figure 27** shows the photo of three large range small angle generators. **Figure 28** and **29** illustrates the evaluation results of the large range small angle generator of TUBITAK when compared to PTB results and the Rotary Table (RT) of TUBITAK. Correlation between results after delivery to TUBITAK taken by the RT and LRSAG of TUBITAK with respect to PTB results taken before transportation (on far end of negative axis) shows a kind of systematic error occurred during transportation. This also proves the importance of on-site calibration of autocollimators if the end user are seeking very precise measurements at the level of nanoradian.



LRSAG-1
by TUBITAK

LRSAG-2
by IK4-TEKNIKER and CEM



LRSAG-3
by CMI

Figure 27. Three novel large range small angle generators (LRSAGs) developed in the project

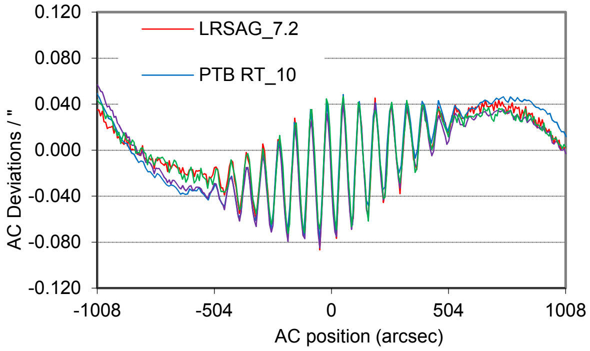


Figure 28. Calibration results of E3000 by PTB's RT at 7.2” and 10” (2014),TUBITAK RT at 7.2” (2015), and LRSAG at 7.2” (2016)

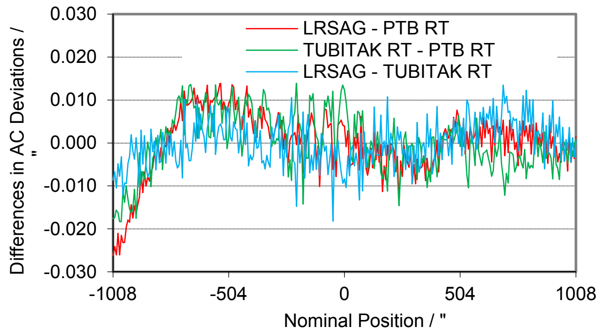


Figure 29. Differences in results of E3000: PTB RT (2014), TUBITAK RT (2015), and LRSAG (2016) with U: 0.015”, 0.035”, 0.01” respectively

The portable LRSAG of TUBITAK (LRSAG-1) was also investigated for larger measurement ranges and also for very small steps. The portable device can generate small angles in measurement steps of 0.0005" (2.5 nrad) and can operate in the range of more than ±4500" which is largeenough for the calibration of the available autocollimators. The device performs well and can be used to investigate autocollimators in detail and to evaluate their capability of achieving angle metrology at the nanoradian level. It is a good candidate for application to on-site/in-situ calibration of autocollimators with expanded uncertainties of 0.01" particularly those used in deflectometry (angle-based surface measuring profilers). The further work after the project will be in-situ calibration of the autocollimator used in the profilometer of REG(HZB) in Berlin. The results also showed that the LRSAG can be used for investigation of angle measurement devices by generating very precise ultra-small angles down to 0.001" (5 nrad).

3.4.3 *Novel calibration methods for ACs using SAGs*

The aim of this work is to investigate error sources of Small Angle Generators (SAGs) more precisely utilising advanced error-separating shearing techniques for calibration of precise autocollimators. Angular scales of SAGs are usually based on linear measurement systems such as laser interferometer or capacitive nanosensor output. Therefore, SAGs will show different systematic errors than angle encoders during investigations using shearing techniques.

Shearing techniques were applied to small angle generators (HPSAG of TUBITAK) for the first time and the results illustrate that standard uncertainty value of 1.38 mas (6.7 nrad) was achieved for calibration of autocollimators by SAGs representing a substantial improvement by a factor of 3-4 compared to previous uncertainty values. Further, it was also proved that shearing method is very powerful for investigation of angle measuring systems since error separation of both measurements devices with state of the art uncertainties is possible as well as investigation/characterisation of the error sources which affect the calibration results such as errors caused by environment conditions. Investigations for TUBITAK’s HPSAG using the shearing technique are illustrated in **Figure 30**. The results showed that shearing methods will definitely provide solutions for challenging applications at the forefront of angle metrology.

Additionally, the LRSAG of TUBITAK described in section 3.4.2 was also investigated by applying the shearing method. Measurement range of the LRSAG up to ±4500" was tested using the shearing method by comparing to the ±1000" measurement scale of the autocollimator with stitching process. By removing the error of the autocollimator, precise evaluation of the LRSAG was achieved.

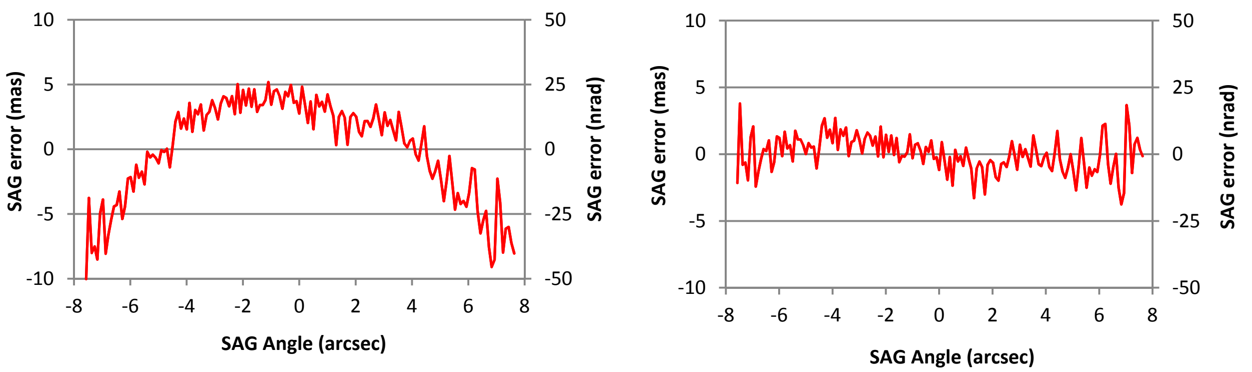


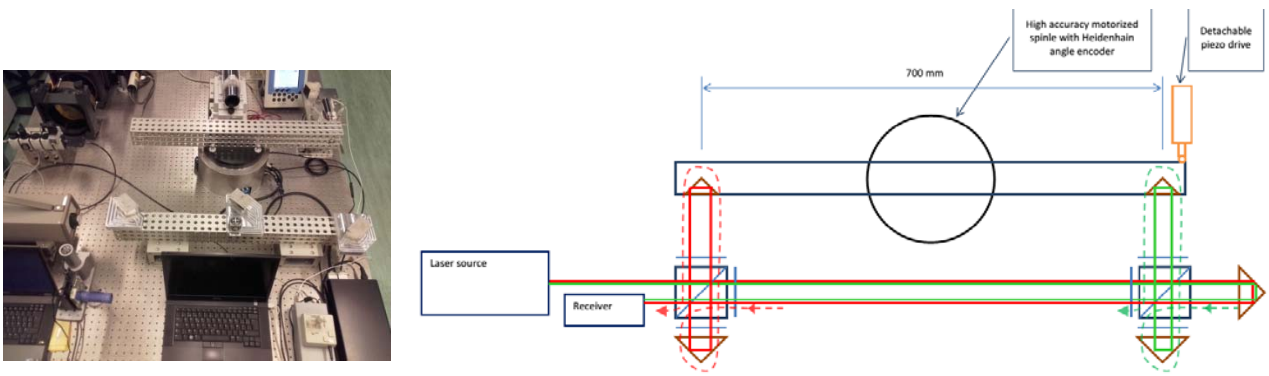
Figure 30. Investigations for error sources of small angle generators using the shearing technique (a) Errors of TUBITAK HPSAG in 3.5 hours measurement (b) Errors after thermal drift corrections and re-analysing the data sets using shearing technique.

3.4.4 *Hybrid angle calibrators (angular interferometer-encoder)*

Hybrid angle calibrators may be considered as a combination of angle encoders and small angle generators. The aim for using such an arrangement is to utilise superior parts of each angle measurement system. Systematic errors of an angle encoder fitted on the Rotary Table (RT) were checked by an angular interferometer and corrected. Special attention will be paid to the development of a good method for the calibration of the encoder over a full circle with the angular interferometer. Difficulties arise particularly in alignment problems for instance, parallelism of laser beams, perpendicular to rotation axis of the RT, errors in optical components used in the angular interferometer as well as interpolation error of the laser interferometer.

Error sources of hybrid angle calibrators based on the integration of rotary tables fitted with an angle encoder and angular interferometer for generation of small angles were investigated by SMD. The target uncertainty is from u ≤ 0.001" for angles up to 1 degree till u ≤ 0.005" for angles up to10 degrees. This was a very challenging value and suffered from several problems such as thermal drift, noise, unstability due to thermal gradients in the air and variations in the refractive index of air

A method has been developed by SMD to link angle measurements with laser interferometer to angle measurements with a calibrated 360° encoder by calibrating the full circle of the encoder with limited ranges of the laser angle interferometer (see **Figure 31**). The associated uncertainty budget has been studied in detail and the indications have been reported on how to evaluate and measure most of the alignment errors. These measurement techniques can also be used for the optimisation of the alignments. Advice has also been given on how to handle best the asymmetric contributions from cosine errors in the report. This analysis is the input for the GUM classical approach and for the Monte Carlo approach. Since asymmetric contributions are better handled by Monte Carlo it was advised to prefer Monte Carlo, which will give more correct (and smaller) uncertainty results.



(a) (b)

Figure 31. Novel Hybrid device set-up in SMD (a) Photo of the set-up (b) Optical arrangement

LNE have characterised two different commercial hybrid systems with their rotary table. Both of them are hybrid systems from Renishaw. These hybrid systems consist of an indexing/rotary table and a small angle measurement system based on an angular laser interferometer. One is the RX10 model based on indexing table and the other XR20 models based on the Rotary table - angle encoder. LNE tested both systems and produced data sets. **Figure 32** illustrates the set-up and investigation results taken for the RX10 model.

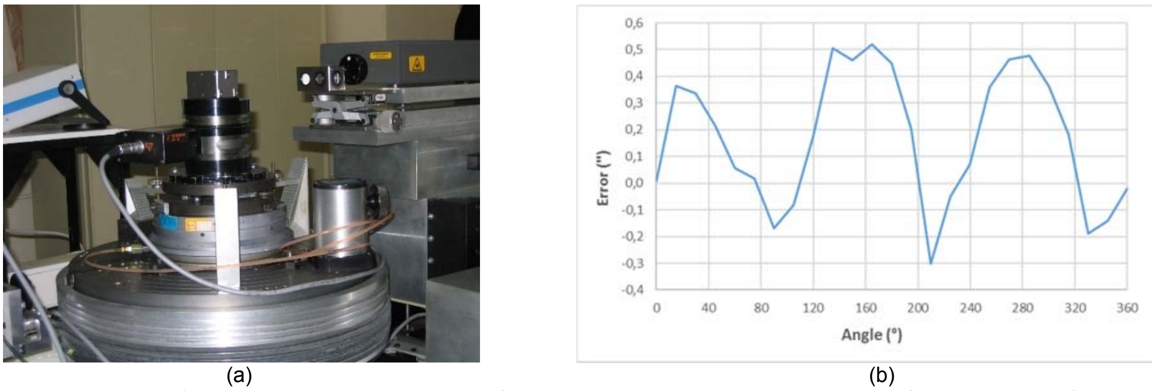


Figure 32. Investigation of hybrid devices in LNE (a) RX10 Calibration setup with angular optics kit (b) Calibration result for 0-360°

3.4.5 *Summary*

Three portable and cost effective small angle generators (LRSAGs) were produced by TUBITAK, CMI and IK4 TEKNIKER & CEM to answer the demands of SR and FEL centers for on-site/in-situ calibration of autocollimators. The objective was to achieve a calibration range of about 3600" (17 mrad) and expanded uncertainty of less than 0.01" (50 nrad). All developed devices can operate in the calibration range of 3600" (17 mrad). Their performance was individually tested for achievable uncertainty. The results showed that the LRSAG by TUBITAK can perform autocollimator calibration with the expanded uncertainty of 0.009" (44 nrad). The LRSAG of CMI was tested in EURAMET.L-K3.2009 comparison measurements with the expanded uncertainty of 0.02" (100 nrad). Nevertheless, the main part of uncertainty is due to an autocollimator that was used as a transfer standard in this comparison. The precision of the LRSAG was tested and is better than 0.01". The measurement repeatability for the device of IK4-TEKNIKER & CEM was about 0.018". With this, expanded uncertainty of the TEKNIKER's device is expected to be more than 0.02" (100 nrad). Improvement is in progress. It can be concluded that all the devices fulfil the criteria for a calibration range of 3600" (17 mrad) as declared in the scientific and technical objectives. The targeted expanded uncertainty value less than 0.01" (50 nrad) was achieved at the end of the project by two of the developed LRSAGs. Additionally, the knowledge gained for achieving uncertainties less than 50 nrad will provide further improvements in the medium term after the conclusion of the project for the on-site/in-situ calibration of autocollimators.

A hybrid angle calibrator based on the integration of a rotary table fitted with an angle encoder and angular interferometer was created by SMD. The device was investigated to achieve the target uncertainty from u ≤ 0.001" for angles up to 1 degree to u ≤ 0.005" for angles up to10 degrees. Various difficulties arose and this challenging target was not achieved. The system suffered from several problems such as thermal drift, noise, unstability due to thermal gradients in the air and variations in the refractive index of air. However, valuable knowledge on hybrid angle calibrators was gained with these investigations and a method has been developed by SMD to link angle measurements with laser interferometer to angle measurements with a calibrated 360° encoder by calibrating the full circle of the encoder with limited ranges of the laser angle interferometer.

Investigations for nrad and sub-nrad level angle metrology according to demands of synchrotron beamlines at storage rings, FELs and XFELOs were carried out. The first angle measurements in steps of 1 nrad (0.0002") with sub-nrad sensitivity was achieved in TUBITAK. Additionally, the use of autocollimators in nanoradian angle measurements were investigated using different small angle generation-measurement concepts. The work showed that the autocollimators can be calibrated in steps, near to their resolution 0.001" (5 nrad), and can be used for non-contact angle measurements with uncertainties down to 1 mas (5 nrad) providing a precise calibration/investigation of these devices. These results provide significant information about the performance of the autocollimators for nanoradian angle metrology. It is expected that the knowledge generated will be of benefit to the synchrotron & FEL community, gamma ray spectroscopy applications, fundamental physics, scientific space missions as well as NMIs and angle measurement device manufacturers.

3.5 Overall results summary

The project was a unique, leading project in the field of angle metrology and worked at the highest level for the benefit of today's science community and industry regarding the practical realisation and dissemination of the SI angle unit. The project brought together competencies and capabilities of the partners in the field of angle metrology, precision engineering, Ultra Violet (UV), Vacuum Ultra Violet (VUV) and X-Ray Optics having the major, most influential and innovative members to achieve its goals.

Overall achievements can be summarised as follows:

- The SIB58 project addressed a wide range of the most pressing problems in the field of angle metrology and produced solutions for better realisation of the SI angle unit radian at the highest scientific level.
- The project focused on the most challenging demands of stakeholders (particularly for synchrotron and FEL communities where the most challenging applications exist) and developed enabling technology for the development of science and technology.
- The project developed novel methods, new instrumentation and new knowledge for improvement of angle metrology and spread such knowledge to many other users at labs, research organisations and Industry by providing useful guides and documents.

In particular, the scientific results achieved are:

- Four position reports presenting the current state of the art in angle metrology, prepared by the project consortium with contribution from the stakeholders, are available in the project website.
- The project advanced the available knowledge on distance-dependent angle measuring errors of autocollimators. Experimental results of project partners obtained at distances between the autocollimator and the reflecting surface between 90 mm to 1800 mm (mostly used by the synchrotron community) were supported by raytracing simulations which demonstrate excellent agreement. It will help autocollimator users and manufacturers to minimise measurement errors due to distance-dependent effects.
- A milestone was achieved by advancing autocollimator calibration from plane to spatial angles. Two different innovative set-ups for 2D calibrations of autocollimators to address influences of the sagittal beam deflection by the optical surface and investigations on applications of autocollimators in challenging conditions of profilometry have been accomplished. They are a Spatial Angle Autocollimator Calibrator and an interferometer-based 2D autocollimator calibration set-up. These are the first devices for the traceable realisation and dissemination of spatial angles worldwide. They greatly extend the frontiers of angle metrology, ending its former limitation to plane angles. The first spatial angle (2D) calibration of an autocollimator was achieved with these devices promising substantial information for the first time for autocollimators when used for form measurement of highly curved optical surfaces. Intercomparison measurement for 2D calibrations of autocollimators, for the first time in the world was also carried out in the project. The service for two-axis (2D) calibration of autocollimators will be available in PTB and VTT following the quality management process.
- The improvement of autocollimator performance at small apertures was achieved in the project by cooperation between PTB and MWO. PTB has developed a novel reticle design for autocollimators which markedly reduces measuring errors (i.e., interpolation errors), and submitted a patent on this innovation. Its application in commercial products is expected particularly to increase the performance autocollimators when used with small apertures (< 2.5 mm diameter) for inspection of future X-ray and EUV optics. A novel reticle design markedly reduces measuring errors. The goal has even been surpassed. Over the tested aperture range (5 mm – 50 mm), the interpolator errors fell below the threshold of detectability. Development of new generation autocollimators commercially available in the near future is expected.

- Crucial investigations for reaching fundamental metrological limits in the autocollimator-based form measurement of curved optics (e.g., beam-shaping optics for synchrotrons and FEL applications) were completed. Collaborative work between PTB and REG(HZB) based on the extensive experimental data taken using various optical surfaces with different curvature and reflectivity created a report which addresses the influences of the reflectivity and curvature of optical surfaces on the angle response of autocollimators from an experimental point of view (by means of extended autocollimator calibrations) and a theoretical one (by raytrace modelling). It was found that autocollimators show different behaviours (even individual exemplars of the same type) and ray tracing simulations are not sufficient as stray light influences cannot be modelled adequately.
- A novel aperture centring device, ACenD (with reproducibility < 0.1 mm) was developed for the first time for efficient use of autocollimators in deflectometric profilometry. Further progress has been achieved with respect to the precise centring of small apertures when used with autocollimators. The ACenD has been tested experimentally by the project partners (the first intercomparison in the world). As a result of these activities, the device has been made available as a commercial product by MWO and 6 units were already sold out. This device is expected to provide solutions for form measurement and then fabrication of future synchrotron optics.
- A new angle reference standard called RES (also REAC) was established in INRIM aiming to reduce the non-uniformity and interpolation errors.
- A self-calibration method for the fast and precise in-situ calibration of multiple head angle encoders without recourse to external reference standards was created at PTB, together with a mathematical framework for the optimal in-situ self-calibration of angle encoders. The outcome of this work will be the use of a minimal number of reading heads for self-calibration angle encoders in cost-effective industrial applications. This was also followed by uptake activity. Vermont Photonics, US, will realise a geometrical read head arrangement which will be optimised based on the knowledge gained in this project.
- Investigations on alignment/form effects for performance of angle encoders with one reading head were completed by collaborative work between TUBITAK, CEM, FAGOR, GUM, AIST and LNE. The approaches included investigation of form errors against errors of angle encoder and their effects, calibration of angle encoders using available methods but further correcting with supplementary correction data, investigations in encoder calibration using another encoder with controlled and measured alignment methods using a special set developed and investigations on calibration of encoders using self-calibration and comparison versus a second commercially available encoder taken as a standard. As a result, a good practice guide was prepared and partners obtained the ability to investigate their angle comparators to achieve better uncertainties than before (2 to 3 times).
- New tools utilising flexures and micrometer actuators were developed by IK4-TEKNIKER and FAGOR for measuring encoders on the RTs fitted with one reading head angle encoder in CEM. An experimental set-up was realised and the tests were completed.
- The first adaptation of advanced error-separating shearing techniques to the precise calibration of autocollimators with different angle encoders were completed by large number of the project partners. For separation of autocollimator and angle encoder errors, state of the art uncertainties down to 0.001" (5 nrad) were achieved providing improvement by a factor of three when compared to uncertainties reachable by conventional calibration methods.
- Performance of autocollimators, angle encoders and interpolators were studied without recourse to external standards using the shearing method. The work was carried out with help of various angle encoders and interpolators. TUBITAK, INRIM, GUM, CEM, LNE and IPQ used angle encoders with single reading head, PTB and AIST used angle encoders utilising multiple reading heads. The results showed that the shearing method is ideally suited for the calibration of interpolation errors of the devices at small angular scales which are difficult to characterise with other methods. Angle encoder interpolation error was also measured using a capacitive sensor and correction of the encoder errors was demonstrated at INRIM. Investigations for testing of interpolation errors were made at SMD using the hybrid set-up. Additional investigations for determination of interpolation errors were carried out in TUBITAK using an inductive probe. A new type of reading head applying a special algorithm to reduce

nonlinearity errors for encoders was developed. The outcome of these works will provide new knowledge for evaluation and improvements of the interpolators and will provide traceability with the desired uncertainty levels to tackle the challenging problems in high level scientific work.

- Investigations were used for drafting of 2 EURAMET Calibration guides: Calibration of autocollimators and calibration of angle encoders (EURAMET Calibration Guide 22 and 23) and also for giving recommendations to DG3 CCL Discussion Group in Angle standards under Consultative Committee for Length (DG3 CCL) of CIPM (International Committee for Weights and Measures) for use of angle encoders in CCL-K3 intercomparisons.
- Extensive experimental investigations on small angle generation at nanoradian and sub-nanoradian level were carried out. The first angle measurements in steps of 1 nrad (0.0002”) were achieved in TUBITAK. Differential Fabry-Perot Interferometer (DFPI) of TUBITAK were applied to detection of very small angles (currently 1 nrad steps using available TUBITAK High Precision Angle Generator) utilising the frequency stabilised lasers as an alternative and outperforming method to conventional angle interferometers.
- The specific needs of the end users have been determined in detail for calibration of autocollimators used in challenging conditions. In order to tackle these high demands, 3 different novel large range small angle generators working in the range of about 3600” (17 mrad) were developed by TUBITAK, IK4-TEKNIKER & CEM and CMI for calibration of autocollimators in addition to angle interferometers based on displacement interferometry by CMI and a Fizau angle interferometer (FAI) by INRIM. The measurement repeatability for the device of CMI was better than 0.01” for the device of IK4-TEKNIKER & CEM was about 0.018" and of TUBITAK was better than 0.005". CMI has used the new system for additional measurements in EURAMET L-K3 comparison measurements. The test results of TUBITAK showed that the error of the system is less than 0.01" for the largest autocollimator range (2300"). The device is ready to be tested for on-site calibration of autocollimators. The autocollimators were tested by TUBITAK using the new device in very small angular steps, e.g. 0.001" (5 nrad), the resolution of the current state of the art autocollimators. The test results provided significant information about the performance of the autocollimators for nanoradian angle metrology.
- First application of shearing techniques to small angle generators by TUBITAK illustrated that standard uncertainty value of 1.38 mas (6.7 nrad) was achieved for calibration of autocollimators representing a substantial improvement by a factor of 3-4 compared to previous uncertainty values. Further, it was also proved that the shearing method is very powerful for investigation of angle measuring systems since error separation of both measurement devices with state of the art uncertainties is possible as well as investigation/characterisation of the error sources which affect the calibration results such as errors caused by environment conditions.
- Error sources of hybrid angle calibrators based on the integration of rotary tables fitted with an angle encoder and angular interferometer for generation of small angles were investigated by SMD. A method has been developed by SMD to link angle measurements with laser interferometer to angle measurements with a calibrated 360° encoder by calibrating the full circle of the encoder with limited ranges of the laser angle interferometer. The associated uncertainty budget has been studied in detail and the indications have been reported on how to evaluate and measure most of the alignment errors. These measurement techniques can also be used for the optimisation of the alignments. LNE have characterised two different commercial hybrid systems with their rotary table. LNE tested both systems and produced data sets.

4 Actual and potential impact

4.1 Metrology achievements

The following metrology subjects were investigated in detail through extensive experimental research supported by theoretical work:

- Metrological characterisation of autocollimators
- Application of autocollimators in profilometry

- Precise angle encoders
- Small angle generators and hybrid devices

Investigations on the subjects include development of novel methods, tools, instruments, guides and new services but more importantly milestones that greatly extend the frontiers of angle metrology, ending its former limitation to plane angles. The first devices for the traceable realisation and dissemination of spatial angles worldwide have been developed and tested. The first spatial angle (2D) calibration of an autocollimator with these devices promises substantial information for the first time for autocollimators when used for form measurement of highly curved optical surfaces. Besides, the performance of the autocollimators for nanoradian angle metrology applications were investigated achieving uncertainties down to 0.001" (5 nrad). New devices, methods and references were developed for sub-nrad sensitivity angle measurements. They are described in scientific papers (see the list in section 4.2) which allows the user community to have access to the relevant knowledge.

Investigations for calibration of angle encoders were used for drafting 2 EURAMET Calibration guides: Calibration of autocollimators and calibration of angle encoders (EURAMET Calibration Guide 22 and 23) were submitted to EURAMET and approved. They will be soon available for the readers via the EURAMET website.

A report compromising recommendations to the DG3 CCL Discussion Group in Angle standards under Consultative Committee for Length (DG3 CCL) of CIPM (International Committee for Weights and Measures) was submitted for use of angle encoders in CCL-K3 intercomparisons.

Four position reports presenting the current state of the art in angle metrology, prepared by the project consortium with contribution from the stakeholders, are available in the project website.

All these publications will allow the knowledge developed during the project to be shared with other NMIs, and metrology, SR and FEL communities which require state of the art information on angle metrology.

Futher publications are in preparation on the outputs from the project’s investigations.

4.2 Dissemination activities

4.2.1 *Scientific publications*

The project has generated eighteen high impact publications in key journals, fifteen proceedings, one chapter as contribution to book and one masters thesis. These incorporate the significant scientific outputs of the project. A list is provided in section 6.

4.2.2 *Conferences and relevant fora*

The work carried out in the project has already reached both wider scientific audiences in general conferences such as euspen, Macroscale or IMEKO as well as targeted audiences in specialised conferences such as SRI 2015 - 12th International Conference on Synchrotron Radiation Instrumentation (July 6-10, 2015, New York, USA), IWXM 2015 - International Workshop on X-Ray Optics and Metrology (July 13-16, 2015, Berkeley, USA), SPIE 2014, Advances in Metrology for X-Ray and EUV Optics V 17-21 (August 2014, San Diego, California, USA) and AOMATT 2016 - 8th International Symposium on Advanced Optical Manufacturing and Testing Technologies (April 26-29 2016, China).

In total, four invited lectures have been given by the coordinator (2) and project partners (2). Twenty eight oral presentations and four poster presentations have been given in the conferences by partners during the life time of the project. Positive reactions were received to all these contributions attracting discussions and comments. Particularly the invited presentations were very impressive for the SR and FEL community.

Presentations of the outcomes of the project have also been given at a number of key fora, in particular at EURAMET and CIPM-CCL working groups' meetings where it has resulted in the influence future strategy ensuring on-going impact of the project in to the future. The project name 'SIB58 Angles' with its website is also referenced in the strategy document of CIPM-CCL for detailed information on angle metrology applications for the future. In total, the project contributed fifty six presentations to conferences and input to various committees.

Furthermore, the activities for nrad applications also has significant synergy with EMRP project SIB08 'subnano' where the Differential Fabry Perot Interferometer (DFPI) developed was applied to angle measurements in sub-nrad sensitivity. Additionally, the activities regarding angle encoders have synergy with EMRP project IND53 'LUMINAR' where the accuracy limitation for a laser tracker system for large volume measurement applications is investigated. The new generation angle encoders with an optimum number of reading heads will be of interest for laser trackers since the fundamental accuracy of laser tracker systems will not improve without improved angular scales operating reliably (and stably) at significantly sub-arcsecond level (0.1” and better).

4.2.3 *Stakeholder Engagement and standards*

The main objective of the project was the high level development of special tools, methods, and devices. Therefore, these outcomes are not directly applicable as standard 'routine' methods and therefore not directly transferable to standardisation bodies.

Care was taken during the life time of the project to keep relevant standardisation bodies regularly informed of the project activities and outcomes.

HZB attended the meetings of the CC-UPOB e.V. and presented the project at the 6th High Level Expert Meeting on Asphere Metrology, November 13-14th 2013, Braunschweig (Germany). HZB is member for VDI/VDE Community of X-Ray and EUV Optics. The project results have been presented to the working groups in Sept. 29th 2014 Berlin and in April 18th 2016 Berlin.

The coordinator and participants gave presentations on the project results and update information during life time of the project in the meetings of

- EURAMET Technical Committe of Lenght (TC-L) open workshop on EMRP/EMPIR (Oct. 2013, Braunschweig, Germany),
- BIPM CCL Working Group Meetings (WG-MRA, WG-S, WG-N) Nov. 2013, Taiwan,
- SPIE, Community of X-Ray and EUV Optics, 18 and 19 August 2014, San Diego, California (USA)
- EURAMET Technical Committe of Lenght (TC-L), and BIPM CCL Working Group Meetings (WG-MRA, WG-S, WG-N), 27-28 Oct. 2014, BEV - Wien
- BIPM CCL Working Group Meetings (WG-MRA, WG-S, WG-N), Sept. 15, CCL meeting in Paris
- COOMET Lenght and Angle (TC 1.5, Sept 15, COOMET TC Lenght & Angle meeting, Istanbul
- EURAMET Technical Committe of Lenght (TC-L), Oct. 2015, Madrid, Spain
- APMP Technical Committe of Lenght (TC-L), Nov. 2015, Beijing, China
- BIPM CCL Working Group Meetings (WG-MRA, WG-S, WG-N), Oct 2016, WG-MRA, Delf
- EURAMET Technical Committe of Lenght (TC-L) open workshop on EMRP/EMPIR, Oct. 2016, Delf, The Netherlands.

A detailed report consisting of proposals and a technical appendix was submitted to DG3 CCL (Discussion Group in Angle standards) for the use of angle encoders in CCL-K3 intercomparisons. Furthermore it was shared in the WG-MRA meeting of CCL in Delf (2016). The project results were used for designing new in CCL-K3 intercomparisons particularly for use of angle encoders. Using the experimental results from the project, the protocol was designed.

Furthermore, 2 EURAMET Calibration guides: Calibration of autocollimators and calibration of angle encoders (EURAMET Calibration Guide 22 and 23) were shared with the metrology and SR&FEL community to get their feedback. Then they were submitted to EURAMET and approved. They will be soon available for the readers via the EURAMET website.

The Stakeholder Committee (SC) established at the beginning of the project was informed about project results and also in some occasions, they were gathered and results of the project was presented by the coordinator.

Through these activities, some of the methods developed in the project were introduced to and are now used in organisations (e.g. Diamond Light Source in UK, NMI of Thailand) other than participants of the project and new devices developed have been sold to six organisations.

4.2.4 *Workshops*

Two stakeholder workshops have been organised during life time of the project.

The first workshop targeting the Synchrotron & FEL community were held at ALS of Lawrance Berkeley Nat. Lab, Berkeley, California, USA attached to the 5th Int. Workshop on X-ray mirrors design, fabrication, and metrology – IWXM (13-16 July 2015) in order to use the opportunity where large numbers of participants from the Synchrotron & FEL community (including people from industries, standardisation bodies, research organisations, universities and supplier companies) are available. 5 presentations from the project partners were presented in addition to key information on the project and its results. Face-to-face communications were carried out following the presentations. The following important outcomes were achieved, 1] Introduction of newly developed autocollimator centring device through the project (commercially available now), 2] presentation of a new method (Shearing method) and new upcoming services (e.g. 2D calibration of autocollimators, task specific calibrations etc.).

The second workshop was held on 28 October 2015 in Madrid (hosted by CEM) following the EURAMET TC-L meeting. 13 presentations from the project partners were delivered to about 50 participants ranging from various communities (industry, academia, public bodies, agencies, higher education, public organisations and contact persons of NMIs attended to EURAMET TC-L meeting).

For both the workshops, the delegates showed very positive interest about the outputs of the project in particular emphasising the role of NMIs in the development of metrology standards and their cooperation with other communities. The project established an excellent link between the SR&FEL community and the metrology community.

4.3 Effective cooperation between project partners

The European Metrology Research Programme (EMRP) is a metrology-focused European programme of coordinated R&D aimed at facilitating closer integration of national research programmes and ensuring collaboration between National Measurement Institutes, reducing duplication and increasing impact.

This project has been a good example of the implementation of this programme, including 10 European National Metrology Institutes (NMIs) of all sizes and capabilities with high levels of various facilities for angle metrology, 2 leading NMIs in angle metrology from outside Europe (Japan and Korea), 2 world leading producers of angle metrology equipment (autocollimator producer, MWO and angle encoder producer FAGOR) and a research institute IK4-TEKNIKER for development of precision equipment. The project was supported by Research Excellent Grant (REG) researcher from HZB and an excellent network was established with the stakeholders since REG (HZB) is very well known in the community of metrology for X-Ray and EUV Optics, SR & FEL with his previously delivered high level of contributions.

The project acted like a bridge between communities of metrology, SR&FEL and metrology for X-Ray and EUV Optics by providing knowledge transfer between them. The project had cooperation with its stakeholders in the schemes of ‘Collaborator’ and ‘Stakeholder Committee member’. This improved the research activities carried out in the project and produced high level impact. The project brought the stakeholders together to provide solutions to the current problems by a systematic approach. Development of an aperture centring device by the autocollimator manufacturer MWO, (one of the project partners), according to defined parameters in the project (led by HZB and PTB) and its application at project partners (NMIs) and collaborators (synchrotron and FEL metrology laboratories) was given as an example.

Moreover, various collaborators existed from NMIs and the SR&FEL community. Two of them officially made agreement with the project consortium signing Exchange of Letters. They are Diamond Light Source (DLS) of UK and NIMT (NMI of Thailand). They both used the shearing method developed in the project for testing their high level angle metrology equipment. They also shared the results with the consortium. The results were used to evaluate the performance of the method in different devices.

Exchanges between the partners have taken place. These include short visits within a training remit. A Masters thesis was completed in IPQ for adaptation of the shearing method for IPQ's angle metrology equipment. Additionally, an exchange of information between project partners took place during the meeting including a training session (REG(HZB)) in order to answer specific demands of stakeholders particularly, those from the communities of X-Ray and EUV Optics, SR & FEL.

To sum up, the consortium worked well together, so transferring the knowledge to each other and learning from other works completed by different partners. This was a real strength apart from capabilities, motivation and ambition of all partners. The different expertise and facilities of each partner were jointly used to fulfil the objectives of the project that were impossible to be covered by a single consortium member due to the range of skills and resources required. The balanced contributions from different partners (according to their capabilities) enabled us to improve the performance of the national metrology systems and to implement smart specialisation strategies. Application of new developed methods, tests, procedures in different partners' premises and knowledge sharing resulted in a better evaluation of the project outputs. The information between partners was shared through various instruments such as electronic mails, visits, ad-hoc and planned meetings. All the work requiring cooperation were successfully completed.

Some examples are the evaluation of ACenD through the intercomparison between the partners, the first 2D calibration of autocollimators and intercomparison measurements, training activities on the new subjects (e.g. shearing techniques, new generation angle encoders etc.), preparation and joint submission of EURAMET calibration guides, joint proposals to the committees, checking the test results during presentations in the meetings with recommendations and pre-reviewing of the papers to be submitted.

In this way, several tasks have taken benefit from the collaboration between the partners, as demonstrated by the several joint publications and presentations (see below).Different methods and devices have been validated thanks to the joint collaboration of partners. High level cooperative work also existed during development of the devices. For example, Angle scale (based on an angular interferometer) for the device developed by IK4-TEKNIKER & CEM was made and delivered by CMI. PTB analysed TUBITAK's autocollimator by performing extensive calibration in various conditions such as large and small ranges in various sampling steps. These results were used by TUBITAK for evaluation of their large range small angle generator developed during the project.

4.4 Examples of early impact

4.4.1 *Standards and regulation*

Two EURAMET Calibration guides has been prepared during the project and submitted to EURAMET:

- Calibration of autocollimators (EURAMET Calibration Guide 22)
- Calibration of angle encoders (EURAMET Calibration Guide 23)

It was approved and proof reading was completed. Both guides will be soon available for the readers via the EURAMET website.

4.4.2 *User uptake*

<u>Use of developed new tool 'ACenD' by end users</u>

Aperture Centring Device (ACenD) - A useful alignment tool to centre an aperture up to 0.1 mm to the optical axis of the autocollimator, developed in the project is now commercially available to end users. The device provided a 'measurable, documentable, transferable aperture positioning' facility which did not exist previously.

The aperture centring device was created by unfunded industrial project partner Möller-Wedel Optical GmbH (MWO) during the project. The device has been tested by partners within the project and as a result has been made available as a commercial product by Möller. It is reported by MWO that six units of ACenD have already been sold to use in deflectometric profilers.

Use of developed new method 'shearing technique' by end users

Diamond Light Source (DLS) of UK and NIMT (NMI of Thailand) made an agreement with the project consortium signing Exchange of Letters to apply the shearing method developed in the project. They both used the shearing method for testing their high level angle metrology equipment. DLS also gained the ability for analysis of shear results by utilising documentation and reference data sets created in the project.

New calibration service for autocollimators

CMI used their large range small angle generator developed in the project for calibration of autocollimators now. They even participated in the EURAMET-L.K3 comparison for validation of the system.

All NMIs improved their services for calibration of angle measurement standards by better analysis of their reference systems using the methods developed in the project. Most of them are making preparations for task specific calibration of autocollimators that will be available to customers. This includes calibration of autocollimators with/without aperture, with varying distances, with SUTs various surface properties (e.g. reflectivity), using ACenD etc.

New reference angle comparator

Unfunded project partners FAGOR established a new angle comparator together with IK4-TEKNIKER on their premises. It is expected that this will improve their capability for production of angle encoders. On the other side, the device was manufactured by unfunded project partner IK4-TEKNIKER improving their capability for production of angle comparators. The work had not been planned in the project. The FAGOR realised and understood the need of it for improvement of the products during life time of the project. They have used the knowledge gained during their investigation for deliveries of the project and also the project's publications.

Self-calibrating angle encoder based on an optimised geometrical arrangement of multiple read heads

Vermont Photonics (a company in USA) obtained a grant from NIST to create an angle encoder based on the principles of self-calibration developed in the project. The geometrical read head arrangement will be optimised based on the knowledge gained in this project.

New 2D calibration service for autocollimators

A new 2D autocollimator calibration device allows faster, more precise calibration of autocollimators and better characterization of artefacts related to 2 axes of the autocollimator. The service for two-axis (2D) calibration of autocollimator will be available in PTB and VTT following the quality management process.

New portable device for calibration of autocollimators

A new portable device (Large Range Small Angle Generator) for precise calibration of autocollimators developed in the project will be used in TUBITAK for their services. It has also potential to be used onsite for calibration of ACs in Synchrotron and FEL metrology labs. Therefore it has potential to become commercially available.

4.4.3 *Scientific uptake and impact*

A detailed report consisting of proposals and a technical appendix, as highlighted in section 4.2.3, was submitted to DG3 CCL.

Angle metrology position papers prepared during the project and available on the project website was referenced in the CCL strategy document to guide NMIs for demands and future applications of angle metrology.

New projects are being planned for the application of the LRSAG of TUBITAK for in-process calibration of autocollimators in HZB’s premises. Improvements are considered for inspection of high precision mirrors.

Other exploitable foreground is the task specific calibration of autocollimators using the knowledge and devices developed in the project for scientific experiments e.g. improved determination of the constant of gravitation G.

BIPM measurement of G relies on the precise determination of angular deflections. A torsion balance is used and the torque constant is obtained from the change in total electrostatic energy as a function of angle. In the last experiment, the deflection of the balance was measured as 31.5" with a standard uncertainty of 0.0015" (7 nrad). The angle measurement in this experiment is one of the principle uncertainty source and uncertainty of the angular value of 0.0015" has contributed about 47 ppm to the standard uncertainty of 56 ppm (for the determination of *G* by the Cavendish method). Although several measurements of this constant have been performed, recent experiments differ about 40 times the uncertainty of the most precise experiment. Resolving the current discrepancies with better measurements is motivated by e.g. the search for a theory unifying gravitation with quantum electrodynamics, understanding the subtleties involved in precisely and absolutely measuring a small force in many fields of physics and metrology, including the Casimir effect, spring constants of atomic force microscopy (AFM) cantilevers, intermolecular forces in DNA.

4.4.4 *Patents, trademarks and registered designs*

Position measuring apparatus and position measuring method

KRISS developed a new type reading head for encoders. This new type reading head applies a special algorithm to reduce nonlinearity errors. Patent number: 10-1361625-0000 (Korea).

Aperture Centring Device (ACenD)

Aperture Centring Device (ACenD) - A useful alignment tool to center an aperture up to 0.1 mm to the optical axis of the autocollimator was created by MWO. It was applied for utility model (the utility model number registration number is 20 2015 002 992). MWO also applied for European patent, EP3086151A1, published on 26th of October 2016.

Optimised reticle design

PTB developed a novel reticle design for autocollimators which markedly reduces measuring errors. Patenting documents were being prepared with the help of a patent attorney during preparation of this report.

4.5 Potential impact

For the first time in the world, the provision of spatial angle calibrations of autocollimators (even at various distances) are provided. It is considered as a milestone in angle metrology since there is currently lack of traceability in spatial high precision angle measurements. This will have high level impact on angle-based scientific and industrial applications. For instance, autocollimator manufacturers (e.g. project partner MWO) will be able to improve their products by minimising cross-talk between the measuring axes and distance-dependent influences. Autocollimator users, especially users of deflectometric profilometers at synchrotrons, FEL (e.g. Project partner HZB), NMIs, industry and academia (e.g. for big science studies) will be able to benefit from the traceable spatial angle calibration capabilities for the first time. Through these users, the traceable calibration of interferometers by use of optical flatness standards (at NMIs) and the manufacturing of beam-shaping optics for synchrotrons and FEL applications can be improved.

Using the results of investigations on reticle design and influence of the measuring conditions in the project, new generation electronic autocollimators are expected to be developed in the next five years. The first device worldwide for the accurate centring of the beam-limiting aperture in front of autocollimators is commercially available. The device has been tested by partners within the project and as a result has been made available as a commercial product by MWO.. MWO provides to its customers such a new device; six units have already been sold. We expect that especially users of deflectometric profilometers for the precision measurement of the form of optical surfaces at synchrotrons and FEL will widely adopt the use of this device and benefit from its application. They, in turn, will advance the testing and manufacturing of beam-shaping optics for these applications as their manufacturing is currently limited by the form measurement. This will result in reduced beam cross-sections and increased beam brilliances, advancing basic and applied research with synchrotrons and FEL. Developed Large Range Small Angle Generators (LRSAGs) will enable in-situ calibration autocollimators used in angle-based profilometry applications providing characterisation of autocollimators on-site.

All these developments will have high level impact and give benefit to the metrology community for the X-ray and EUV optics (with applications at upcoming FEL's, Diffraction Limited Storage Rings and upcoming Laser-Plasma-Wakefield-Accelerators as well as X-ray telescopes in the field of astrophysics). In addition to scientific applications, a strong interest may occur for alternative concepts on EUV-Lithography – to inspect optical components for future optical systems in the semiconductor industry and micro-optics development.

Apart from this, the above developments will also be used by NMIs and calibration labs to answers task specific calibration demands in autocollimator calibration.

It is expected that there will be new type angle encoders applying self-calibration methods and new alignment tools for calibration of angle encoders through the investigations and knowledge produced in the project. The application of self-calibration to the in situ calibration of angle encoders without reference to external standards and investigation results on alignment of angle encoders will lead to a lower calibration uncertainty of primary angle standards for the SI unit radian which will be disseminated directly to various customers in industry and research by means of improved calibrations of angle encoders, autocollimators, and angle artefacts. This will also provide recommendations to NMIs and calibration labs for encoder calibration and finally find a usage for intercomparison measurements in international metrology systems and conformity assessment activities. Currently, this was partly achieved.

Since angle encoders are used in numerous industrial and scientific applications, e.g., in industrial robots, automation, manufacturing, and Large Volume Metrology equipment - laser trackers (devices for dimensional control of large science instruments, structures, and facilities), it is expected that industry (e.g. Encoder manufacturers like FAGOR in the project) might be interested in using research results (e.g. Self-calibration technique of PTB) and in designing special encoders based on the research work produced in the project. The statement of the JRP-Coordinator of EMRP project, IND53 ('LUMINAR') for angle metrology (according to state of the art knowledge in precise Large Volume Metrology (LVM) applications) justifies the above issues:

"Work in EMRP-funded project 'LUMINAR' (IND53) is seeking ways to compensate for refractive index and refraction effects over long range and the accuracy limitation for laser tracker system will then once again be primarily in the angular rotation measurements. Without improved angular scales operating reliably (and stably) at significantly sub-arcsecond level (0.1" and better) the fundamental accuracy of these popular instruments will not improve." by Andrew Lewis.

In this context, we believe that new generation angle encoders (fulfilling such demands) will definitely find a place in industrial and scientific applications particularly for control of large science instruments, structures, and facilities when integrated into LVM devices.

It is now possible to generate ultra-small angles at least down to 1 nrad (0.2 miliarcsec) step size and perform nrad sensitivity and further nrad uncertainty angle measurements (achieved in the project).

Currently, an angular positioning mechanism aiming to achieve less than 10 nrad positioning accuracy for high-precision x-ray crystal optics such as those used for the hard x-ray crystal based inelastic scattering beamline is not available. Energy determination of crystal optics relies on the precise knowledge of the angular change to the level of less than 10 nrad. For the future X-ray Free Electron Laser Oscillators (XFELOs), there is a similar demand for the angular stabilisation of X-ray optical components at levels less than 10 nrad to provide precise control of the cavity geometry. The current state of the art is about 50 nrad and achieving stability at the 10 nrad level is indeed challenging.

The high resolution gamma ray spectroscopy facility (GAMS) is aiming to contribute to our understanding of the structure of nuclei to the determination of standards and fundamental constants or to deduce information. The core of the spectrometer is a pair of silicon crystals acting as diffraction gratings that allow the selection of the gamma ray energy by tuning the angle between them. The angle is at present measured through a complex interferometer which in turn is calibrated through a reference polygon used in combination with an autocollimator. At present the accuracy of the experiment is limited by the knowledge of the angle between the crystals. The realisation of a small angle generator capable of generating traceable rotations with an uncertainty of the level of the nanoradian or better will greatly improve such kind of experiments.

The Bepi-Colombo mission is a challenging ESA-JAXA mission to explore the planet Mercury. It will be made of two satellites one of which, the Mercury Planetary Orbiter (MPO), will orbit around the planet to map the gravitational field of the same. The orbit will be measured by radiometric tracking which cannot take in account the effect of non–gravitational acceleration (e.g. due to solar radiation pressure). To measure non-gravitational acceleration a very sensitive three axis accelerometer (the Italian Spring Accelerometer, ISA) has been developed. The calibration of such accelerometer on Earth is critical. The approach that will be used is to exploit Earth gravitational acceleration g in combination with a tilter capable of generating microradian angles with an accuracy of 20 nrad on a 0.1 Hz band. After task specific calibration of autocollimators using the knowledge produced in the project, it is now possible to achieve such demanded values.

In the project, Differential Fabry-Perot Interferometer (DFPI) of TUBITAK was applied to detection of very small angles (currently 1 nrad steps using available TUBITAK High Precision Angle Generator) utilising the frequency stabilised lasers as an alternative and outperforming method to conventional angle interferometers. Use of DFPI provided displacement measurements with picometre sensitivity free from linearity errors. It is expected that produced knowledge will be benefit to synchrotrons & FEL community, gamma ray spectroscopy applications - fundamental physics, scientific space missions as well as NMIs and angle measurement device manufacturers.

The divergence of the measuring conditions of autocollimators during calibration and during their use is a perpetual problem in autocollimator calibration. Making use of the greatly improved knowledge on the influence of the measuring conditions on the angle response of autocollimators, it will be possible to give customers a better qualitative and quantitative understanding of this problem. This, in turn, will improve the dissemination of the SI unit radian and associated traceability issues providing new calibration services even new Calibration and Measurement Capability (CMC) entries in the BIPM website as a result of this project. This will be in two schemes: First, services dedicated to task specific calibration work of the customers e.g. Autocollimator calibrations with unprecedented repeatability of the aperture centring for users in e.g. EUV and X-ray-Optics, EUV-Lithography and micro-optics communities. Greatly improved knowledge on the influence of the measuring conditions on the angle response of autocollimators by experimental data and the ray tracing of autocollimators will be used to provide customers better and comprehensive services for use of calibration results as this is crucial for autocollimator calibration and application in inspection of synchrotrons and FEL optics. Second, there will be improved autocollimator calibrations for customers in need of the lowest uncertainties e.g. based on the errors-separating shearing techniques or on new calibration devices developed. Additionally, measurement of interpolation errors (angle deviations at small scales) of angle measurement devices (such as autocollimators, angle encoders, small angle generators, angle interferometers, hybrid comparators) will be carried out at ultimate precision providing solutions for performance checking of interpolators and algorithms. The production of useful guides for easy application of new metrological methods will benefit all involved in angular measurements. For example, NMIs, calibration labs, angle measurement equipment producers, robotics & automation industry, machine tool, automotive and semiconductor industry, fundamental scientific metrology, nanosciences and precision engineering, medical & aerospace industry, synchrotron and FEL community will all benefit from this work.

Improved angle metrology targeting at nanoradian uncertainty is demanded in “The Strategic Research Agenda of EURAMET” for fundamental scientific metrology and dimensional control of large science instruments and structures as well as in World metrology Strategy (2013-2023) document (of Consultative Committee for Length - CCL). This is because improved angle metrology will have environmental, financial, and social impact specifically as follows:

Environmental impact: Research carried out at synchrotron & FEL centres impacts broadly on medical, material, and energy sectors, facilitating a better environment and sustainable energy sources.

Financial impact: Around 50 synchrotrons centres worldwide rely on angle metrology for form measurement of precision optics and alignment of the facilities. Angle metrology is an enabling technology for a broad range of measuring and manufacturing equipment in almost all sectors of industry.

Social impact: Sectors using angle metrology are important to the employment and wealth of the EU. Advanced particle beam therapies and beams from synchrotron sources have applications in healthcare provision – 2009 & 2012 Nobel Prizes in chemistry.

It is expected that outcomes of the project will provide significant support to, e.g., the inspection of the quality and alignment of optical components at accelerator based synchrotron radiation facilities, the measurement of long distances utilising angle metrology, and angle measuring methods for nrad level rotation and tilt control in industrial production will have at least **substantial** impact regarding to above mentioned areas.

Apart from these technological advances, we expect that the project will have achieved a closer networking and collaboration of NMI’s especially with stakeholders from the synchrotron and FEL community, providing stimulus for further research and advances in angle metrology in the future.

5 Website address and contact details

A public website has been open, where the main public deliverables have been made available for the end users as well as information about project meetings and events:

http://www.anglemetrology.com/

The contact person for all questions about the project, is

Assoc. Prof. Dr. Tanfer YANDAYAN, TUBITAK (tanfer.yandayan@tubitak.gov.tr)

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