Final Publishable JRP Summary for SIB58 Angles
Angle Metrology

Overview

Angle metrology, or the measurement of angles, is important for many science and industry areas where the EU is globally competitive. The ability to measure angles is needed for the measurement of machine geometries such as straightness, flatness and parallelism of surfaces. This is used in industrial applications such as the manufacture of cars and aeroplanes, industrial robots, space missions, and complex scientific applications including the precise measurement of optical surfaces.

Current manufacturing demands an ever greater accuracy in measurements and therefore improvements in the devices used to make angle measurements, and in their calibration are needed. However, prior to this project there was a lack of precise calibration and traceability for angle measuring devices, such as autocollimators and angle encoders.

This project has improved traceability for precise angle measurements and achieved the low less than 50 nrad uncertainty demanded for advanced scientific and industrial applications. The project developed novel methods, instruments, and guides, and has provided the foundations for greater accuracy in angle metrology to meet end user requirements for greater precision.

Need for the project

The need for traceable high precision angle metrology exists in most industrial sectors and high level scientific applications. For instance, most measurement equipment used in geodesy (long distance measurement), and large volume metrology, such as laser trackers and theodolites, are fitted with angle measuring devices. The same holds true for robots and machine tools used in industry; the accuracy of which determines manufacturing accuracy.

Angle measuring devices used in applications where high precision straightness, flatness and parallelism of surfaces is demanded include:

- Autocollimators: versatile instruments for the precise and contactless measurement of angles of reflecting surfaces, used to align components.
- Precise angle encoders: instruments for the precise measurement of rotation angles; they convert the angular position of a shaft or axle to an electrical signal. They are also essential components of a wide range of rotating precision devices.
- Small angle generators: provide small angles traceable to the radian, the SI unit for angle.

Meeting the demands from the production industry to use these devices for accurate traceable angle measurement generation at low sub-nrad (less than 10^{-9} radian) sensitivity is very challenging and has previously not been addressed.

In addition, there is a need for advanced angle metrology for highly curved optical surfaces. These are used in synchrotrons (a circular particle accelerator which produces a very bright light) and FEL (Free Electron Laser, used in chemistry, biology, medicine and non-destructive testing) metrology laboratories worldwide. Research is needed to generate an improvement in autocollimator performance at the small apertures used in these applications as well as checks using small angle generators.

EMRP
European Metrology Research Programme
Programme of EURAMET

The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union

Scientific and technical objectives

This project aimed to perform investigations and experimental work, and develop prototype angle measuring devices for the SI angle unit the radian with an uncertainty less than 50 nrad. This will ensure the reliable and SI traceable measurement of angles in industrial and scientific applications of angle measuring instruments including autocollimators, angle encoders and small angle generators. The project's objectives were:

1. ***Metrological characterisation of autocollimators:*** improve autocollimator performance at small apertures (small beam diameters), to develop facilities and methods for the two-axis calibration of autocollimators, to develop optical tracing modelling of autocollimators, and to characterise the influence of the distance between the autocollimator and the optical surface.
2. ***Application of autocollimators in profilometry:*** 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.
3. ***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 autocollimators.
4. ***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, and to perform investigations for nrad and sub-nrad level angle metrology.

Results & Conclusions

1. *Metrological characterisation of autocollimators*

A review of the state of the art of autocollimator application, performance, and calibration was carried out, and is available on the project website. The project partners produced 27 experimental calibration data sets for investigations of distance-dependent effects of autocollimators, and the experimental and theoretical results (optical tracing simulations) demonstrated excellent agreement. This result will help autocollimator users, particularly in the synchrotron community, and manufacturers, to minimise measurement errors of their autocollimators due to distance-dependent effects which exist during inspection of optical surfaces.

Autocollimators used in profilometry (measurement of a surface's profile) require two-axis calibration (or spatial angle calibration) as the two axes of the autocollimators are simultaneously used for the form measurement of highly curved optical surfaces. The project developed advanced autocollimator calibration facilities and methods for the two-axis calibration of autocollimators addressing the influences of the beam deflection by the optical parts. The new facilities are a Spatial Angle Autocollimator Calibrator at PTB and an interferometer-based two-axis autocollimator calibration set-up at VTT. These are the first facilities for the traceable realisation and dissemination of spatial angles in the world and they greatly extend the frontiers of angle metrology, ending its previous limitation to plane angles. The first spatial angle two-axis calibration of an autocollimator was also achieved with these devices in the project.

The improvement of autocollimator performance at small apertures is important for achieving improved lateral resolution during precise form measurement of optical surfaces, as well as angular displacement measurement of reflecting surfaces in very small sizes. PTB developed a novel reticle (optical detection unit) design for autocollimators which markedly reduces measurement errors, and has led to the submission of a patent. The application of the reticle design for autocollimators in commercial products is expected to increase the performance of autocollimators when used with small apertures (< 2.5 mm diameter) for inspection of future X-ray and extreme ultra violet optics. This will support the development of new generation autocollimators in the near future.

Through the work on this objective the project has advanced knowledge on distance-dependent angle measuring errors of autocollimators with small and full aperture sizes. The investigations for the influence of the distance between the autocollimator and the optical surface will enable end users to achieve the required residual slope deviation of 50 nrad for the inspection of synchrotron and FEL optics. The novel reticle design

with improved algorithms, will increase the performance of autocollimators when used with small apertures, and the two-axis calibration of autocollimators is now available as a new calibration service at PTB and VTT.

2. *Application of autocollimators in profilometry*

The project reviewed current measurement practices and literature values to asses the state of the art for autocollimator-based form measurement of optics. Subsequently, experimental investigations were carried out, particularly for the influences of the reflectivity and curvature of optical surfaces on the angle response of autocollimators. These investigations are important for reaching the limits of autocollimator-based form measurement of optics, such as beam-shaping optics for synchrotrons and FEL applications.

A novel autocollimator aperture centering device (ACenD) was developed, which for the first time allowed the efficient use of autocollimators in deflectometric profilometry. ACenD can be used to centre an aperture up to 0.1 mm to the optical axis of the autocollimator.

ACenD was also tested on the precise centring of small apertures when used with autocollimators. The project verified that ACenD is capable of achieving a reproducible aperture alignment less than 0.1 mm, the target value. ACenD also produced a significant improvement when compared with currently available laser target devices, such as a reduction in the standard uncertainty of autocollimator calibration, by a factor of 3. Importantly, ACenD provided a 'measurable, documentable, transferable aperture positioning' facility which previously did not exist. Correction of the autocollimator errors due to pressure variations in the environment was first applied to repeated results by PTB, in order to determine the precise performance of ACenD. The ACenD device is now available as a commercial product by Möller-Wedel Optical in Germany, and is expected to provide solutions for form measurement and subsequently fabrication of future synchrotron optics.

3. *Precise angle encoders*

A review of the state of the art of angle encoder application, performance, and calibration was produced and is available on the project website. A new angle reference standard 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 using external reference standards was created at PTB, together with a mathematical framework for the optimisation of the in-situ 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 also completed. New tools using flexures and micrometer actuators were developed and tested for measuring encoders on rotary tables fitted with one reading head angle encoder. The results provide a valuable understanding of the error sources influencing the angle encoder's performance and guidance for the development of future angle encoders on rotary tables to improve the accuracy of angle measurements.

The first adaptation of advanced error-separating shearing techniques to the precise calibration of autocollimators with different angle encoders and to investigations of interpolation errors were completed. For separation of autocollimator and angle encoder errors, state of the art uncertainties down to 0.001" (0.001 acrseconds, equivalent to 5 nrad) were achieved, giving improvement by a factor of three when compared with uncertainties from conventional calibration methods. The performance of autocollimators, angle encoders and interpolators were also studied without the use of external standards using the shearing method (an advanced error-separating method used to separate the errors of test and reference measurement system). 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. The angle encoder interpolation error was also measured using a capacitive sensor and correction of the errors was demonstrated.

A new type of reading head for encoders was developed by partner KRISS. This new type of reading head applies a special algorithm to reduce nonlinearity errors and will provide new knowledge for the evaluation and improvements of the interpolators.

4. Small angle generators and hybrid devices

After an initial review of current capabilities and extensive consultation with users at synchroton and FEL facilities three different portable long range small angle generators were developed by the project. The aim was to achieve a calibration range of about 3600" (17,000,000 nrad) and expanded uncertainty of less than 0.01" (50 nrad) using these three different portable long range small angle generators. The aim was fully achieved with 2 novel devices developed by TUBITAK and CMI, and partly achieved by the device at IK4-TEKNIKER & CEM where further improvements are progress.

A hybrid angle calibrator based on the integration of a rotary table fitted with an angle encoder and angular interferometer was created by partner SMD in Belgium. The aim was to achieve a target uncertainty from less than or equal to 0.001" for angles up to 1 degree to less than or equal to 0.005" for angles up to 10 degrees. A variety of difficulties arose and unfortunately this challenging target could not be achieved. The hybrid angle calibrator suffered from problems such as thermal drift, noise, instability due to thermal gradients in the air and variations in the refractive index of air. However, valuable knowledge on hybrid angle calibrators was gained and a method was developed by SMD to link angle measurements made with a laser interferometer to angle measurements made with a calibrated 360 degree encoder by calibrating the full circle of the encoder with the limited ranges of the laser angle interferometer.

Investigations were carried out by the project for nrad and sub-nrad level angle metrology according to the demands of synchrotron beamlines at storage rings, FELs and X-ray free electron laser oscillators. The first angle measurements in steps of 1 nrad (0.0002") with sub-nrad sensitivity were achieved using frequency stabilised lasers as an alternative and an improved method (to conventional angle interferometers) using a short range small angle generator for the very short angular ranges. Further to this, the use of autocollimators in nrad angle measurements were investigated using different small angle generation-measurement concepts in short ranges i.e. a few arcseconds. The work showed that the autocollimators and small angle generation-measurement concepts can be precisely calibrated, near to their resolution 0.001" (5 nrad) and used for the non-contact angle measurements with uncertainties down to 0.001" (5 nrad). This was validated by applying the shearing method (for the first time) to the calibration of autocollimators using small angle generators. The uncertainty value achieved (5 nrad) represents a substantial improvement by a factor of 3-4 compared to previous uncertainty values.

Actual and potential impact

Dissemination

The project generated 18 high impact publications in key journals, 15 proceedings and a book chapter. The project also contributed 25 presentations to conferences such as AOMATT 2016 - 8th International Symposium on Advanced Optical Manufacturing and Testing Technologies, 11th IMEKO Symposium, Laser Metrology for Precision Measurement and Inspection in Industry (LMPMI) (International) and SRI 2015 - 12th International Conference on Synchrotron Radiation Instrumentation.

Contribution to Standards

The project contributed to the following standards:

- EURAMET Calibration Guide 22: calibration of autocollimators
- EURAMET Calibration Guide 23: calibration of angle encoders
- VDI (Association of German Engineers) revision of VDI/VDE 5575 - Blatt 4 / Part 4, "X-ray optical systems - X-ray mirrors - Total reflection mirrors and multilayer mirrors".
- VDI revision of VDI/VDE 5575 - Blatt 10 / Part 10 X-ray optical systems – Diffraction Gratings.

During the project regular communication took place with the BIPM Consultative Committee for Length Discussion Group 3 on Angle (CCL-DG3), in particular regarding the organisation of a CCL comparison on calibration of angle standards (CCL-K3). The project results were used for designing the new CCL-K3 intercomparisons protocol.

Presentation of the project's results were also given at working group meetings of BIPM-CCL, COOMET, EURAMET and APMP's Technical Committees for Length, where it is expected to influence future strategy.

Early impact

The project has demonstrated significant interest from end users particularly from the synchrotron and FEL community. Some of the devices developed in the project are commercially available and already being used.

- The following three patents have been, or will be, applied for: 10-1361625-0000 (new type reading heads and algorithms for encoders) applied for by KRISS in Korea, European patent EP3086151A1 (ACenD for precise positioning of apertures) applied for by partner MWO (Möller-Wedel Optical), PTB (new reticle design and algorithm for autocollimators to be used with small apertures) are currently preparing an application.
- The service for two-axis (2D) calibration of autocollimator will be available in PTB and VTT following completion of the quality management process. This new two-axis autocollimator calibration device allows faster, more precise calibration of autocollimators and better characterisation of artefacts related to the 2 axes of the autocollimator. This milestone in angle metrology extends plane angle calibration to spatial angle calibration.
- The Aperture Centring Device (ACenD) is commercially available at Möller-Wedel Optical, and 6 units have already been sold for use in deflectrometric profilers (objective 2).
- Diamond Light Source, the UK's national synchrotron science facility, and NIMT (NMI of Thailand) both used the shearing method developed in the project for testing their high level angle metrology equipment..
- CMI has used their new large range small angle generator for autocollimators calibration services.
- All NMIs in the project (TUBITAK, CEM, CMI, INRIM, IPQ, LNE, GUM, VTT, PTB) have improved their services for the calibration of angle measurement standards using the methods developed in the project.
- Unfunded project partners FAGOR AUTOMATION and TEKNIKER have established a new angle comparator in order to improve their angle comparator production capacity.
- Vermont Photonics (USA) obtained a grant from NIST to create an angle encoder based on the principles of self-calibration developed in the project.
- One of the new portable Large Range Small Angle Generators for precise calibration of autocollimators, developed in the project, will be used by TUBITAK for their calibration services.
- Knowledge gained in the project has been used for the construction of the European X-Ray FEL facility. The project's methods were used to inspect the optics that will be used to focus photons at the Single Particles, Clusters and Biomolucules experimental station at the European X-Ray FEL facility, currently under construction in Hamburg.

Potential future impact

The project partners are currently developing task specific calibration of autocollimators that will be available to customers. These include the calibration of autocollimators with and without apertures, with varying distances, or with various surface properties (e.g. reflectivity), using ACenD etc.

The new portable large range small angle generator developed in the project has the potential to be used for on-site calibration of autocollimators in synchrotron and FEL metrology labs, and therefore to become commercially available. The improved angle metrology developed in the project is important for synchrotron applications because it will help overcome the angle measurement based form measurement of beam shaping optical surfaces that currently limits manufacturing. Research carried out at synchrotron & FEL centres impacts the medical, material, and energy sectors, and around 50 synchrotrons centres worldwide rely on angle metrology for form measurement of precision optics and alignment.

The project's results s will also benefit the metrology community for the X-ray and extreme ultra violet optics with applications in FEL's, Diffraction Limited Storage Rings, and X-ray telescopes. In addition, 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) and it is expected that industry will widely benefit from the project's results. Further to this, a strong interest is likely for alternative concepts in extreme ultra violet lithography, where it can be used to inspect optical components for future optical systems in the semiconductor industry and micro-optics development.

In summary this project has produced a range of new techniques, instruments and knowledge that will enable angle metrology users to deliver their own advanced products, facilities, and measurement services. These will contribute to better efficiency in industries, by using fewer manufacturing resources and creating less waste.

List of publications

[1]. Geckeler RD, Link A, Krause M, and Elster C, "Capabilities and limitations of the self-calibration of angle encoders", *Meas. Sci. Technol.* **25** (2014) 055003 10pp

[2]. Youichi Bitou and Yohan Kondo, "High-lateral-resolution scanning deflectometric profiler using a commercially available autocollimator", *Meas. Sci. Technol*. 24 July 2014, Vol. 25, 095202 (6pp)

[3]. F. Siewert, J. Buchheim, T. Zeschke, M. Störmer, G. Falkenberg, R. Sankari, "On the Characterization of ultra-precise X-ray optical components – advances and challenges in ex-situ metrology" , *J Synchrotron Radiat.* Sep 1, 2014; 21(Pt 5): 968–975. Invited paper at Journal of Synchrotron Radiation, Special Issue on Diffraction Limited Storage Rings and New Science Opportunities. Published online Aug 27, 2014. doi: 10.1107/S1600577514016221

[4]. Geckeler RD and Just A 2014, "A shearing-based method for the simultaneous calibration of angle measuring devices", *Meas. Sci. Technol.* **25** 105009 15pp

[5]. S. Roling, H. Zacharias, L. Samoylova, H. Sinn, Th. Tschentscher, O. Chubar, A. Buzmakov, E. Schneidmiller, M. V. Yurkov, F. Siewert, S. Braun, P. Gawlitza, "Time-dependent wave front propagation simulation of a hard x-ray split-and-delay unit:", *PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS*, 17, 110705 (2014) DOI:10.1103 /PhysRevSTAB.17.110705

[6]. Ralf D. Geckeler, Michael Krause, Andreas Just, Oliver Kranz, and Harald Bosse, "New frontiers in angle metrology at the PTB", Measurement, 73 231–238 (DOI:10.1016/j.measurement.2015.05.010)

[7]. Oliver Kranz, Ralf D. Geckeler, Andreas Just, Michael Krause, Wolfgang Osten, "From plane to spatial angles: PTB's Spatial Angle Autocollimator Calibrator", Advanced Optical Technologies DOI: 10.1515/aot-2015-0017.

[8]. Z. Yin, H. B. Peters, U. Hahn, M. Agåker, A. Hage, R. Reininger, F. Siewert, J. Nordgren, J. Viefhaus, and S.Techert., "A new compact soft x-ray spectrometer for resonant inelastic x-ray scattering studies at PETRA III", Review of Scientific Instruments, 86, 093109 (2015); doi: 10.1063/1.4930968.

[9]. Siarhei Dziarzhytski, Natalia Gerasimova, Rene Goderich, Tobias Mey, Ruben Reininger, Michael Rübhausen, Frank Siewert, HolgerWeigelt and Günter Brenner, "Microfocusing at the PG1 beamline at FLASH", *Journal of Synchrotron Radiation*, ISSN: 1600-5775 doi:10.1107/S1600577515023127

[10]. M Çelik E Şahin, T Yandayan, R Hamid, A Akgöz, B Özgür, M Çetintaş and A Demir, "Application of Differential Fabry-Perot Interferometer (DFPI) in angle metrology", Meas. Sci. Technol. 27 (2016) 035201 (10pp), doi:10.1088/0957-0233/27/3/035201.

[11]. Valeriy V. Yashchuk, Nikolay A. Artemiev, Gary Centers, Arthur Chaubard, Ralf D. Geckeler, Ian Lacey, Harry Marth, Wayne R. McKinney, Tino Noll, Frank Siewert, Mathias Winter, and Thomas Zeschke, "High precision tilt stage as a key element to a universal test mirror for characterization and calibration of slope measuring instruments", Review of Scientific Instruments, 87, 051904 (2016); doi: 10.1063/1.4950729

[12]. R.D. Geckeler, N.A. Artemiev, S.K. Barber, A. Just, I. Lacey, O. Kranz, B. V. Smith, and V.V. Yashchuk, "Aperture alignment in autocollimator-based deflectometric profilometers", Review of Scientific Instruments, 2016 May; 87(5):051906. doi: 10.1063/1.4950734

[13]. T. Yandayan, R. D. Geckeler, M. Aksulu, S. A. Akgoz, and B. Ozgur "Application of advanced shearing techniques to the calibration of autocollimators with Small Angle Generators and investigation of error sources", Review of Scientific Instruments, 87, 051903 (2016); doi: 10.1063/1.4950720

[14]. F. Siewert, T. Zeschke, T. Arnold, H. Paetzelt, V. Yashchuk, "Linear chirped slope profile for spatial calibration in slope measuring deflectometry", Review of Scientific Instruments, 2016 May;87(5):051907. doi: 10.1063/1.4950737.

[15]. Manuel Sanchez del Rio, Davide Bianchi, Daniele Cocco, Mark Glass, Mourad Idir, Jim Metz, Lorenzo Raimondi, Luca Rebuffi, Ruben Reininger, Xianbo Shi, Frank Siewert, Sibylle Spielmann-Jaeggi, Peter Takacs, Muriel Tomasset, Tom Tonnessen, Amparo Vivo and Valeriy Yashchuk, "DABAM: an open-source database of x-ray mirrors metrology", Journal of Synchrotron Radiation, 2016 May; 23(Pt 3):665-78. doi:10.1107/S1600577516005014.

[16]. Marco Pisani and Milena Astrua, "The new INRIM Rotating Encoder Angle Comparator (REAC)", Meas. Sci. Technol. 28 (2017), doi: 10.1088/1361-6501/aa5af6 045008.

[17]. Ville Heikkinen, Ville Byman, Ilkka Palosuo, Björn Hemming and Antti Lassila, "Novel interferometric spatial angle calibration set-up for autocollimators". Metrologia. 542017, 253-261. doi: 10.1088/1681-7575/aa648d

[18]. Jong-Ahn Ki, Jae Wan Kim, Chu-Shik Kang, Jonghan Jin, Tae Bong Eom, Absolute angle measurement using a phase-encoded binary graduated disk, Measurement, 80 (2016) 288–293. doi: 10.1016/j.measurement.2015.11.037

[19]. Frank Siewert, Optical Metrology – On the Inspection of Ultra-Precise FEL-Optics, published as a book chapter in: “Optical technologies for extreme-ultraviolet and soft X-ray coherent sources”, *Springer Series in Optical Sciences*, ISBN 978-3-662-47442-6, Springer Berlin Heidelberg, September 2015

[20]. Tanfer Yandayan, Ralf Geckeler, and Frank Siewert, “Pushing the limits - latest developments in angle metrology for the inspection of ultra-precise synchrotron optics” *Proc. SPIE 9206, Advances in Metrology for X-Ray and EUV Optics V*, 92060F (September 5, 2014); doi:10.1117/12.2060953 Invited paper at SPIE 2014, Advances in Metrology for X-Ray and EUV Optics V (International) 17-21 August 2014, San Diego, California (USA)

[21]. Tanfer Yandayan, Ralf D. Geckeler, Marco Pisani, Emilio Prieto and Frank Siewert, “Recent developments in angle metrology”, *2nd MacroScale Conference, Recent Developments in Traceable Dimensional Measurements*, 28th to 30th October 2014

[22]. Fernanda Saraiva, Rastreabilidade metrologica do angulo plano e a cristalografia (Metrological traceability of plane angle and crystallography), 19ª Conferência Nacional de Física | 24º Encontro Ibérico para o Ensino da Física, ISBN: 978-989-8481-45-0.

[23]. Tsukasa Watanabe, Yohan Kondo and Hiroyuki Fujimoto, “Evaluation of dynamic spindle run out ability of self-calibratable rotary encoder”, *11th IMEKO Symposium, Laser Metrology for Precision Measurement and Inspection in Industry (LMPMI)*, 02.-05. Sept. 2014, Tsukuba, Japan.

[24]. Youichi Bitou and Yohan Kondo, “Scanning deflectometric profiler with small beam size using a commercially available autocollimator”, *11th IMEKO Symposium, Laser Metrology for Precision Measurement and Inspection in Industry (LMPMI)*, 02.-05. Sept. 2014, Tsukuba, Japan.

[25]. Ralf D. Geckeler, Michael Krause, Andreas Just, Oliver Kranz, and Harald Bosse, “New Frontiers in Angle Metrology at the PTB”, *11th IMEKO Symposium, Laser Metrology for Precision Measurement and Inspection in Industry (LMPMI)*, 02.-05. Sept. 2014, Tsukuba, Japan.

[26]. Oliver Kranz, Ralf D. Geckeler, Andreas Just, Michael Krause, “Charakterisierung und Justage des Spatial Angle Autocollimator Calibrators der PTB”, *DGaO,* June 2014, Karsruhe (Germany)

[27]. Aitor Olarra, Andoni Delgado, Mikel Zubieta, Gorka Kortaberria, Emilio Prieto, Maria del Mar Perez, Tomás Morlanes, "Development of a novel high precision Large Range Small Angle Generator", Proceedings of the 16th International Conference of the European Society for Precision Engineering and Nanotechnology, EUSPEN 2016, 30 May – 3 June 2016, Nottingham, UK. ISBN: 9780956679086.

[28]. Marco Pisani and Milena Astrua, "The new INRIM rotating encoder angle comparator: REAC", Proceedings of the 16th International Conference of the European Society for Precision Engineering and Nanotechnology, EUSPEN 2016, 30 May – 3 June 2016, Nottingham, UK. ISBN: 9780956679086.

[29]. Tanfer Yandayan and Ralf Geckeler, "Demands for nanoradian angle metrology and performance requirements on autocollimators", euspen’s 17th International Conference & Exhibition, Hannover, DE, May 2017. (www.euspen.eu).

[30]. Tanfer Yandayan " A portable Large Range Small Angle Generator (LRSAG) for precise calibration of autocollimators ", euspen’s 17th International Conference & Exhibition, Hannover, DE, May 2017. (www.euspen.eu).

[31]. Katarzyna Nicińska, Joanna Przybylska, “Udział Laboratorium Kąta w projekcje EMRP SIB 58 Angles” (Participation of Angle Laboratory in the Project EMRP SIB 58 Angles), Konferencja Podstawowe Problemy Metrologii, Kościelisko 15 – 18 June 2014, ISBN: 978-83-930505-9-8

[32]. Joanna Przybylska, Katarzyna Nicińska, „Wzorcowanie precyzyjnych autokolimatorów i enkoderów katowych z zastosowaniem shearing techniques – efekt prac w ramach wspólnego projektu EMRP SIB 58 Angles”, VII Kongres Metrologii, Lublin - Nałęczów, 28 June – 01 July 2016, ISBN 978-83-79471-96-6

[33]. Tanfer Yandayan “Recent developments in nanoradian-angle metrology” Proc. SPIE 10385, Advances in Metrology for X-Ray and EUV Optics VII, 06-10 August 2017, San Diego, California (USA). doi: 10.1117/12.2274192 .

[34]. Tanfer Yandayan “A portable device for calibration of autocollimators with nanoradian precision” Proc. SPIE 10385, Advances in Metrology for X-Ray and EUV Optics VII, 06-10 August 2017, San Diego, California (USA). doi: 10.1117/12.2274178 .

JRP start date and duration:	01 September 2013, 36 months
JRP-Coordinator: Dr. Tanfer Yandayan, TUBITAK Tel: +90 262 679 5000 E-mail: tanfer.yandayan@tubitak.gov.tr JRP website address: http://www.anglemetrology.com/	
JRP-Partners: JRP-Partner 1 TUBITAK, Turkey JRP-Partner 2 CEM, Spain JRP-Partner 3 CMI, Czech Republic JRP-Partner 4 INRIM, Italy JRP-Partner 5 IPQ, Portugal JRP-Partner 6 LNE, France JRP-Partner 7 GUM, Poland	JRP-Partner 8 VTT, Finland JRP-Partner 9 PTB, Germany JRP-Partner 10 SMD, Belgium JRP-Partner 11 AIST, Japan JRP-Partner 12 FAGOR, Spain JRP-Partner 13 IK4-TEKNIKER, Spain JRP-Partner 14 KRISS, Korea JRP-Partner 15 MWO, Germany
REG-Researcher (associated Home Organisation):	Frank Siewert, Germany HZB, Germany

The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union