High precision (Advanced) angle metrology: pushing the limits for nanoradian uncertainty demands

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Abstract. 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. Recently, an angle metrology project supported under European Metrology Research Programme (EMRP) has been completed. This project has made a significant contribution to traceable angle metrology targeting at nanoradian uncertainty (less than 50 nrad) for stringent demands and achieved milestones. It has provided novel methods, tools, instruments, guides and knowledge that will help to ensure use of precise angle metrology equipment for the demands which have not been answered before. Some of the new devices are already commercially available and have been started to be used for critical needs. This paper gives highlights of the project’s outputs and inform the community about recent developments in high precision advanced angle metrology.

1. Introduction
High precision angle metrology 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. Angle measuring devices used in high precision applications include:

- Autocollimators: versatile instruments for the precise and contactless measurement of angles of reflecting surfaces, used to measure surface topography of optical surfaces very precisely.
- 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 to use these devices for accurate traceable angle measurement generation at low sub-nrad 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 (SR) and Free Electron Laser (FEL) 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.

European National Metrology Institutes (NMIs) have taken into account these challenging demands and conducted an angle metrology project called SIB58 Angles [1] with participation of 16 worldwide partners. The project run between Sept. 2013-2016 to improve the dissemination of the SI angle unit ‘radian’ for the most challenging applications. It 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. This paper gives a summary information on the results of the project SIB58 Angles. Investigations consist of extensive research work for metrological characterisation of autocollimators, and their application in profilometry, precise angle encoders and small angle generators.

2. Metrological characterization of autocollimators and their applications in profilometry

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 0.001" (arcsec or 5 nrad) are utilized to this purpose. For example, the improved determination of the constant of gravitation $G$ relies on the precise determination of angular deflections [2]. Autocollimators are also used in profilometry for the inspection of ultra-precise X-ray optical components [3]. Extensive research for ‘Metrological characterization of autocollimators and their application in profilometry’ was required for reaching metrological limits in the autocollimator-based form measurement of curved optics and nanoradian angle metrology applications. Figure 1 illustrates the measuring conditions for an autocollimator when used in profilometry.

2.1. Metrological characterization of autocollimators

A review of the state of the art of autocollimator application, performance, and calibration carried out is available on the project website [1]. 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 [4]. 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. Figure 2 illustrates the calibration results of an autocollimator obtained at two different optical path lengths, 300 and 600 mm by TUBITAK (NMI of Turkey). The influence of optical path length variation seen on the autocollimator’s angular response is less than 0.1 arcsec ("). Some autocollimators produce angular errors of a few arcsecs for such optical path length changes.

Autocollimators used in profilometry require two-axis (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. The new facilities are a Spatial Angle Autocollimator Calibrator at PTB (NMI of Germany) [5] and an interferometer-based two-axis autocollimator calibration set-up at VTT (NMI of Finland) [6]. 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. The application in autocollimators is expected to increase the performance when used with small apertures (< 2.5 mm diameter) for inspection of future X-ray and extreme ultra violet optics.

2.2. Applications of autocollimators in profilometry

The project reviewed current measurement practices and literature values to assess the state of the art for autocollimator-based form measurement of optics [1]. Subsequently, experimental investigations were carried out, particularly for the influences of the reflectivity and curvature of optical surfaces on the angle response of autocollimators [1]. These investigations are important for reaching the limits of autocollimator-based form measurement of optics in SR and FEL applications.
A novel autocollimator aperture centring device (ACenD) was developed, which for the first time allowed the efficient use of autocollimators in profilometry. ACenD can be used to centre an aperture up to 0.1 mm to the optical axis of the autocollimator. ACenD was tested on the precise centring of small apertures when used with autocollimators. The project partners verified that ACenD is capable of achieving a reproducible aperture alignment less than 0.1 mm. 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. The device is now available as a commercial product by Möller-Wedel Optical in Germany [7], and is expected to provide solutions for form measurement and subsequently fabrication of future SR optics.

3. Precise angle encoders
A review of the state of the art of angle encoder application, performance, and calibration was produced [1]. A new angle reference standard was established in INRIM (NMI of Italy), reducing non-uniformity and interpolation errors [8]. A self-calibration method for precise in-situ calibration of multiple head angle encoders was created at PTB for the optimisation of the in-situ calibration of angle encoders particularly in cost-effective industrial applications [9]. Investigations on alignment-form effects for the performance of angle encoders were completed in TUBITAK. New tools were developed in CEM (NMI of Spain) for calibration of encoders on rotary tables. 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. The first adaptation of the shearing techniques (a method used to separate the errors of test and reference measurement system) to the precise calibration of autocollimators with angle encoders was completed [10]. For separation of autocollimator and angle encoder errors, uncertainties of 0.001° (5 nrad) were achieved, giving an improvement by a factor of 3 compared to previous values. The performance of angle encoders and interpolators were also studied using the shearing method [11]. The results showed that the shearing method is ideally suited for the calibration of interpolation errors of the devices which are difficult to characterise with other methods. Two EURAMET calibration guides were prepared [12, 13].

4. Small angle generators
After an initial review of current capabilities and extensive consultation with users at SR and FEL facilities [14] three different portable long range small angle generators (LRSAGs) were developed by the project. The aim was to achieve a calibration range of about 3600° 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 (Figure 3) [15] and CMI, and partly achieved by the device at IK4-TEKNIKER & CEM [16] where further improvements are progress. Investigations were carried out by the project for nrad and sub-nrad level angle metrology according to the demands of SR and FEL beamlines. The first traceable angle measurements in steps of 1 nrad (0.0002°) with sub-nrad sensitivity were achieved using frequency stabilised lasers and a short range small angle generator as an alternative to conventional angle interferometers [17].

Figure 1. Measuring conditions for an autocollimator in a profilometer.

Figure 2. Angle deviations of an autocollimator (Elcomat 3000) at optical lengths of 300 and 600 mm (by TUBITAK).
to this, the use of autocollimators in nrad angle measurements were investigated using different small angle generation-measurement concepts. 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) [18]. This was validated by applying the shearing method first time to the calibration of autocollimators using small angle generators [19]. The uncertainty value achieved (5 nrad) represents a substantial improvement by a factor of 3-4 compared to previous uncertainty values. Figure 4 illustrates calibration of an autocollimator in 5 nrad steps using the LRSAG of TUBITAK.

5. Conclusions

Highlights from the recent high level research work carried out in an angle metrology project, SIB58 Angles were reported. It was presented that the project succeeded in nanoradian uncertainties (e.g. 5 nrad) for realisation of SI angle unit radian and achieved milestones. It was also shown that the project has produced a range of new techniques, devices and knowledge that will enable angle metrology users to deliver their own advanced products and services in the demanded nanoradian uncertainties.

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