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Demands for nanoradian angle metrology and performance requirements on autocollimators

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Abstract
The demands for nanoradian angle measurements with unprecedented accuracy for scientific and industrial applications continue to grow. Autocollimators, optical measurement devices which measure the angular tilt of reflecting surfaces are good candidates for this and have wide range of applications in synchrotron radiation, X-ray Free Electron Lasers (XFELs), space missions, the determination of the constant of gravitation G by use of a torsion balance etc,. Uncertainties at the nanoradian scale are required for the traceable calibration of autocollimators and for studies to characterise their performance. The work carried out with respect to the calibration of autocollimators using angle metrology reference standards such as the high precision small generators of TUBITAK UME and the angle comparator of PTB is presented. Examples of achieving standard uncertainties down to 1 milliarcsec (mas) or 5 nrad by applying the shearing method and comparisons of calibrations of autocollimators by TUBITAK UME and PTB (using very small angular steps) by use of different small angle generation concepts are presented. These results represent important outcomes for improving the performance of autocollimators and their stability for nanoradian angle metrology.

SI units, traceability, small angle generator, autocollimators, nanoradian angle metrology, Synchrotron and XFEL optics

1. Introduction

Angle measurement-generation, and the control of angle tilting units at the nrad uncertainty level are essential to numerous applications [1]; 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). 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. ACs, 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 [2]; particularly for applications in synchrotron radiation and X-ray Free Electron Lasers (XFELs). These applications are highly challenging. As an example, the focusing optics proposed at the European XFEL under construction in Hamburg, requires 20 nrad rms residual slope deviation (1 nm pv figure error) [3].

Another example of the precise measurement of angular deflections with ACs is in scientific experiments, such as the improved determination of the constant of gravitation *G*. The 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 [4], the deflection of the balance was measured as 31.5" with a standard uncertainty of 1.5 mas. The angle measurement in this experiment is one of the principle uncertainty source and uncertainty of the angular value of 1.5 mas 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 [4]. 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.

These demands motivated us to investigate the ACs in detail and to evaluate their capability of achieving angle metrology at the nrad and sub-nrad level. TUBITAK UME and PTB performed investigations on the capability of electronic ACs [5] using various reference devices and newly developed methods within the EMRP SIB58 Angles project [1]. They calibrated high resolution electronic ACs in small angular steps between 0.01" and by TUBITAK, 0.001" (5 nrad, at resolution level of the ACs). Investigations were also carried out over larger measurement ranges and angular steps with uncertainties down to 0.001" (5 nrad). The results are reported below together with short descriptions of the reference devices used.

2. Facilities and methods used for nrad angle measurements

ACs are mostly calibrated by measuring the tilt angle of reflectors mounted on rotary tables (RTs) or small angle generators (SAGs). In this way, the angles generated-measured by the RTs or SAGs can be compared with the AC readings directly. RTs mostly use angle encoders as angular scales while SAGs use linear displacement sensors.

TUBITAK UME used two different small angle generators: the HPSAG [6] and LRSAG [7] working in measurement ranges of 16" and 9000", respectively. Their performances have been verified by comparisons with external partners and also by use of novel calibration methods. The HPSAG was used for the generation of ultra-small angles and performed frequency based angle measurement using a Differential Fabry-Perot Interferometer (DFPI). Angular steps of 0.2 mas (1 nrad) were generated by the HPSAG and detected using frequency stabilised lasers with the precision of 0.2 nrad as an alternative method to conventional angle interferometers. The results showed that the HPSAG is able to generate and measure ultra-small angles with sub-nrad precision [8].

PTB used their custom made WMT 220 angle comparator, their primary national standard located in a clean room at highly stable environmental conditions [9]. The system consists of a precision air bearing rotary table equipped with a radial phase grating and an interferential measuring system with a total of sixteen scanning heads. The standard uncertainty of the calibration of the WMT 220 is of the order of u = 0.001" (5 nrad) and has been verified by various internal comparisons (of cross- and self-calibration) and by comparisons with external partners which all demonstrate consistency at the level of several nrad rms.

3. Autocollimators performance and nrad angle metrology

There are various error influences on the angle measurement with ACs. 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 AC'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 are required for their evaluation. One was developed by PTB and was applied in the EMRP SIB58 Angles project for the first time to angle measurement devices [10]. This novel application of the shearing technique provides the simultaneous calibration of an autocollimator and a reference standard. Without recourse to an external standard, the errors of the two devices can be recovered, up to their linear components, from a set of three comparisons with uncertainties down to a few nrad. PTB applied this method to the calibration of ACs with an angle encoder [10] and TUBITAK UME to calibrations with a small angle generator [11]. The AC errors were determined with standard uncertainties down to 1 mas (5 nrad) by PTB and 1.4 mas (7 nrad) by TUBITAK UME. Figure 1. illustrates angle measuring error of an electronic AC (Elcomat HR) as determined by application of the shearing method.

AC performance was also tested by direct comparison of another AC (Elcomat 3000) to the reference devices. Figure 2 shows the results by TUBITAK UME and PTB for the same AC. TUBITAK UME also calibrated the same AC by the LRSAG in the steps 0.001" (5 nrad) to evaluate its performance with angular increments corresponding to its resolution (Fig. 3).

4. Conclusions

The use of autocollimators (ACs) in nanoradian angle measurements were investigated using different small angle generation-measurement concepts. The work showed that the ACs can be calibrated in the steps, near to their resolution 0.001" (5 nrad), and can be used for the non-contact angle measurements with the uncertainties down to 1 mas (5 nrad) providing a precise calibration/investigation of these devices.

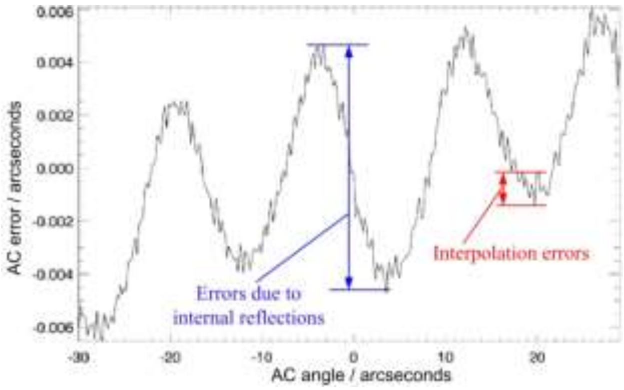

Figure 1. Measurement errors of a high resolution AC (Elcomat HR) as determined by the shearing method with a standard uncertainty of 1 mas (5 nrad) by PTB.

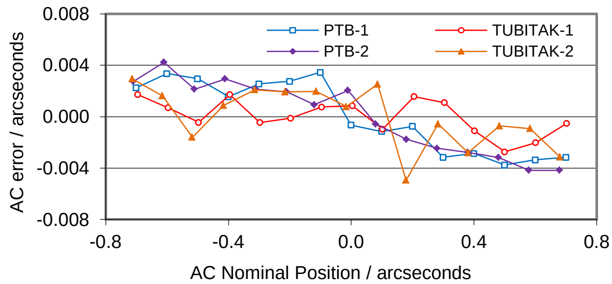

Figure 2. Results of the calibration of an AC (Elcomat 3000) in steps of 0.1" : TUBITAK-1 by use of the LRSAG reference standard, TUBITAK-2 by use of the HPSAG, and PTB-1 and PTB-2 by use of the WMT 220.

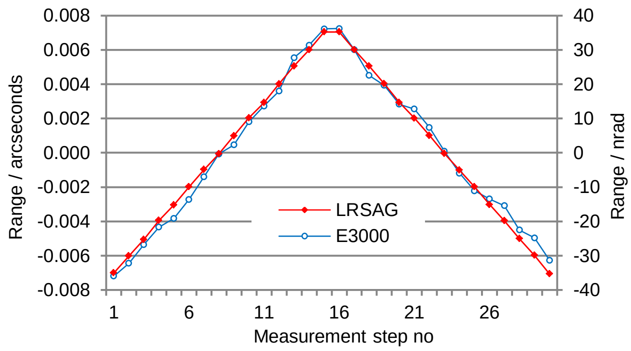

Figure 3. Direct comparison of the angle readings of an AC (Elcomat 3000) and the LRSAG in steps of 0.001" (5 nrad) by TUBITAK UME.

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