Distance-dependent autocollimator errors: Experimental characterisation and ray trace modelling

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Autocollimators (AC) are optical devices for the measurement of the inclination angles of reflecting surfaces. The AC's distance from the surface influences its angle response substantially. At PTB, calibrations at various distances have been performed to investigate the systematic distance-dependent angle errors. Furthermore, the results have been compared with ray-tracing simulations.

1 Motivation

Electronic autocollimators (AC) are utilised versatilely for non-contact angle measurements in applications like straightness measurements and the calibration of angle encoders whereas the most demanding challenges are imposed by their use in deflectometric profilometers [1]. These instruments are used for high precision form measurements of optical surfaces.

An important challenge to autocollimator calibrations originates from the profilometers' working principle (fig. 1): the distance between the surface and the AC varies which influences the AC's angle response substantially [2, 3].

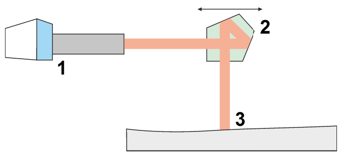

Fig. 1 *Working principle of an AC-based deflectometric profilometer. The measurement beam of an AC (1) is guided by a pentaprism (2) onto the surface under test (3). The local inclination angles of the surface are measured by means of the reflection angles of the beam. The surface is scanned by moving the pentaprism along the AC's optical axis. Its profile is determined by integrating the measured angles.*

To enable the correction of AC measurements at arbitrary distances, we performed calibrations of an AC at distances up to 1.8 m, using our new Spatial Angle Autocollimator Calibrator (SAAC).

2 Calibration set-up

The SAAC is PTB's novel calibration device which allows calibrating ACs at spatial angles of 3000×3000 arcsec² and at distances ranging from 250 mm to 1.8 m. It relies on a Cartesian arrangement of three ACs which measure the tilting angles of a common reflector cube: an AC to be calibrated (placed onto a linear stage) and two accurately calibrated ACs, working as reference measurement systems (fig. 2). This set-up effectively breaks down the spatial angle calibration of the first AC into two separate measurements of plane angles by the latter ACs [4,5]. For the presented results, the horizontal measurement axis of the AC to be calibrated was characterised (measurement values H_0). Therefore, only one reference AC was used (H_1).

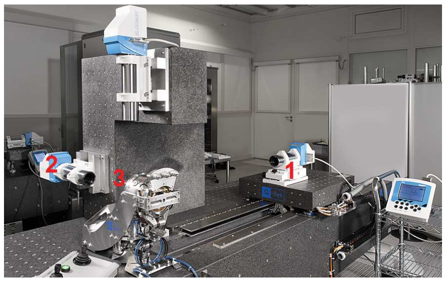

Fig. 2 *PTB's Spatial Angle Autocollimator Calibrator (SAAC) was utilised for the determination of the AC's path-length-dependent angle deviations. The AC (1, placed on linear stage) was calibrated by means of a reference AC (2) and a reflector cube (3).*

3 Calibrations

Calibrations were performed within two distance ranges: D=300 to 1800 mm (steps of 375 mm) and D=300 to 380 mm (steps of 20 mm). The measurement range was H_0=-900 to 900 arcsec. The results for the large distance range are shown in fig. 3, where $\delta H = H_0 - H_1$.

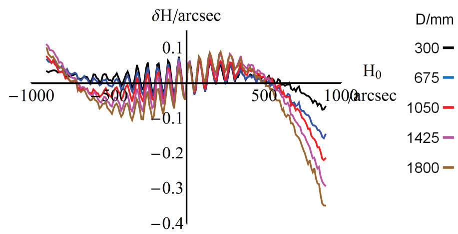

Fig. 3 *Differences between the horizontal measurement values of the AC to be calibrated (H_0) and the reference AC (H_1) for the investigated optical path lengths D ($\delta H(0)=0$).*

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4 Path length effect

The calibration at D=300 mm is considered as a reference calibration. The differences between the angle deviations of the reference calibration and the deviations of the calibrations at other distances are shown in fig. 4 (small distance range) and fig. 5 (large distance range). These are the remaining path-length-dependent angle deviations of the AC.

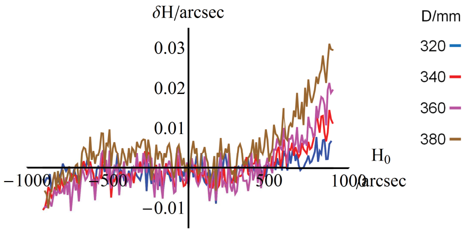

Fig. 4 *Angle deviations of the autocollimator in a path length range of 80 mm. The differences to the reference calibration (D=300 mm) are shown.*

A polynomial approximation of the path-length-dependent angle deviations (fig. 5) can be used to correct the angle measurements of the AC for values of D where no calibration data are available. Note that short-periodic angle deviations are unique for each distance and cannot be corrected by the approximation. However, their magnitude is much smaller than the effect of the path length. The standard deviation of all residues is 0.006 arcsec.

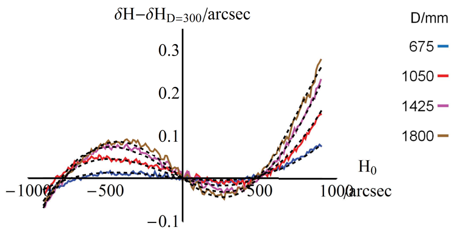

Fig. 5 *Angle deviations of the autocollimator in a path length range of 1.5 m. The differences to the reference calibration (D=300 mm) are shown (solid lines). The dashed lines show polynomial approximations which consider the path length and the measurement angle.*

Fig. 6 shows the standard deviation of the angle differences (fig. 5, regarding the full measurement range) as a function of the path length.

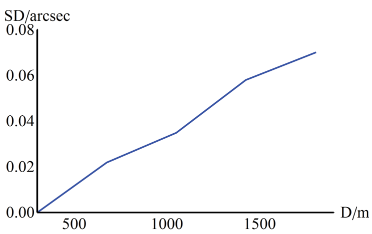

Fig. 6 *Standard deviation of the autocollimator's angle deviations for the full measurement range as a function of the path length D. Reference: D=300 mm.*

The standard deviation of the angle differences exceeds 0.01 arcsec for D>470 mm which is not acceptable for high precision deflectometry.

5 Comparison with ray-tracing simulations

A ray-tracing model of the AC was used to simulate the path length effect. The simulation included realistic values of the AC objective's tilting and of the sensor's defocusing. The results are in good agreement with the experiments (fig. 7).

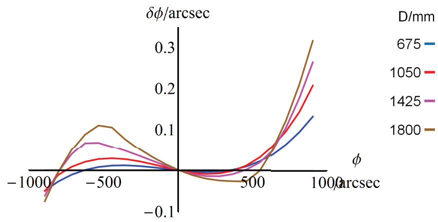

Fig. 7 *Result of the ray-tracing simulations. The path-length-dependent angle deviations are in good agreement with the measurement results if the objective's tilting and the CCD defocusing are taken into account.*

6 Conclusion

We performed calibrations of an AC at different distances to characterise its path-length-dependent angle deviations. The results are in good agreement with ray-tracing simulations. A polynomial approximation of the path length effect can be derived from calibrations at different path lengths and be used to correct the AC measurements for distances where no calibration data is available.

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