Advancing from plane to spatial angle in autocollimator calibration

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In this contribution, we present our latest efforts at the Physikalisch-Technische Bundesanstalt (PTB) to develop a novel autocollimator calibration device, the Spatial Angle Autocollimator Calibrator (SAAC). It will address the extension of traceable angle calibrations from the plane to spatial angles and the calibration of the effects of optical path length changes of the autocollimator beam.

1 Motivation

Autocollimators (AC) are well suited for use in profilometers (see figure 1) which have successfully been applied to the definition of flatness standards at NMIs and the measurement of beam-shaping surfaces for beamlines of synchrotrons and Free Electron Lasers (FEL).

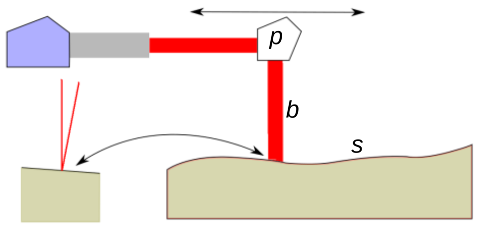

Figure 1
Schematic view of a profilometer: A moving pentaprism (p) guides the AC beam (b) towards the surface under test (s) where it is reflected. The AC measures the displacement d of the reticle image in its focal plane, d=f tan(2α)*, f: focal length,* α*: angle between the surface normal and the optical axis. Integrating the measured angles yields the surface topography.*

In practical applications, the AC beam is reflected simultaneously in two orthogonal angular directions (both measurement axes of the AC are engaged), and the optical path length changes due to the movement of the pentaprism scanning the surface under test. Both effects influence the AC's angle measurement and need to be calibrated [1]. For a comprehensive overview of the use of ACs in deflectometry and the specific challenges associated with this application, see [2].

2 Setup of the SAAC

Figure 2 presents the basic setup of the SAAC system. It makes use of an innovative Cartesian arrangement of the three ACs (two reference ACs and the AC to be calibrated, all orthogonal with respect to each other) which has been developed at PTB. It allows measuring the angular orientation of a reflector cube in space.

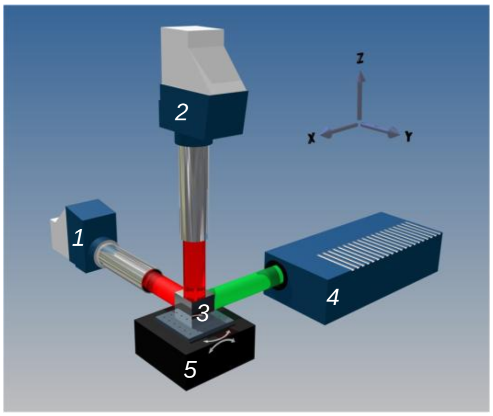

Figure 2
Key components of the SAAC are two reference ACs (horizontal (1) and vertical (2)), a reflector cube (3) and the AC to be calibrated (4). The reflector cube's yaw and pitch angles (as seen from the AC to be calibrated) are manipulated by a two-axis tilting system (5).

The variable optical path length is realised by a linear stage onto which the AC to be calibrated will be placed. The differential tilting between the reflector cube and the linear stage will be monitored by an angle interferometer.

3 Traceability to the national standard

The SAAC uses a Cartesian arrangement of three ACs, see figure 2. The two rotational axes of the reflector cube are coaxial to the optical axes of the reference ACs. Therefore, each of the reference ACs is primarily sensitive to rotations around one of the two axes, whereas the AC to be calibrated is sensitive to rotations around both axes (see figures 3 and 4). In this way, the measurement of the angular orientation of the reflector cube is effectively divided into two separate measurements of plane angles by the reference ACs. Therefore, each reference AC can be calibrated in a conventional manner and traceability to the national angle standard, the WMT 220 – which is based on the subdivision of the full circle in a plane as a natural, error-free angular standard of 2π rad [3] – can be established.

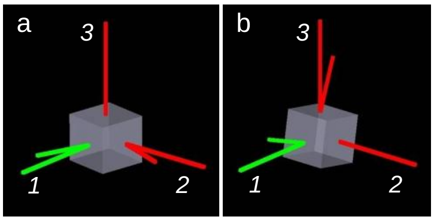

Figure 3
Deflection of the autocollimators' beams for horizontal (yaw) (a) and vertical (pitch) (b) cube angles. (1) AC to be calibrated, (2) horizontal reference AC, (3) vertical reference AC.

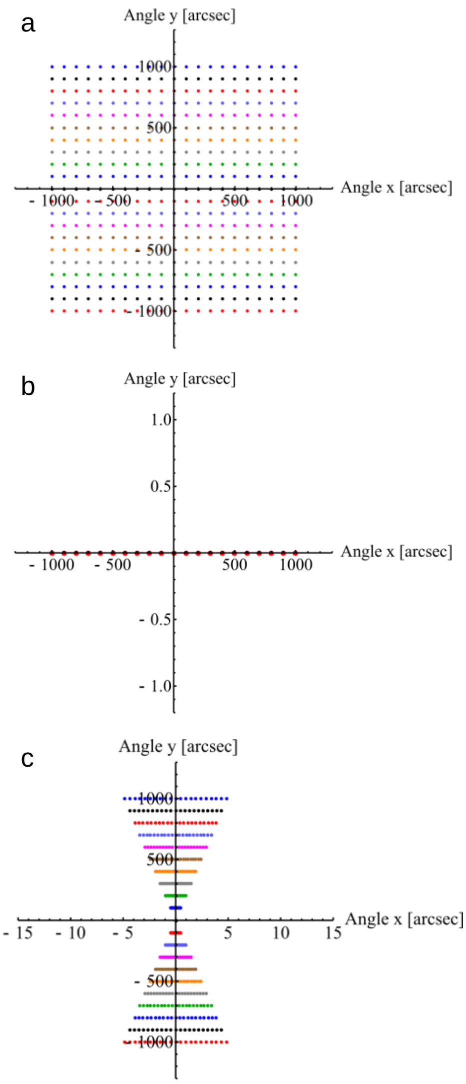

Figure 4
Response of the ACs to a typical n×n calibration grid of pitch and yaw angles. (a) AC to be calibrated, (b) horizontal reference AC, (c) vertical reference AC.

In case of the vertical reference AC, not only the main measurement axis is engaged (y-axis in figure 4a), but also – to a smaller degree – the orthogonal axis (x-axis; notice the highly different scaling of the axes). This effect results from the combination of rotations of the reflector cube around two axes, i.e., it is connected to the mechanical coupling of the two stacked rotational axes of the tilting unit. To account for possible influences of this effect on the angle measurement of the affected reference AC, it needs to be calibrated more extensively.

4 Influence and correction of errors

Even after careful manufacturing and alignment of the SAAC's components, a number of errors will affect its operation, e.g., the residual alignment errors of the components, the non-orthogonality of the reflector cube's surfaces, and the non-orthogonality of the rotational axes of the tilting unit. Some errors, e.g., the relative angular orientations of the cube's surfaces, can be characterised in advance. The remaining ones, however, need to be characterised, preferably in-situ. To this purpose, the reflector cube is rotated in pitch and yaw (e.g., to scan a regular grid of angles as shown in figures 4a-c) to obtain a suitable set of calibration measurements. An optimisation algorithm uses a mathematical model of the system to retrieve the missing parameters and the true angular orientations of the reflector cube from the redundant set of measurements by the reference ACs. Afterwards, the parameter set from the calibration can be used during the operation of SAAC for an online correction of the error influences.

5 Conclusion

The SAAC will be the first realisation of a two-axis angle calibration device for ACs by an NMI. Its aim is to precisely characterise the crosstalk between the two measurement axes of ACs and the impact of variable path lengths. It has the potential to increase the precision of form measurements with AC-based profilometers, to help AC manufacturers improve their instruments, and to advance angle measurement in precision engineering.

References

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