Recent advances in spatial angle autocollimator calibration at PTB

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In this paper, we present our latest improvements of the Spatial Angle Autocollimator Calibrator (SAAC) at the Physikalisch-Technische Bundesanstalt (PTB). The SAAC is capable of traceable spatial angle calibration of autocollimators (AC) at a variable optical path length. The main focus is set on the mathematical modelling of the spatial orientation of the components.

1 Introduction

Autocollimators are optical instruments for the measurement of the inclination angle of reflecting surfaces. They are widely applied, for example, in angle metrology, precision engineering and in deflectometry. A detailed overview of the demands on autocollimator calibration is given in [1].

2 SAAC

The Spatial Angle Autocollimator Calibrator (SAAC) is designed to improve calibration capabilities in multiple ways with the extension to spatial calibration being the most important. See [2] for a detailed description of the concept.

The SAAC consists of a Cartesian arrangement of three autocollimators, each facing one side of a reflector cube (see Fig. 1). The reflector cube is mounted on a tilting unit and is rotatable around two axes, which correspond to the axes to which the autocollimator to be calibrated (AC-C) is sensitive. The two reference autocollimators AC-H and AC-V are sensitive to only one of these axes of rotation each.

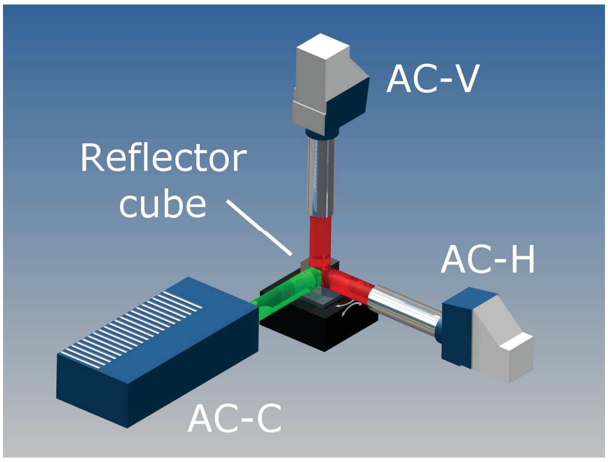

Fig. 1 *Principle design of the SAAC with two reference autocollimators (AC-H and AC-V) and the autocollimator to be calibrated (AC-C). All are facing one side of the reflector cube in the centre, mounted on a 2D tilting unit.*

This arrangement allows it to split a 2D angle measurement into two 1D measurements of the two reference autocollimators. The angle measurement of the two reference autocollimators can be traced to the primary standard of plane angle WMT 220 [3].

A typical calibration consists of a regularly spaced grid of sampling points in both measuring axes of AC-C (see Fig. 2). The modelling (see next section) is completely based on the calibration grid, i.e. no auxiliary measurements are necessary. The small spreading in the secondary axis of AC-V is caused by unavoidable crosstalk between the axes of rotation of the tilting unit.

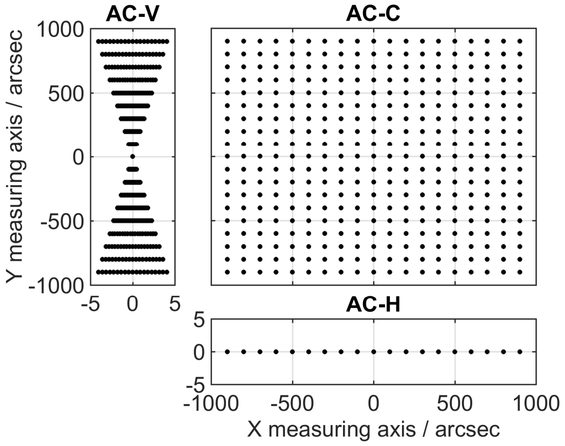

Fig. 2 *Simulated measurement values of all autocollimators in a typical calibration grid measurement with equal spacing in both axes. Note the highly different scaling in the secondary axes of the reference autocollimators.*

3 Mathematical modelling

The main purpose of modelling the SAAC is the calculation of the cube's angular orientation at every sampling point and, furthermore, calculation of the reference measurement values of the autocollimator to be calibrated. In [4] a complete model with an alternative analytical approach is described.

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The new, improved model describes the path of the light geometrically, starting with the autocollimators’ outgoing beams, the reflection at the cubes surfaces and their projections on the measurement axes back in the autocollimators.

Each element (measuring beams and axes, optical axes, surface normal vectors) is modelled by a three-dimensional vector, which is consecutively rotated and/or reflected to archive the designated spatial orientation (for example, the alignment of the autocollimators). The rotations and reflections are described numerically, which has multiple advantages. The two most important are the possibility of using every single sampling point to reduce uncertainty and a high flexibility in choosing the measurement parameters and sampling points.

To calculate the alignment parameters and the cube’s orientation from angular readings of the autocollimators, as in a measurement, it is necessary to solve the inverse problem of the described process. This is solved by using the Nelder-Mead optimisation algorithm [5] to calculate the best-fit parameters in a least-squares sense.

The alignment parameters are used to calculate the reference measurement values of the autocollimator to be calibrated. The strength of the model is that the alignment can be calculated and corrected in situ within a single calibration grid.

4 Monte Carlo Simulation

To evaluate the uncertainty of the optimisation process, extensive Monte Carlo simulations were performed. Tab. 1 shows the main results of these simulations for three different calibration grids with different spacings. The table lists the uncertainty propagation factors, which are the ratio of the uncertainty of the calculated value and the uncertainty of the measurement values of the reference autocollimators u_{ref} .

In the upper part of the table, the propagation factors of the alignment parameters of all autocollimators are listed. They heavily depend on the size of the calibration grid and the number of sampling points and are spread over several orders of magnitude.

In contrast to this, the all-important propagation factor relating to the uncertainty of the reference measurement values of the autocollimator to be calibrated u_{cal} is independent of the calibration grid and, even more important, is 1.0. Therefore, the uncertainty of an autocollimator calibration at the SAAC is almost completely determined by the uncertainty of the reference autocollimators.

$u_{ref} \rightarrow \ldots$	Uncertainty propagation coefficients		
	1800x1800” 19x19 samples	1800x1800” 31x31 samples	90x90” 31x31 samples
$u_{\alpha H}$	29	18	340
$u_{\beta V}$	28	18	360
$u_{\gamma V}$	0.076	0.045	0.046
$u_{\alpha C}$	0.054	0.031	0.032
$u_{\beta C}$	0.053	0.032	0.033
$u_{\gamma C}$	14	8.6	170
u_{cal}	1.0	1.0	1.0

Tab. 1 *Overview of uncertainty propagation factors of several parameters for different calibration grids. These factors are calculated with parameters and uncertainties which are typically achievable within the SAAC. All factors are given with two significant digits.*

5 Summary

The SAAC is capable of 2D autocollimator calibration with varying calibration conditions. With the new model described above and its numerical formulation, the flexibility in choosing the parameters of the calibration grid is increased. Furthermore, the uncertainty of autocollimator calibration is reduced.

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