Guidelines on the Calibration of Autocollimators

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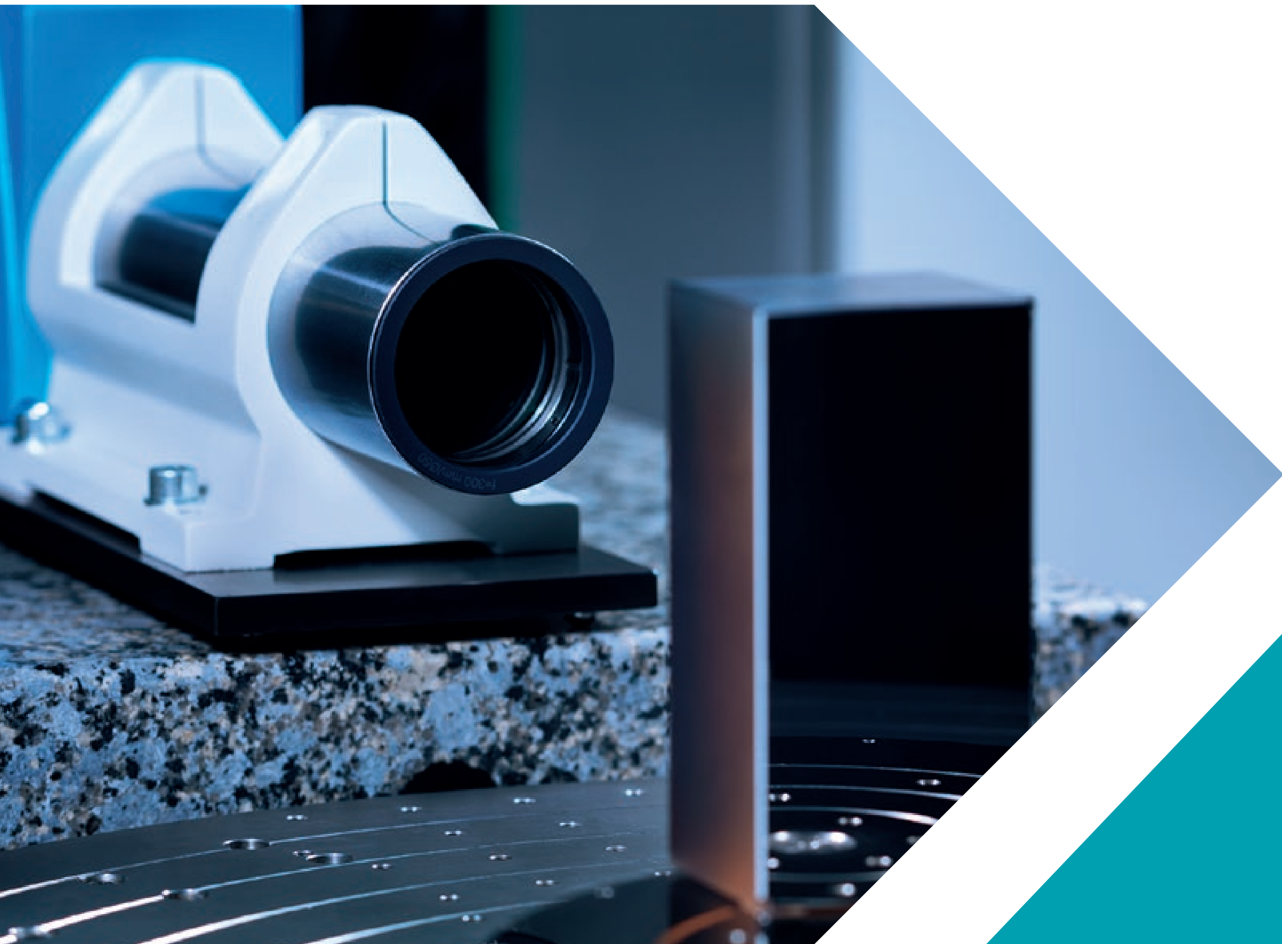
Version 1.0 (07/2017)



Length

Authorship and Imprint

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Guidance publications

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Purpose

This document has been produced to enhance the equivalence and mutual recognition of calibration results obtained by laboratories performing calibration of autocollimators.

Content

1 INTRODUCTION

The aim of this document is to provide guidelines and improve harmonisation for calibration of autocollimators. It gives advice to calibration laboratories to establish practical procedures. The guideline is based on the knowledge produced under SIB58 Angles EMRP project [1], published papers [2-23] and EURAMET.L-K3a.2009 key comparison protocol for calibration of autocollimators [10]. In the first part (sections 2, 3 and 4), the general definitions and the technical requirements for the calibration of autocollimators are given. The second part of this guideline is of procedural nature and gives practical advice to calibration laboratories. In sections 5 and 6 an example of a typical calibration procedure is presented. It is noted that laboratories working according to ISO/IEC 17025 shall validate their calibration procedures. This may lead to modification of the principles and examples given in this document.

2 SCOPE AND FIELD OF APPLICATION

This guideline refers to angle measuring instruments - autocollimators used for the precise and non-contact angular displacement measurement of a mirror or other suitable reflecting surfaces.

The autocollimators are well suited for a broad range of applications in metrology and industrial manufacturing, e.g., angle adjustment, measurement of straightness, parallelism and rectangularity of machine tools, etc. In recent years, electronic autocollimators have also proved to be capable of providing highly accurate angle metrology for the form measurement of challenging (due to their size / topography range / gradients) optical surfaces.

The guideline is intended for precise calibration of electronic autocollimators since they have increasing demand for wide range of scientific and industrial applications, e.g., in precision engineering, optics, synchrotron beam line metrology, aerospace, geodesy, navigation, and astronomy. However, the procedure described in the guide can also be utilised for calibration of analogue autocollimators.

2.1 Components

An electronic autocollimator consists of an optical unit comprising various electro-optical parts and an electronic display unit [2]. The principle of the instrument is illustrated in figure 1. The image of the illuminated object reticle (e.g. slit) located at the focal plane of the collimator objective (lens of the autocollimator) is projected to infinity. In some distance, the collimated beam is reflected back into the device from a mirrored surface (a reflective surface) and the resulting image of the object in the focal plane is picked up by a light-sensitive receiver (e.g. a CCD). The beam splitter provides separation of outgoing light and the light reflected back into to the autocollimator by the mirrored surface. If the reflective surface is tilted by an angle α with respect to the optical axis, the reflected beam will enter the objective lens with an angle 2α. This leads to a shift s of the image which can be calculated with the objective focal length f by

$$s = f \times \tan(2\alpha) \quad (1)$$

Thus, the sample angle is proportional to the measured shift of the image (s). The resolution of an autocollimator increases proportionally and the angular field of view reciprocally with the focal length of the objective lens.

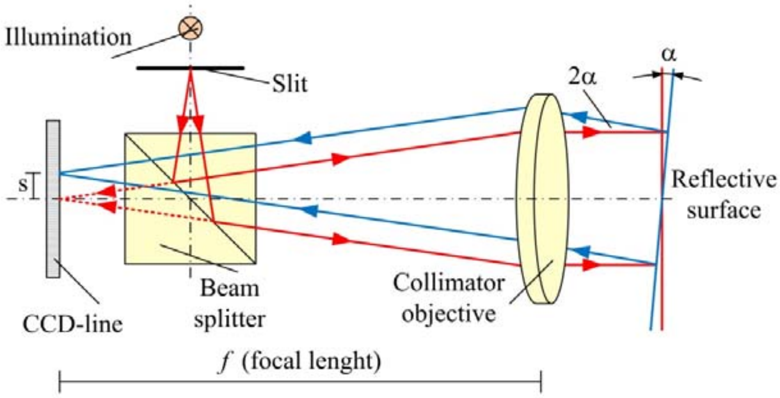


Figure 1: Schematic diagram for principle of electronic autocollimator.

2.2 Laboratory environment / Site of calibration

The autocollimator shall be calibrated in a laboratory that provides adequate control for environmental conditions (stable ambient temperature, low vibration, and a stable laminar air flow). In order to achieve the required uncertainty for high resolution electronic autocollimators (e.g. less than 0.1 arcsec), temperature stability to within ±0.3ºC (in the laboratory) is desirable. Additionally, it is recommended to shield the calibration set-up e.g. using a foam box in order to obtain stable results if there is no very stable laminar air flow. This also gives additional temperature stability to within ±0.05ºC around the beam path of the autocollimator (providing that no significant heat sources, e.g. electronic circuits or motors with high heat dissipation are in the box).

Additional care is required for air-pressure and humidity since both are influencing the refractive index of air and have an impact on the instrument performance. It is recommended to report these environment conditions in the certificate particularly for specified uncertainties of less than 0.1 arcsec.

2.3 Calibration conditions

The autocollimator must be operated in the experimental set-up under the same measurement conditions under which it was calibrated if the user wants to make full use of the autocollimator’s calibration values for correcting its angle measuring deviations. In other words, the calibration is only valid if the calibration and measurement conditions are identical. Any deviation between both leads to additional errors in the autocollimator’s angle response which need to be characterised by additional calibrations or ray trace modelling [1, 8]. This is particularly important if the user wants to achieve accuracies better than manufacturer tolerances (i.e. use of the autocollimator with its ultimate limits).

On the other side, the need for a high lateral resolution in deflectometric profilometry is driving the autocollimator apertures towards ever smaller diameters, issues such as the limits of the validity of the calibration and proper specifications for the adjustment of the optical components in deflectometric set-ups become ever more significant. Detailed information for the current limitations of angle metrology with autocollimators can be reached through references [1, 3-9].

In short, the factors influencing the angle response/calibration of an autocollimator can be sub-divided into two broad categories: external vs. internal [8]. Internal factors are specific to each autocollimator's internal design (and are therefore generally beyond user control). External factors are given by the measuring conditions under which the device is used (and can thus be specified by the user). They are:

- Surface under test (SUT) reflectivity
- Surface under test (SUT) curvature
- Distance (path length) to the SUT
- Diameter and shape of the aperture stop
- Position of the aperture stop along the autocollimator's optical axis
- Lateral position of the aperture stop perpendicular to the optical axis

The figure 2 illustrates the conditions that should be considered for the autocollimators being used in deflectometric profilometry [9].

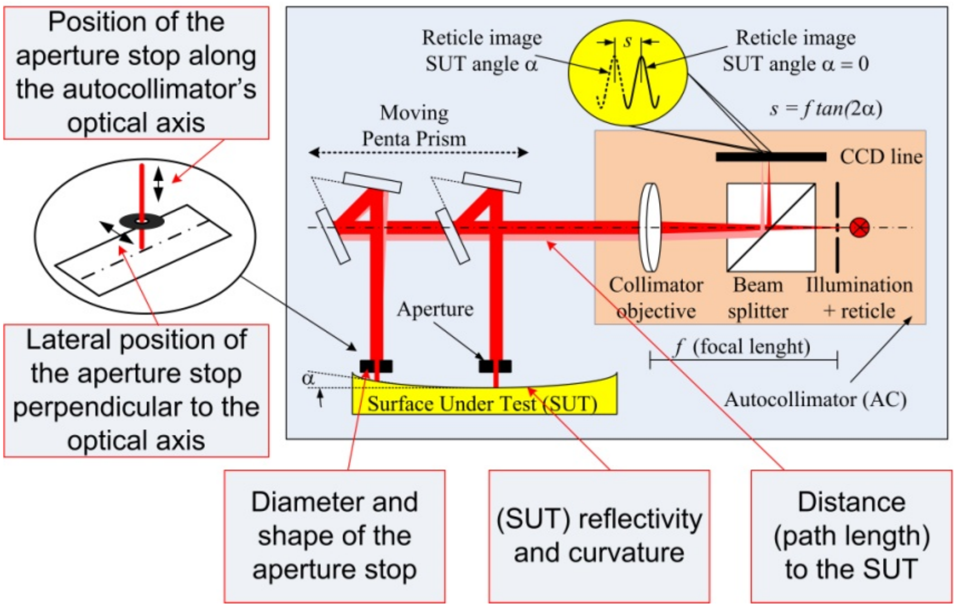


Figure 2: Measuring conditions for autocollimator when used in profilometry [9, 22].

Significant differences in the calibration may occur in case of changes in one or several parameters. Therefore, the above conditions must be taken into account during calibration of the autocollimators and shall be specified in the calibration certificate (see section 8 for the details).

3 TERMINOLOGY

The definitions used in this guideline are in compliance with the EURAMET.L-K3a.2009 key comparison protocol - Angle Comparison Using an Autocollimator [10]:

Table 1: Overview of measurands / parameters used in EURAMET.L-K3a.2009 Intercomparison protocol.

Symbol	Description
$\delta(\alpha_{AC})$	angle deviation of the autocollimator at the sampling point α_{AC}
$\sigma(\delta)$	repeatability (standard deviation) of δ , calculated from repeated measurements
α_{AC}	x-angle measured by the autocollimator (sampling point)
$\sigma(\alpha_{AC})$	repeatability (standard deviation) of α_{AC}
$\beta_{AC}\ (\alpha_{AC})$	y-angle measured by the autocollimator at the sampling point α_{AC}
n_{AC}	number of repeat measurements with the autocollimator which are averaged to obtain δ within an individual calibration
n_{REF}	number of repeat measurements with the reference system which are averaged to obtain δ within an individual calibration
n_r	number of individual repeat calibrations (in case that several independent calibrations are averaged to obtain the final calibration result) (if applicable, the laboratories may perform calibrations in different relative angular orientations between the autocollimator and the reference system, see section 5.2)
$u(\delta)$	standard measurement uncertainty associated with δ
$v_{eff}(\delta)$	effective degrees of freedom associated with δ
k	coverage factor for 95% coverage probability associated with δ

4 EQUIPMENT AND DEVICES

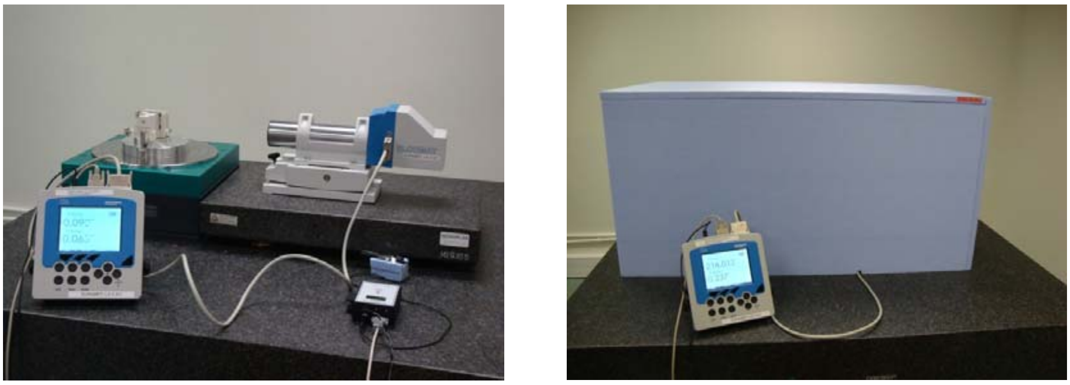
The autocollimators shall be calibrated by reference angle measuring devices / standards that are traceable to the SI unit radian. The auxiliary devices also play an important role for calibration results. For example, systematic errors due to the mirror's (SUT) curvature and reflectivity may occur. In order to prevent this, suitable SUT (mirror) agreed with the customer shall be used and its specifications shall be reported in the certificate. The below equipment and devices are recommended for calibration of autocollimators.

4.1 Reference standards / devices (systems)

Traceable reference standard / devices (reference systems) to SI unit radian [14] shall be used. Prior to use, they shall be fully investigated and uncertainty values that will contribute shall be determined. The method for investigations and calibration of the angle reference systems vary with their types. The recommendations are given in sections (4.1.1 to 4.1.4) with related publications for the mostly used angle reference systems.

4.1.1 Angle comparators (Rotary tables fitted with angle encoders)

The angle comparators are rotary tables (mostly air-bearing rotary tables) equipped with angle encoders. The method for achieving traceability to the SI unit radian is based on a subdivision of the natural and error-free standard of the full circle, 360° = 2π rad. These tables must be calibrated and fully investigated prior to use for calibration of autocollimators. The examples for these tables and their investigation for calibration of autocollimators are given in [11, 12] for those fitted with multiple read-head angle encoders and in [13] with one read-head angle encoders. After the investigations, the user may also decide to choose convenient angular displacement steps for calibration of the autocollimators with respected uncertainty values. The figure 3 illustrates photos of calibration set-ups in TUBITAK UME (National Metrology Institute of Turkey).

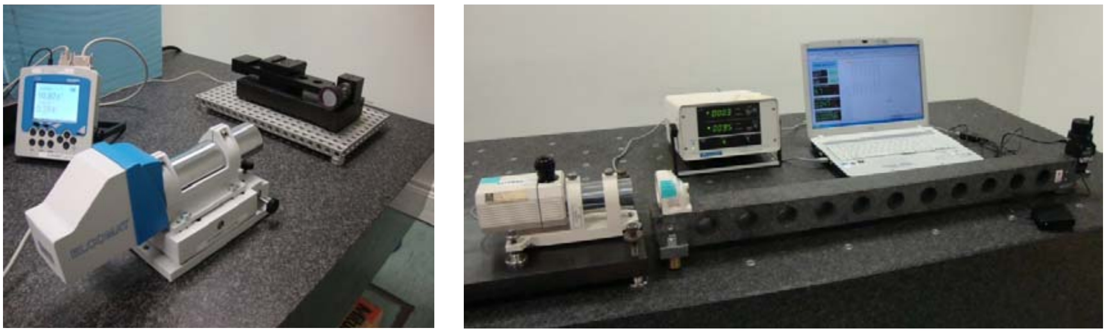


(a) (b)

Figure 3: Calibration of an electronic autocollimator (a) using TUBITAK UME angle comparator (b) shielded with foam for calibration with more stable ambient conditions.

4.1.2 Small angle generators (SAGs)

The calibration of autocollimators shall be carried out by the use of so-called small angle generators - SAGs (sine or tangent arm) in which the angle measurement is traceable to the length unit (ratio of two lengths) [14]. Various types of SAGs exist [15-17]. They must be fully evaluated before use and achievable uncertainty budget can be estimated according this evaluation. See the references for details [15-17, 23]. The figure 4 illustrates autocollimator calibration set-ups in TUBITAK UME using small angle generators.

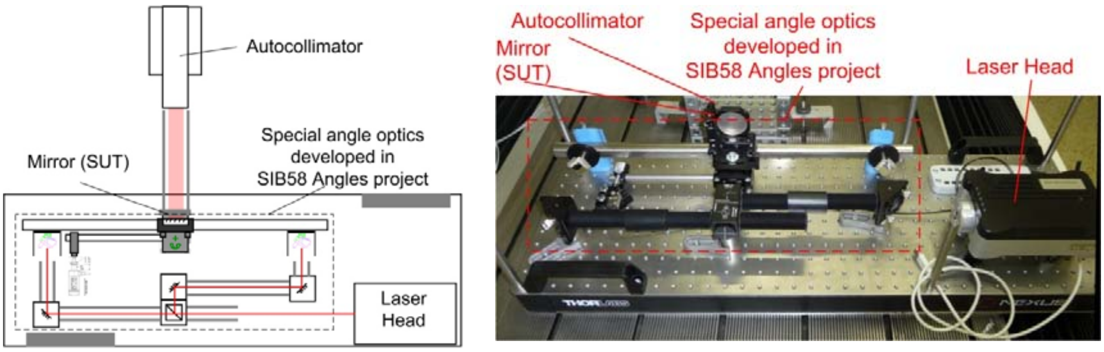


(a) (b)

Figure 4: Calibration of an electronic autocollimator (a) using high precision small angle generator (b) 1m small angle generator of TUBITAK UME.

4.1.3 Angular interferometers

The angular interferometers shall be used for calibration of autocollimators with suitable angle generation or tilting mechanism that will achieve the angular displacement steps. The angular interferometers suitable for angle generators often use arm lengths below 1 m and optical wavelengths (like 633 nm) as a scale. They can be classified into the following categories: 1D or 2D versions of angular interferometers, where one or two mostly independent angular changes are measured. The 1D version can measure different angular changes around different rotation axes sequentially (2D version simultaneously). The 2D version is generally available in principle for all setups however it is not so common in commercial devices. Details for use of angular interferometers with advantages and disadvantages are given in [18]. The figure 5 illustrates photos of calibration set-ups in CMI (National Metrology Institute of Czech Republic).



(a) (b)

Figure 5: Calibration of an electronic autocollimator using CMI's special angular interferometer (a) Schematic arrangement of the laser beam paths with test autocollimator (b) photo of angle optics with laser head.

4.1.4 Optical wedges

Optical wedges can be arranged in a suitable set-up with precise rotating mechanism to generate small angles. They are sometimes called rotating wedge small angle generators [19]. They may be used for calibration of autocollimators. Prior to use, they must be calibrated (mostly by another traceable autocollimator).

4.1.5 Reference autocollimators

Reference autocollimators traceable to SI unit radian through another angle reference system can be used with a suitable tilting or small angle generation mechanism. A piezo driven tilting mechanism / Rotary Table may be used when coupled with a suitable mirror and reference autocollimator. Schematic arrangement is illustrated in Figure 6 for this application.

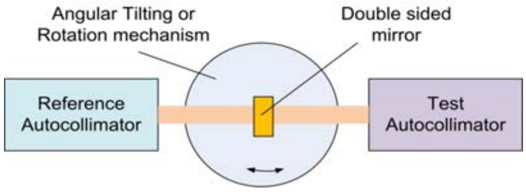


Figure 6: Schematic diagram for calibration of an electronic autocollimator using reference autocollimator (previously calibrated) utilising a rotary table or an angular tilting mechanism.

4.2 Auxiliary devices

Auxiliary devices are used to facilitate the autocollimator calibration process. Some auxiliary devices with different properties affect the calibration results. Therefore, they need to be reported in the calibration certificate. The basic auxiliary devices used in autocollimator calibration are shortly described below.

4.2.1 Surface Under Test (SUT) – as a reflector (mirror)

Angular deflection of the plane mirror mounted on the reference device is measured by the test autocollimator during the calibration process. Below given specifications for the mirror are recommended as default unless specified by the customer:

- **Reflectivity:** A metallic coating (usually aluminium) to obtain a reflectivity approaching 100% (approx. 95%).
- **Size of the reflecting area:** 50 mm in diameter in order to provide an unobstructed reflection over the effective, illuminated autocollimator aperture (usually in the ranges 30-40 mm in diameter).
- **Flatness deviation of the measurement face**: $\lambda/8$ (peak-to-valley) for a region at least 30 mm in diameter.

The realization of the above parameters is essential since deviations from the stated measuring conditions may alter the autocollimator's angle response significantly [1-10] particularly for calibration uncertainties less than 0.1".

It should be noted that the influence of flatness deviations of the reflecting mirror on the angle response of autocollimators were investigated [3]. In the case of two mirrors with different flatness deviations of 4 nm and 20 nm (root-mean-square), systematic changes in the angle response of a few 0.01 arcsec were found [3].

In addition to above parameters, the use of a double sided mirror, with a parallelism of 1 arcsec is recommended particularly for the precise adjustment described in section 5.1.

The reflectivity of the mirror may change with the customer demands. Some autocollimators are used in profilometry for flatness measurement of uncoated optical surfaces. In this case, it is recommended to use uncoated mirror to match the similar properties with the test surfaces. It may also be possible to calibrate the autocollimators with both coated and uncoated mirrors, and then certify the results separately in the calibration certificate.

4.2.2 Additional optics e.g. dove prism for X to Y (or Y to X) axis translation

Autocollimators are calibrated separately for X (yaw angular motion) and Y (pitch angular motion) axis. It is possible to rotate most of the autocollimators (in roll direction) in its mount for matching of the axis to be calibrated with respect to the angular axis of the reference device. For instance, after calibration of the X axis, the autocollimator is rotated in its mount to proceed to calibration of Y axis.

However, this is not always the case for all autocollimator types. Some autocollimators cannot easily be rotated. In this case, additional optics (e.g. dove prism) for the rotation of the beam deflection plane shall be used to match the autocollimator axis (to be calibrated) with the reference device's axis. It is recommended to use open type dove prism with reflecting surfaces having flatness value of better than $\lambda/8$ (peak-to-valley). Validation of autocollimator calibration with dove prism was carried out in PTB and no significant difference was found [12].

4.2.3 Autocollimator holder and tilting plate

In order to position and adjust the autocollimator in front of the mirror (SUT) mounted on the reference angle device, a stiff adjustment mechanism is recommended. The holders delivered with the autocollimator may be used but care must be taken while locating the test autocollimator on the same plane with the reference device (in order to eliminate drifts and effect of vibrations). Springs on the adjustment mechanism may cause drifts. Therefore their performance must be investigated in advance.

5 EXAMPLES OF A CALIBRATION PROCEDURE

For calibration of the autocollimators, the deflection of SUT (e.g. reflective plane mirror) mounted on the angle reference device, is measured from a certain distance (e.g. 300 mm) by the test autocollimator. This measurement is usually taken with the full autocollimator aperture unless the customer asks for calibration with a limited aperture. In case of calibration with limited aperture, a diaphragm is mounted centrically to the optical axis of the autocollimator and directly in front of the SUT (i.e. plane mirror).

Precise adjustment of the aperture (e.g. centring of the aperture with autocollimator axis in ± 0.1 mm) is required for the autocollimators used in profilometry [1-9]. For this, additional precautions shall be taken and calibrations shall be performed using special tools. For example, a new tool called Aperture Centring Device (ACenD) developed under SIB58 Angles project [1] may be used. This new device has been successfully evaluated by the project partners through comparison measurements. See the project website for the details [1].

The distance between SUT (the plane mirror) and the autocollimator shall be arranged with the customer and reported in the certificate. If there is no customer recommendation, a distance, equal to the focal length of the autocollimator is recommended as, in this case, error influences are minimised [10]. It should be noted that significant changes in the angle response of autocollimators in the case of a variable distance to the reflecting mirror was demonstrated [1-10].

5.1 Handling, preparation and adjustments

Before proceeding with the calibration, the following steps shall be taken:

- Familiarize yourself with the functioning and handling of the autocollimator by means of its manual.
- Check the operability of the autocollimator.
- Allow approx. 24 hours for the thermal adaptation of the autocollimator to your laboratory environment.
- Start-up the autocollimator at least 6 hours before the beginning of the measurements to enable an adequate warming-up.

Unless there is problem/requirement (e.g. agreement with customer), cleaning of the autocollimator should be avoided. The optical surfaces (e.g. the autocollimator objective) should be handled with utmost care and they should never be touched. Apart from blowing away dust particles using dry, clean air or other clean gases, no cleaning of the optical surfaces shall be carried out unless there is a special need.

The user may follow their adjustment procedures for autocollimator calibration considering their own reference device. In figure 3, the measurement set-up for the calibration of electronic autocollimators against the angle comparator (rotary table) is illustrated. The optical axis and the measuring axes of the autocollimator, as well as the plane mirror, need to be adjusted with respect to the comparator's rotational axis and the associated rotation plane. As an example, the adjustment procedures recommended in EURAMET.L-K3a.2009 protocol by PTB (Table 2) shall be used since it was applied successfully by most of EURAMET.L-K3a.2009 participants [10]. The adjustment procedure presented in table 2 shall be adapted according to different angle reference devices.

Table 2: Adjustment procedures for autocollimator calibration at PTB (applied by most EURAMET.L-K3a.2009 participants)

#	Adjustment step(s)	Tolerance
1	The height and lateral position of the autocollimator is adjusted with respect to the plane mirror so that the illuminated aperture of the autocollimator is entirely covered (to avoid vignetting). For the adjustment steps 1-2, the laser attachment6, which is supplied with the autocollimator, can be used.	Mirror covers illuminated autocollimator aperture
2	The optical axis of the autocollimators is adjusted to intersect the rotational axis of the angle comparator.	<= 1 mm
3	The front surface of the plane mirror is adjusted with respect to the rotational axis of the angle comparator (so that the surface incorporates the axis).	<= 1 mm
4	The autocollimator's x measurement axis is adjusted parallel to the rotational plane of the angle comparator by rotating the autocollimator in its holder around its optical axis. When the comparator is rotated, the change Δx of the angle in the x-axis of ±1000 arcsec must result in minimal change Δy in the y-axis reading (e.g. $< \pm 1$ arcsec for ±1000 arcsec range). See explanations in reference [13] how to calculate error contribution if different criteria is used.	$\Delta y / \Delta x < 0.001$

5	The front surface of the plane mirror is adjusted to be orthogonal to the rotation plane of the angle comparator (done by reversal measurements at 0° and 180° rotational angle by use of a double-side mirror).	< 1 arcsec
6	The optical axis of the autocollimators is adjusted to be orthogonal to the front surface of the plane mirror (and therefore parallel to the rotational plane of the angle comparator). The autocollimator is adjusted until the y-axis reading is close to zero.	< 1 arcsec
7	The plane mirror is rotated by the angle comparator to the starting position so that the reading of the x-axis of the autocollimator is close to zero.	< 0.1 arcsec

Note: The figures in Table 2 are to be taken as recommendations to minimize the error sources rather than strictly necessary conditions. The user may calculate the error contribution for their specific conditions and take into their uncertainty budget.

5.2 Determination of autocollimator deviations and calculation of data sets

In general, the result of the calibration is the deviation δ of the angle measured by the autocollimator from the angle provided by the reference system according to (to fix the sign convention)

$$\delta = \alpha_{AC} - \alpha_{REF} \ , \qquad (2)$$

with

δ : the angle deviation of the autocollimator,
α_{AC} : the angle measured by the autocollimator, and
α_{REF} : the angle measured by the reference system.

For the final calibration value δ, multiple measurements may be obtained and processed, e.g. [10]

- multiple measurements both with the autocollimator and the reference system may be performed or
- the entire calibration run may be repeated several times.

As an illustration, the data acquisition during autocollimator calibration is described below [12, 13].

For a specific calibration and at a specific angle setting, n_{AC} = 50 and n_{REF} = 50 angle readings α_{AC} and α_{REF} , respectively, are recommended to obtain with the autocollimator and the reference system in a time-shared sequence (see Note 5.2.1).

Average values and standard deviations are calculated for further analysis, including the average autocollimator angle measurement α_{AC} and the average autocollimator deviation $= \alpha_{AC} - \alpha_{REF}$. The procedure is repeated until the autocollimator deviations have been obtained for all desired angle settings within the measurement range. This data set defines an individual calibration. Reduced measurement deviations (referred to the mean value 0 arcsec) in the defined range may be calculated and reported. An example is given in Appendix A.

At PTB, $n_r = 3\times2 = 6$ independent individual calibrations are performed at three different relative angular positions between the autocollimator and the primary standard, including a reversal of the standard's direction (forward & backward) of rotation at each relative position to eliminate linear drifts from the average [12] (see also Note 5.2.2).

At TUBITAK UME, $n_r = 2\times6 = 12$ independent individual calibrations are performed at two different relative angular positions between the autocollimator and the primary standard (e.g. at reference value set as 0 degrees and 180 degrees to this reference value), including a reversal of the standard's direction (forward & backward) of rotation at each relative position to eliminate linear drifts from the average [13] (see also Note 5.5.2 and figure 7).

These n_r individual repeat calibrations are then averaged to obtain the final calibration result. Analysis of the repeatability of the individual calibrations yields an estimate of the Type A uncertainty component for the calibration's uncertainty budget (see Section 7). It should be noted that these approaches were successfully evaluated in EURAMET.L-K3a.2009 comparison [10].

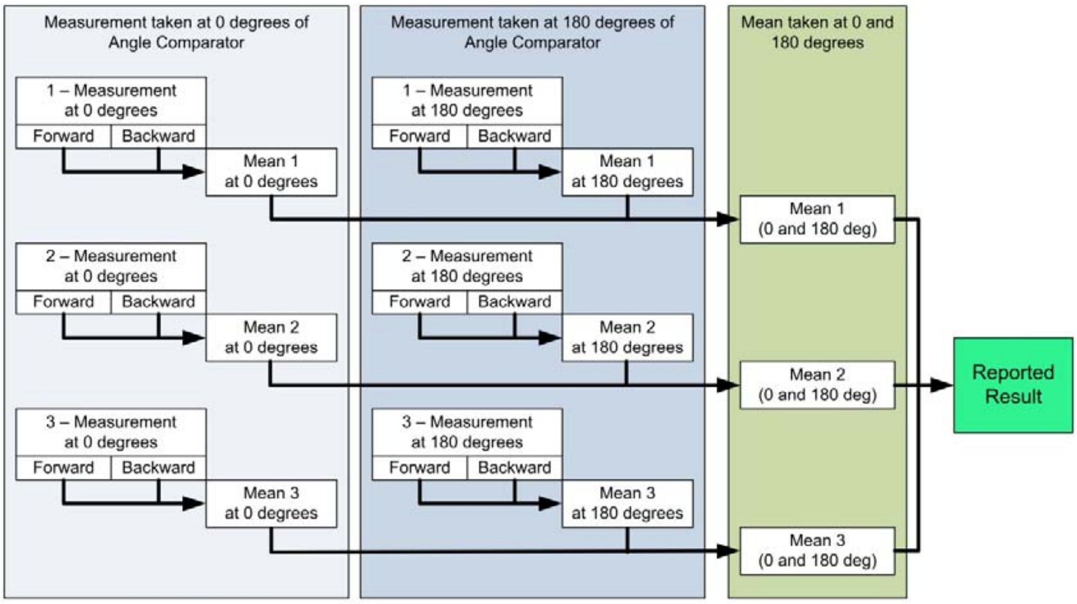


Figure 7: Determination of reported results by forward and backward measurements recorded in two relative positions between the mirror and the angle comparator (e.g. at reference value set as 0 degrees and 180 degrees to this reference value on the comparator scale - Example from a procedure in TUBITAK UME).

- Note 5.2.1: Number of data (n) taken at each setting may vary depending on the used software, noise of the reference system and also the autocollimator. At least $n_{AC} = 50$ angles readings are recommended for the autocollimators to reduce the noise level. At PTB, $n_{AC} = 100$ angles readings are taken while $n_{AC} = 50$ angles readings at TUBITAK UME. For the reference system, $n_{REF} = 50$ angle readings are obtained in TUBITAK while $n_{REF} = 25$ angle readings in PTB.

- Note 5.2.2: The aim for performing calibrations at different relative angular positions between the autocollimator and the primary standard is to minimise residual error sources. Facility of the reference system for rotation of the SUT (mirror) to achieve calibrations at different relative angular positions plays an important role for the number of position. Automatic system at PTB allows relatively large number of calibrations without disturbing the set-up [12]. Since manual adjustment is time consuming, TUBITAK UME performs this at 0 and 180 degrees reducing the errors of the comparator particularly due to the first harmonic error (eccentricity) and increasing the calibration accuracy [13].

5.3 Determination of autocollimator deviations in long scale (e.g. Full scale ±1000”)

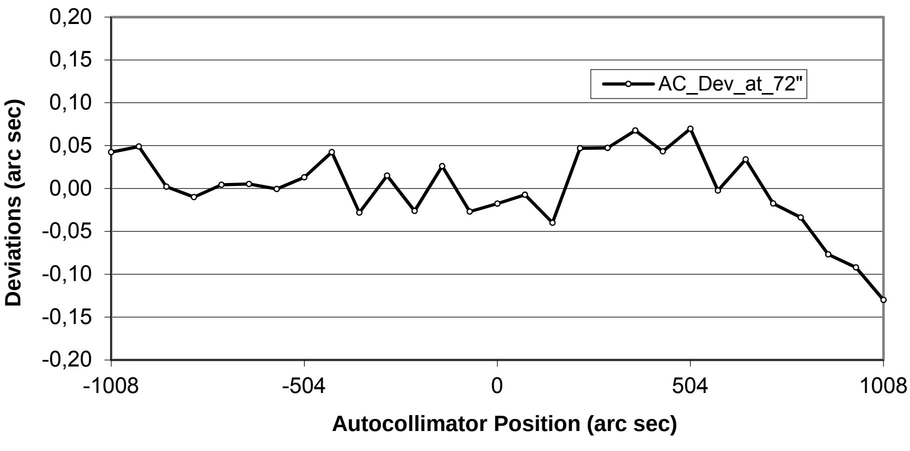
The measurement deviations of autocollimators cover a wide range of angular scales, extending from a few arcseconds (connected to the pixels of the autocollimator’s CCD detector) to the full measurement range (due to aberrations in the autocollimator’s optical elements and detector misalignment). Therefore, sampling the angle deviations on both short and long angular scales may be required.

The selection of measurement ranges and the step size for sampling depends on the following:

- Autocollimator measurement range
- Customer demand
- Angle reference system

Step size shall be selected also considering the aliasing effect. The importance of this phenomena was demonstrated in [12]. Figure 8 illustrates autocollimator calibration results taken with steps of 72” and 7.2” for the range of ±1008” demonstrating the aliasing effect with experimental results.

(a) Result s taken at 72“ angular steps



(b) Results taken at 7.2" angular steps

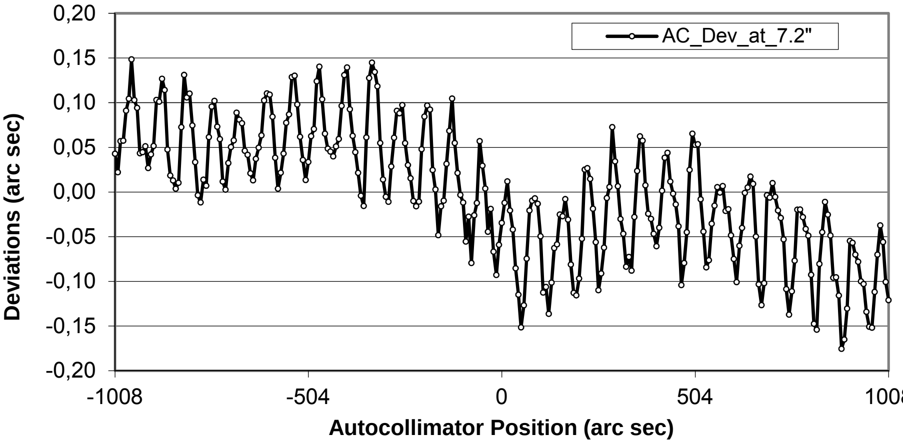


Figure 8: Autocollimator deviations taken at two different angular steps: (a) 72" and (b) 7.2" demonstrating the importance for selection of calibration steps – Results from Calibration of an electronic autocollimator by TUBITAK UME.

It is recommended to select a step size so that the selected measurement range can be divided into 100 steps. For calibration of a full range in an electronic autocollimator used in the EURAMET.L-K3a.2009 comparison, the below range and steps were chosen.

Measurement range 1: ±1000 arcsec in steps of 10 arcsec
Another important issue for selection of the suitable steps size also depends on the reference system capability. In order to achieve lower uncertainty, sometimes it is preferable to perform calibration in the steps that corresponds to the basic resolution of the reference unit. For example, TUBITAK UME calibrates the autocollimators 7.2" angular steps in order to minimise the interpolation error of their reference system (assured by EURAMET.L-K3a.2009). Detailed explanations for this work are given in [13]. With the improved interpolators (using compensation mechanism), it is possible to achieve the same level of accuracy as in any other step sizes. This was tested by applying the shearing method [1].

5.4 Determination of autocollimator deviations in short scale (e.g. scale ±10")

Electronic autocollimators show measurement deviations attributed to short-period scaling errors of the CCD line used. In order to reveal them, there may be the need to perform calibration in smaller steps in a small range. For example, the below range and steps (for Elcomat 3000 of MWO [2]) were chosen in EURAMET.L-K3a.2009 comparison [10].

Measurement range 2: ± 10 arcsec in steps of 0.1 arcsec.

Most angle measurement systems suffer from interpolation errors. According to current knowledge obtained from the SIB58 Angles project, typical interpolation errors are:

- 1 – 2 % of the basic resolution (e.g. 1 % of 7.2" resolution: 0.07" or 1 % of 36'': 0.3"): If no compensation mechanism is used.
- If compensation mechanism is used, this value is 3-4 times smaller.

In order to achieve smaller uncertainty, error-separating shearing techniques shall be applied. The first adaptation of advanced error-separating shearing techniques to the precise calibration of autocollimators with angle encoders (i.e. Angle Rotary Tables) were carried out by PTB and with Small Angle Generators by TUBITAK UME under SIB58 project [20, 21]. The error-separating shearing technique provides calibration of autocollimators without recourse to an external standard achieving state of the art uncertainty values. The standard uncertainty that was achieved is about 1 milliarcsec (5 nrad) [20, 21]. The results showed that the shearing method is ideally suited for the calibration of interpolation errors of the devices at small angular scales which are difficult to characterise with other methods.

6 EVALUATION OF THE RESULTS

Calibrations results can be used to check the manufacturer's specifications. For the customer specific use (on demanded conditions) the results varying with the parameters described in Section 2.3 shall be evaluated by the user according to their needs.

Influences of the path length on the autocollimator's angle response are of special importance to deflectometric profilometers, where the length of the beam to the SUT changes by the entire scanning length (up to 1.2 m) as different points on the optical surface are accessed by a movable pentaprism. The same is true for applications in precision engineering (e.g., the measurement of machine geometries) where path length changes also occur. In the case of deflectometric profilometers, this effect causes the dominant uncertainty component in the form measurement of extended, highly curved optical surfaces.

The work carried out under SIB58 project [1] concluded that the experimental results and the ray tracing simulations of the autocollimator has demonstrated excellent agreement. Therefore, the calibration results may help autocollimator users (particularly the synchrotron community) and manufacturers to minimise measurement errors due to distance-dependent effects in order to achieve the demanded uncertainty values of less than 0.01 arcsec (50 nrad).

7 MEASUREMENT UNCERTAINTY

The standard measurement uncertainty should be evaluated according to the Guide to the Expression of Uncertainty in Measurement [24]. Alternatively, the laboratories may choose to use the approach according to the Supplement 1 to the GUM [25] by propagating distributions (to obtain the Probability Density Function – PDF – of the output quantity from which an estimate of the output quantity itself, the standard uncertainty associated with it, and the coverage interval for a given coverage probability can be derived). In this section, the standard approach is outlined [10].

For each measured deviation δ, its associated standard uncertainty $u(\delta)$ needs to be provided. For the derivation of the expanded uncertainty, the coverage factor k for a 95% coverage probability is provided and the expanded uncertainty shall be calculated as $U = u\times k$.

Note that the standard uncertainty – not the expanded uncertainty - is the basic statement on the uncertainty of a measurement. The coverage factor k can be defined using the value for effective degrees of freedom $\mathrm{v}_{\mathrm{eff}}(\delta)$.

For deriving the uncertainty budget, the deviation $\delta = \alpha_{AC} - \alpha_{REF}$ of the autocollimator measurement from the measurement of the reference system, see Section 5.2, Equation (2), needs to be expressed as a function of the *N* input quantities x_i, $i \in [1, \dots R]$ according to

$$\delta = f(x_1, \dots, x_i, \dots, x_R) \ . \tag{3}$$

Their uncertainty contributions $u_i(\delta)$ are

$$u_i = |c_i| \times u(x_i), \tag{4}$$

with the sensitivity coefficients c_i according to

$$c_i = \frac{\partial \delta}{\partial x_i} \tag{5}$$

The square of the combined standard uncertainty, $u^2(\delta)$, is derived from the quadratic sum of the uncertainty contributions, $u_i^2(\delta)$, according to

$$u^2(\delta) = \sum_{i=1}^{R} u_i^2(x_i) = \sum_{i=1}^{R} c_i^2 u^2(x_i) \, . \tag{6}$$

In some cases, higher order terms might have to be taken into account in Equation (6). If a correlation between the input quantities x_i is present, it also needs to be considered:

$$u^2(\delta) = \sum_{i=1}^{R} \sum_{l=1}^{R} c_i \, c_l \cdot u(x_i, x_l) = \sum_{i=1}^{R} c_i^2 \, u^2(x_i) + 2 \sum_{i=1}^{R-1} \sum_{l=i+1}^{R} c_i c_l \cdot u(x_i, x_l), \tag{7}$$

with the covariances $u(x_i \, x_l)$ associated with the input quantities x_i and x_l , $i, l \in [1, \dots R]$.

The effective degrees of freedom $v_{eff}(\delta)$ are given by the Welch-Satterthwaite equation 8

$$\frac{u^4(\delta)}{v_{eff}(\delta)} = \sum_{i=1}^{R} \frac{u_i^4(\delta)}{v_i} = \sum_{i=1}^{R} \frac{c_i^4 u^4(x_i)}{v_i} \ , \tag{8}$$

with the degrees of freedom v_i associated with the input quantity.

For the uncertainty estimation, the laboratories are encouraged to use all known and significant influencing parameters associated with their applied methods. An example of uncertainty budget with recommendations is illustrated in Appendix B.

8 CALIBRATION CERTIFICATE

The certificate of calibration shall contain the following information:

- The manufacturer, type and serial number of the components of the autocollimator.
- The settings of the control elements of the electronic display unit during calibration (measuring range, digital resolution of the display etc.).
- The environmental conditions including temperature, air-pressure and humidity.
- The calibrated axis of the autocollimator (ACx or ACy).
- The distance between SUT (mirror) and the autocollimator during calibration.
- The properties of the SUT (e.g. plane mirror), its reflectivity.
- The aperture size if used. If not used, it should be reported that results were taken with full aperture or full aperture size of the autocollimator may be written (e.g. diameter 32 mm).
- The calibrated measurement range of the autocollimator and sampling steps.
- The measurement results may be presented in tabular form (see Appendix 1). Remarks for the results; e.g. reduced measurement deviation (e.g. referred to mean value 0 arcsec) in the range from -1000 arcsec to +1000 arcsec shall be written.
- The uncertainty of the calibration.

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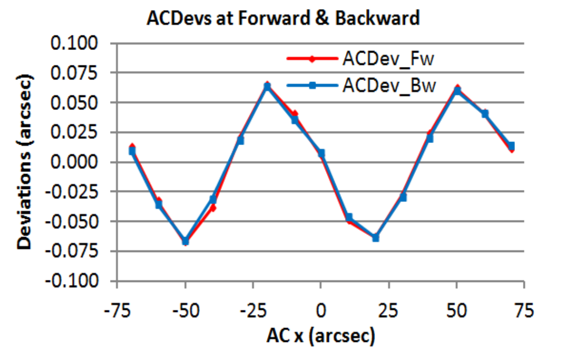
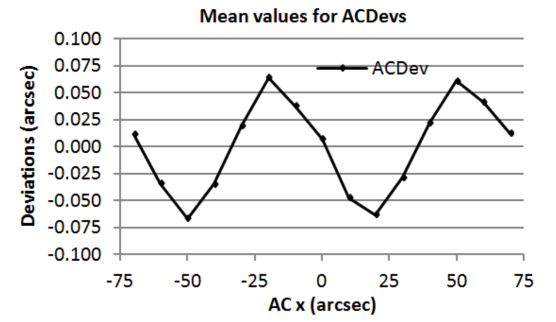
APPENDIX A: Calculation of DATA sets for calibration of autocollimators

Raw Results taken at Forward and Backward direction (each is the mean value of 50 readings)				Calculation of AC deviations in Fw & Bw directions $\delta = \alpha_{AC} - \alpha_{REF}$		Reduced measurement deviations (referred to the mean value 0 arcsec)		Mean values of Fw & Bw ACx and ACDev (arcsec)	
ACx_Fw	Ref_Fw	ACx_Bw	Ref_Bw	ACDev_Fw	ACDev_Bw	ACDev_Fw	ACDev_Bw	ACx	ACDev
-70.001	-70.001	-70.006	-70.000	0.000	-0.005	0.012	0.010	-70.003	0.011
-60.045	-60.001	-60.052	-60.001	-0.045	-0.051	-0.033	-0.036	-60.049	-0.034
-50.080	-50.001	-50.082	-50.001	-0.080	-0.082	-0.068	-0.066	-50.081	-0.067
-40.051	-40.001	-40.047	-40.001	-0.051	-0.046	-0.039	-0.031	-40.049	-0.035
-29.993	-30.000	-29.997	-30.001	0.008	0.003	0.020	0.019	-29.995	0.019
-19.948	-20.000	-19.952	-20.000	0.052	0.048	0.065	0.064	-19.950	0.064
-9.972	-10.000	-9.980	-10.000	0.028	0.020	0.040	0.036	-9.976	0.038
-0.006	0.000	-0.008	0.000	-0.006	-0.008	0.006	0.008	-0.007	0.007
9.938	10.000	9.939	10.000	-0.062	-0.061	-0.050	-0.046	9.939	-0.048
19.925	20.000	19.922	20.000	-0.075	-0.078	-0.063	-0.063	19.924	-0.063
29.961	30.000	29.955	30.000	-0.039	-0.045	-0.027	-0.030	29.958	-0.029
40.012	40.001	40.006	40.001	0.012	0.005	0.024	0.021	40.009	0.022
50.050	50.001	50.046	50.001	0.050	0.045	0.062	0.060	50.048	0.061
60.030	60.001	60.026	60.001	0.029	0.026	0.041	0.041	60.028	0.041
69.999	70.001	70.000	70.001	-0.002	-0.001	0.010	0.014	69.999	0.012
			Mean	-0.012	-0.015	0.000	0.000		





Note A1: The laboratories may take 3 set of these results (3 sheets) and calculate the final mean values for them.

Note A2: It is possible to take further 3 sets at different relative angular positions (e.g. 0º and 180º in total) as described in section 5.2.

Note A3: The laboratories shall decide the number of sets and relative position considering their own angle reference system and their set-up.

APPENDIX B: Example of an Uncertainty budget for calibration of autocollimators

Prior to drafting of the uncertainty budget for calibration of the autocollimators, the reference system used in the calibration must be investigated and its performance must be determined for the specific task. Since the output of these investigations is used for determination of uncertainty components, the uncertainty budget must be studied together with these investigations. In this document, only a short list of uncertainty budget [13] is given as an example in Table B1. For investigation of various type angle reference systems and drafting of the uncertainty budget in calibration of the autocollimators, the reader may refer to following references and then draft their own uncertainty budget according to investigation results of their reference system. For calibration of autocollimators using the reference systems, the reader may refer to followings;

ref. [12] using rotary tables with multiple read-head angle encoders,
ref. [13] using rotary tables with single read-head angle encoders, and
ref. [17] using small angle generators.

For application of the shearing method in calibration of autocollimators (described in section 5.4), the reader may refer to following references;

ref. [20] using rotary tables with angle encoders (more specifically with multiple read-head angle encoders),
ref. [21] using small angle generators.

Table B1. Example of uncertainty budget for calibration of electronic autocollimators using rotary tables fitted with one read-head angle encoders [13].

Uncertainty component	Estimate (arcsec)	Distribution function	Type	Uncertainty contribution (arcsec)	Degrees of freedom ν
Standard deviation of the mean value	0.003	Normal	A	0.003	2
Measurement deviation of the angle comparator	0.008	Rectangular	B	0.005	∞
Uncertainty of the angle comparator calibration	0.030	Normal	B	0.015	1000
Interpolation deviations of the angle comparator	0.010	Rectangular	B	0.006	∞
Resolution of the angle comparator	0.0009	Rectangular	B	0.0003	∞
Resolution of the test autocollimator	0.001	Rectangular	B	0.0003	∞
Uncertainty contribution from the mirror and set-ups	0.002	Rectangular	B	0.0012	∞
				u_c = 0.017 U (k = 2) = 0.034 arcsec	

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