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Physikalisch Technische Bundesanstalt PTB

Eidgenössisches Institut für Metrologie METAS

EURAMET.L-K3.2009.2

Angle comparison using an autocollimator

Bilateral follow-up comparison between PTB and METAS

Technical protocol

Wabern, January 2017

Contents

Document control

Version 1 Issued on 31 January 2017.

1 Introduction

This is a bilateral follow-up comparison to EURAMET.L-K3.2009, which was piloted by PTB. Due to large interpolation errors of the rotary table, which could not be compensated, METAS had to withdraw measurement results from the afore mentioned comparison and asked the pilot to carry out a bilateral comparison in order to confirm its CMCs. The present technical protocol follows the protocol of EURAMET.L-K3.2009.

2 Organization

2.1 Participants

List of participant laboratories and their contacts.

Laboratory Code	Contact person, Laboratory	Phone, Fax, email
PTB	Andreas Just Physikalisch Technische Bundesanstalt 5.21 Length and Angle Graduations Bundesallee100 D - 38116 Braunschweig Germany	Tel. +49 531 592 5221 e-mail: andreas.just@ptb.de
METAS	Rudolf Thalmann Federal Institute of Metrology METAS Lindenweg 50 CH-3003 Bern-Wabern Switzerland	Tel. +41 58 387 03 85 e-mail: rudolf.thalmann@metas.ch

2.2 Schedule

RMO	Laboratory	Starting date of measurement
EURAMET	PTB	January 2017
	METAS	March 2017
	PTB	April 2017

2.3 Reception, transportation, costs

The shipment is agreed between the participants by an appropriate carrier. METAS will be responsible for customs formalities to and from Switzerland. Transportation cost will be carried by METAS. METAS will confirm the reception of the package and will inform PTB when the package is sent back.

All items are packed together in an aluminium container (dimensions 800 x 600 x 630 cm^3) and are protected by damping foam material inside. 'Shockwatch' and 'Tiltwatch' indicators are attached to the outside of the aluminium container. It contains the autocollimator and its accessories, packed in its own special protecting case, the precision plane mirror (provided by the PTB), also in a protecting case, and the adjustable holder for the autocollimator with a double sided clam. The transportation packaging was designed to protect the content from possible damages during transport.

3 Standard

3.1 Description of standard

For this comparison, an electronic autocollimator type Elcomat 3000 by Möller-Wedel Optical GmbH (MWO), Wedel, Germany, has been kindly made available by the manufacturer.
As the participants will be provided with a detailed technical manual of the autocollimator, only its basic properties are summarised here shortly:

- Two axis electronic autocollimator (the comparison will be performed on the horizontal x-axis only)
- Measuring range: 2000 x 2000 arcsec (up to 2.5 m distance to the reflector)
- Highest resolution: 0.001 arcsec
- Focal length: 300 mm
- Diameter of the illuminated (effective) aperture: 32 mm (tube diameter: 65 mm)
- Dimensions: 420 x 95 x 135 mm
- Weight: 3.8 kg
- Serial number S.N. 1192

3.2 Mounting

An adjustable holder for the autocollimator with a double-sided clam fixture (type D65, MWO no. 223 0243) will be provided by the PTB (kindly made available by MWO). It allows the rotation of the autocollimator in its mount (around the autocollimator's optical axis) by 90° for the flexible measurement of the x-axis in a vertical orientation. As the autocollimator's angle deviations are stable with respect to rotations of its body, NMIs can calibrate the x-axis of the device in a horizontal or vertical orientation, depending on the requirements set by their equipment, and can avoid the use of additional optics for the rotation of the beam deflection plane.

- Before the autocollimator can be switched on, all connecting cables (autocollimator – Control Unit; Control Unit – PC) need to be plugged in.
- Check the operability of the autocollimator.
- Remove the external data logger from the autocollimator tube, see its accompanying manual.
- 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.
- Provide adequate, clean storage when the autocollimator is not in use, e.g., during adaptation to the environmental conditions.
- Cleaning of the autocollimator should be avoided. All optical surfaces (the autocollimator objective and the measurement faces of the precision plane mirror) 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 must be carried out.

3.3 Environmental conditions

The environmental conditions (temperature, air-pressure and humidity) and the NMI's height above sea level should be reported.

4 Measuring instructions

There are a number of factors influencing the angle response / calibration of an autocollimator which can be categorised as external vs. internal. Internal factors are specific to the individual autocollimator with its 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).

Based on our comprehensive experience in autocollimator calibration at the PTB, the influence factors include the following parameters:

- Reflectivity of the mirror
- Curvature of the mirror
- Distance (optical path length) between the autocollimator and the mirror
- If an aperture stop is used:
    - 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

According to our experience in autocollimator calibration, significant differences in the calibration may occur in case of changes in one or several parameters.

With the measuring instructions presented in this section, we attempt to achieve a balance between allowing NMIs to calibrate the reference autocollimator under measurement conditions which are typical for routine calibrations at their facilities, and ensuring optimal comparability of the calibration results achieved at different NMIs. On the one hand, the calibration results should provide realistic information on the calibration capabilities and limits at each NMI, on the other hand, systematic errors due to changes in the measuring conditions must be avoided, as they may not be accounted for by the stated measurement uncertainties.

In case of deviations of the measuring conditions from the stated specifications, e.g., due to constraints of the calibration set-up at the NMI, a detailed documentation of the changed condition(s) is necessary.

4.1 Plane mirror

calibrations for customers. To avoid systematic errors due to the mirror's curvature and reflectivity, we specify the following parameters:

- Reflectivity: Use of a mirror with a metallic coating (usually aluminium) to obtain a reflectivity approaching 100%.
- Size of the reflecting area: 50 mm in diameter in order to provide an unobstructed reflection over the effective, illuminated autocollimator aperture (32 mm in diameter).
- Flatness deviation of the measurement face: λ/8 (peak-to-valley) for a region at least 32 mm in diameter.

As deviations from the stated measuring conditions may alter the autocollimator's angle response significantly, we consider the realization of these parameters as essential. If available, please provide optional documentation on your mirror (flatness deviations, reflectivity).

In addition, each participating NMI may decide to perform additional calibrations with a precision plane mirror (Ref. No. 280 345; S.N. 150) provided by the PTB to ensure optimal comparability of the results (optional). In that case, please use face 1 of the double-sided mirror..

4.2 Distance autocollimator - reflector

In the case of different distances between the autocollimator and the reflecting mirror, the beam returning to the autocollimator follows different paths through its optics. In conjunction with aberrations of the optical components and errors in their alignment (and that of the CCD detector), angle deviations are introduced which are varying as a function of the distance to the mirror.

Each participating NMI is allowed to choose the distance between the autocollimator and the reflecting face of the plane mirror according to their usual specifications for calibrations. Please provide information on the distance from the front end of the autocollimator’s tube (which contains the objective) to the reflecting surface in your measurement documentation.

However, if possible with your calibration set-up, we strongly recommend a distance of 300 mm (equal to the focal length of the autocollimator) as, in this case, error influences are minimised. Additionally, we have demonstrated significant changes in the angle response of autocollimators in the case of a variable distance to the reflecting mirror.

4.3 Autocollimator aperture

To avoid vignetting effects, the entire illuminated (effective) autocollimator aperture (32 mm in diameter) will be used in this comparison. No additional aperture stop is required.

4.4 Measurement ranges / steps

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, to appropriately sample the angle deviations on both short and long angular scales, we recommend two different measurement ranges for the comparison:

- Measurement range 1: ± 1000 arcsec in steps of 10 arcsec
- Measurement range 2: ± 10 arcsec in steps of 0.1 arcsec

For the comparison, calibrations are to be performed on the x-axis of the autocollimator. If possible, measurements should be performed at the specified values as indicated by the autocollimator, i.e., the angular positioning of the calibration system is guided by the autocollimator (optional). The starting position should be set to zero to better than 0.1 arcsec.

4.5 Adjustment procedures

Each participating NMI may follow its own adjustment procedures for autocollimator calibration as specified in their procedures.

4.6 Autocollimator settings

For the measurements, the following autocollimator settings need to be considered:

- Switch to ‘abs’ setting (E3000 Manual, p. 18).
- Set unit to ‘arcsec’ (E3000 Manual, p. 14).
- Resolution (E3000 Manual, p. 16): This setting affects the resolution of the display only; it does not affect the values which are provided by the computer interfaces.
- Protocol for the RS-232 computer interface (E3000 Manual, p. 17 and p. 19): We strongly recommend to use the ‘text protocol’, especially for participants with low measurement uncertainties, because the data transfer is more reliable and its resolution is higher (0.001 arcsec in comparison to 0.01 arcsec for the ‘compatible’ format). Please do not use the USB computer interface as we have not tested its reliability for this comparison.

4.7 Measurement results

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)

$$\delta = \alpha_{AC} - \alpha_{REF}, \quad (1)$$

with

δ : the angle deviation of the autocollimator,

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

For all stated values involving angles, the unit 'arcsecond' should be used. Please report any smoothing / filtering of the data values (which should be avoided at all costs).

For the final calibration value δ , multiple measurements may be obtained and processed, e.g., (1) multiple measurements both with the autocollimator and the reference system may be performed or (2) the entire calibration run may be repeated several times. As an illustration, we describe the data acquisition during autocollimator calibration at the PTB.

For a specific calibration and at a specific angle setting, n_{AC} = 100 and $n_{REF} = 25$ angle readings $\propto_{AC}$ and $\propto_{REF}$, respectively, are obtained with the autocollimator and the reference system in a time-shared sequence. Average values and standard deviations are calculated for further analysis, including the average autocollimator angle measurement $\propto_{AC}$ and the average autocollimator deviation $\delta = \alpha_{AC} - \alpha_{REF}$. 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.

Typically, $n_r = 3 \times 2 = 6$ 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 of rotation at each relative position to eliminate linear drifts from the average. These r n 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.

Overview of measurands / parameters from Sections 4 and 5 (optional parameters are marked).

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

4.8 Measurement uncertainty

The uncertainty of measurement shall be estimated according to the ISO *Guide to the Expression of Uncertainty in Measurement*.

5 Documentation and reporting

Descriptions of the (1) calibration device, (2) the measurement results, and (3) a detailed evaluation of the measurement uncertainty have to be reported. For further analysis, it is necessary to complete the report forms by computer and to send them back electronically to the pilot laboratory (and the coordinator). **The reports shall be sent to the pilot laboratory no later than six weeks after completing the measurements**.

The measurement data need to be reported as American Standard Code of Information Interchange (ASCII) files (FILENAME.DAT). The FILENAME should include the acronym of the NMI and should identify the measurement range, e.g., PTB_1000.DAT. The file should contain seven columns; one single header row, and *R* data rows (*R* : number of measurement steps in the defined measurement range). The file should include a header row (one single row) with the column names as given in Table hereafter.

Column name for file header	ACx	sdACx	ACDev	sdACDev	uACDev	k	ACy
Data value (explanation: see Sections 4.7 and 5)	α_{AC}	$\sigma(\alpha_{AC})$	$\delta(\alpha_{AC})$	$\sigma(\delta)$	$u(\delta)$	k	β_{AC}
Optional		X		X			X

Note 1: In the case of entries which are not changing, please nevertheless provide a column containing R identical numbers. This facilitates the analysis of the results and avoids errors in the attribution of parameters.

Note 2: In the case of optional values, if you decide not to include them, please provide a column containing R identical zeros – **do not omit the row(s).**

Note 3: For all stated values, the **unit 'arcsecond'** should be used.

6 Analysis of results

The results shall be analyzed and reported according to the CCL WG-MRA template for reporting bilateral comparisons.

6.1 Linking of result to other comparisons

Linking to the comparison EURAMET.L-K3.2009 is provided through the pilot laboratory PTB.