

Key Comparison
EURAMET.L-K3.2009
Angle Comparison
Using an Autocollimator
(Project # 1074)

Technical Protocol

October 2014

European Association of National Metrology Institutes (EURAMET)
comparison in accordance with the guidelines of the
Consultative Committee for Length (CCL)

Pilot laboratory:

Physikalisch-Technische Bundesanstalt (PTB)

Time schedule:

12/2009 - 05/2015

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1. Introduction

As described in the Mutual Recognition Arrangement (MRA)¹, the metrological equivalence of national measurement standards will be determined by a set of comparisons chosen and organised by the Consultative Committees of the Comité International des Poids et Mesures (CIPM) working closely with the Regional Metrology Organisations (RMO).

At the 13th meeting of the Working Group for Dimensional Metrology (WGDM), 24-25th September 2008, INRIM, Torino, Italy, and at the European Association of National Metrology Institutes (EURAMET) Technical Committee of Length (TC-L) Meeting, 6-7th October 2008, MIKES, Espoo, Finland, the Physikalisch-Technische Bundesanstalt (PTB) first proposed a comparison on the calibration of autocollimators. The initial proposal has been refined over the course of subsequent WGDM and EURAMET TC-L meetings and a total of 28 National Metrology Institutes (NMI) have agreed to join this key comparison as participants with the PTB acting as the pilot laboratory.

Autocollimators are optical devices for the precise and contactless measurement of angles of reflecting surfaces. They 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 importance of measurand traceability (via calibration) for this broad range of autocollimator applications supports the motivation for this comparison of the calibration capabilities of NMIs.



Figure 1. Elcomat 3000 autocollimator by Möller-Wedel Optical GmbH (MWO), Wedel, Germany (Figure courtesy MWO).

2. The standard

2.1 General requirements

The standard for this comparison, see Section 2.2, has been chosen for the following reasons:

1. The comprehensive experience at the PTB in its calibration and the characterization of the parameters influencing the standard's angle response, see Refs. [1-4].
2. Its stability as demonstrated by repeated calibrations of individual instruments over several years at the PTB.

¹ The MRA was signed at the 21st General Conference of Weights and Measures on the 14th October 1999 in Paris; see information on the BIPM website (<http://www.bipm.fr>).

3. Its widespread use for precision angle metrology in research and industry.
4. Its commercial availability so that each participating laboratory may obtain, if desired, a standard of the same type.

2.2 Description of the standard

For this comparison, an electronic autocollimator type Elcomat 3000 by Möller-Wedel Optical GmbH (MWO), Wedel, Germany, see Figure 1, has been kindly made available by the manufacturer².

As all 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. 900

2.3 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.

2.4 Handling

- Familiarize yourself with the functioning and handling of the autocollimator by means of the manual supplied with it and the information given in the Technical Protocol. The manual was also sent to all participants as an electronic file.
- 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

² http://www.moeller-wedel-optical.com/El-Autocollimators/E_Elcomat3000.htm

³ http://www.moeller-wedel-optical.com/Products/E_acc_mech.htm

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. Organisation

Following the guidelines set up by the Bureau International des Poids et Mesures (BIPM)⁴, the PTB has drafted this technical protocol after soliciting responses to a preliminary description of the comparison by several members from the provisional list of NMIs. Their technical comments have been included in this draft. This RMO key comparison EURAMET.L-K3.2009 (EURAMET project #1074) is operated to support the MRA of the CIPM and its progress and results will be reported regularly to EURAMET TC-L as well as the WG-MRA of the CCL. By their declared intention to participate in this comparison, the laboratories accept the general instructions and the Technical Protocol written down in this document and commit themselves to follow the procedures strictly.

Due to the large number of participating laboratories, the time schedule is very tight. Therefore particular attention must be attributed to the availability of the laboratory carrying out the calibrations, to transportation and to customs problems.

3.1 Requirements for participation

According to the WGDM recommendation No.2 (document CCDDM/WGDM/97-50b), the participating laboratories should offer this measurement as a calibration service (now or in future), be willing to participate in a regional comparison in order to provide a link between the interregional and the regional comparisons and have a measurement uncertainty below a certain level. This level shall be fixed to approximately 1 arcsec standard uncertainty. (However, most of the participants do offer calibrations with substantially smaller measurement uncertainties already.)

Different metrological regions are represented in this comparison with a focus on NMIs from the EURAMET and from the Asia Pacific Metrology Programme (APMP). Calls for participation were issued at several WGDM and EURAMET TC-L meeting from September 2008 on and include everybody who was willing to participate in the autocollimator comparison.

⁴ <http://www.bipm.fr>

3.2 Participants

The following Table 1 provides the provisional list (as of 2014/10/10) of the participants.

Table 1. List of participants from 2014/10/10.

NMI	Country	Name	Surname	Email	Address	Phone / Fax
A-STAR	Singapore	Tan	Siew Leng	tan_siew_leng@nmc.a-star.edu.sg chao_zhixia@nmc.a-star.edu.sg	1 Science Park Drive Singapore 118221	Tel: +65 6279 1938 Fax: +65 6279 1994
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VSL	Netherland	Bergmans	Rob	rbergmans@vsl.nl	no information provided	Tel: +31 15 2691500 Fax: +31 15 2691641

3.3 Time schedule

The comparison will be carried out in a mixed form, circulation and star-type. After the standards were circulated in a region, they are sent back to the pilot laboratory for recalibration (stability / quality inspection) before circulation within the next region.

Each laboratory has **four weeks for calibration, including transportation** (during the break of the year, additional time is scheduled). With its confirmation to participate, each laboratory has also confirmed that it is capable to perform the measurements in the limited time allocated to it. Efforts should be made to ensure that the standards arrive in the country of the next participant according to the time schedule. In case of any problems which will affect the time schedule (e.g., technical problems, customs clearance takes too much time, etc.), the laboratory has to contact the pilot laboratory immediately to coordinate the next steps.

The comparison is split into four separate loops, see Table 2 for details:

1. PTB (pilot laboratory)
2. Loop 1: NMIs with an expanded measurement uncertainty $U < 0.1$ arcsec ($k = 2$)
3. PTB
4. Loop 2: NMIs with an expanded measurement uncertainty $U \geq 0.1$ arcsec ($k = 2$)
5. PTB
6. Loop 3: APMP Asian-Pacific NMIs (part 1)
7. PTB
8. Loop 4: APMP Asian-Pacific NMIs (part 2) and new European participants
9. PTB

The separate loop for APMP participants was chosen to provide an optimal arrangement for the shipping of the autocollimator in the Asian-pacific region.

Table 2. Preliminary time schedule of comparison from 2014/10/10**Loop 1: Measurement uncertainty $U(k=2) < 0.1$ arcsec (with exceptions)**

Germany	PTB (pilot)	12 / 2009
United Kingdom	NPL	01 / 2010
Netherlands	VSL	02 / 2010
Finland	MIKES	03 / 2010
Switzerland	METAS	04 / 2010
Germany	PTB (pilot)	05 / 2010
Italy	INRIM	06 / 2010
Turkey	UME	07 / 2010
Romania	INM	08 / 2010
France	LNE	09 / 2010
Germany	PTB (pilot)	11 / 2010

Loop 2: Measurement uncertainty $U(k=2) \geq 0.1$ arcsec

Germany	PTB (pilot)	04 / 2011
Hungary	MKEH	05 / 2011
Israel	INPL	07 / 2011
Czech Republic	CMI	09 / 2011
Poland	GUM	11 / 2011
Slovak Republic	SMU	12 / 2011
Germany	PTB (pilot)	02 / 2012
Spain	CEM	03 / 2012
Greece	EIM	04 / 2012
Belgium	SMD	05 / 2012
Netherlands	VSL	07 / 2012
Portugal	IPQ	09 / 2012
Italy	INRIM	11 / 2012
Germany	PTB (pilot)	12 / 2012

Loop 3: APMP Asian-pacific participants (part 1)

Germany	PTB (pilot)	12 / 2012
Japan	NMIJ	02 / 2013
Australia	NMIA	04 / 2013
China	NIM	08 / 2013
India	NPLI	10 / 2013
Germany	PTB (pilot)	02 / 2014

Loop 4: APMP Asian-pacific participants (part 2) and new European participants

Germany	PTB (pilot)	02 / 2014
Singapore	A-STAR	05 / 2014
Thailand	NIMT	07 / 2014
Serbia	DMDM	09 / 2014
Germany	PTB (pilot)	10 / 2014
Indonesia	KIM-LIPI	11 / 2014
Russia	VNIIM	12 / 2014
Germany	PTB (pilot)	02 / 2015
Bulgaria	BIM	03 / 2015
Slovak Republic	SMU	04 / 2015
Germany	PTB (pilot)	05 / 2015

3.4 Transportation

Transportation to the next participant is each laboratory's own responsibility and must be provided on its own cost.

All items are packed together in an **aluminium container (dimensions 800 x 600 x 630 cm³)** 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 (see Appendix A3 for a detailed description including photographs). The transportation packaging was designed to protect the content from possible damages during transport. For transport, it is mandatory to **use the original transportation packaging** and an experienced carrier service, e.g. TNT.

For countries which are not member of the European Union, the package will be accompanied by an ATA (Admission Temporaire / Temporary Admission) carnet to accelerate customs procedures. **For those countries which have not joined the ATA agreement (e.g., China, Taiwan, etc.), other standard customs procedures have to be followed⁵.**

The value of the package with the standard is estimated to be about **35 000 Euro**.

Please inform the pilot laboratory by fax or / and email immediately after receiving the standard using the form in the Appendix A1. After having completed the measurements, all items have to be transported to the next participant immediately. It is advisable to prepare and organise the transportation beforehand. In case of remaining questions, the pilot laboratory should be contacted. Please inform the pilot laboratory and the next laboratory by fax or / and email about the details of transportation.

3.5 Unpacking, handling, packing

The package contains the following items:

- A special transportation case with the following items (see Appendix A3):
 - The autocollimator with the external data logger for
 - acceleration in 3 axes,
 - temperature, and
 - humidity.
 - The Control Unit 3000.
 - Cables for connecting
 - the autocollimator to the Control Unit,
 - the Control Unit to the PC, and
 - the Control Unit to the voltage supply.
 - The Laser finder with power supply.
 - The autocollimator manual and a software CD.

⁵ Please inform the pilot lab about special customs regulations to be followed in your country. Details of the transport between ATA and non-ATA countries will then be discussed by pilot lab and the involved NMI.

- A box with the precision plane mirror and the calibration certificate of its flatness deviations.
- The adjustable holder with a double sided clam.
- The manual and software CD of the data logger.
- One copy of the Technical Protocol.
- ‘Shockwatch’ and ‘Tiltwatch’ indicators for transport monitoring.
- Photographic documentation of the components of the entire package.

Instructions for **unpacking / packing**:

- After receiving, check the transport vessel for damage. In case of damages, please document them and inform the pilot laboratory. Check the status of the ‘Shockwatch’ and ‘Tiltwatch’ indicators and report it to the pilot laboratory using the fax form, see Appendix A1.
- Open the transport container carefully and only in an appropriate environment.
- Handle the empty aluminium container carefully so that the ‘Shockwatch’ and ‘Tiltwatch’ indicators are not triggered accidentally.
- Inspect the autocollimator carefully for damage, scratches or dirt. In case of damages, please document them and inform the pilot laboratory.
- 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.
- After unpacking / before re-packaging of the items: Check the packing list and the photographic documentation for completeness of the items and the packaging material.
- Familiarise yourself with the functioning and handling of the data logger by means of the documentation which is provided together with it.

As noted, any damage has to be communicated to the pilot laboratory immediately.

3.6 Financial aspects, insurance

Each participating laboratory covers the costs for the measurements, transportation and eventual customs formalities as well as for any damages not covered by transportation insurance that may have occurred within its country. The overall costs for the organisation of the comparison are covered by the organising pilot laboratory. All procurement and manufacturing costs of the standards were covered by Möller-Wedel Optical GmbH.

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 later group of factors includes the following parameters (see [2-4] for details):

- 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

Each participating NMI is allowed to use its own plane mirror which is normally used for 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: $\lambda/8$ (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 [2-4], 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), see Figure 2. In that case, please **use face 1 of the double-sided mirror**.

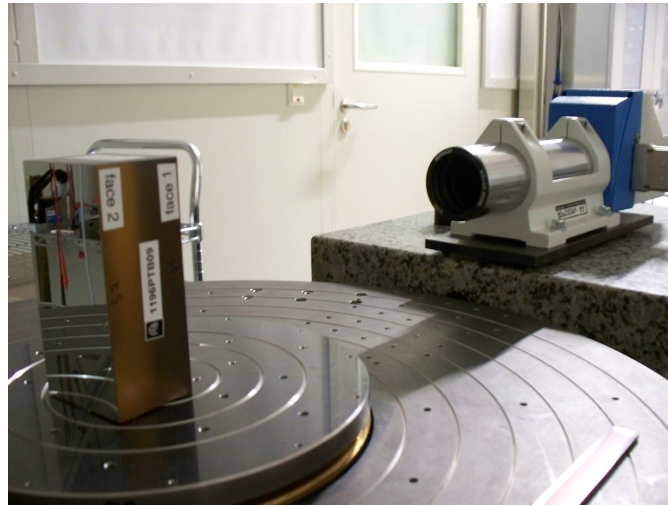


Figure 2. Precision plane mirror provided by the PTB (its use is optional). Please use face 1 of the double-sided mirror.

We have investigated the influence of flatness deviations of the reflecting mirror on the angle response of autocollimators. 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 [2].

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 [3].

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, see [5-6]. Additionally, we have demonstrated significant changes in the angle response of autocollimators in the case of a variable distance to the reflecting mirror [3].

4.3 Autocollimator aperture

To avoid vignetting effects [4], the entire illuminated (effective) autocollimator aperture (32 mm in diameter) will be used in this comparison. No additional aperture stop is required. See also 4.1.

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.

Qualification #1: If calibrations are not possible over the entire angle range, participants are allowed to calibrate over a limited range.

Qualification #2: If calibrations can not be performed at all specified measurement points (e.g., due to manual operation of the equipment), participants are allowed to calibrate at a selected subset of points. In this case, we suggest choosing a step width which is a multiple of the recommended step width.

Qualification #3: There is a small subset of participants which is not able to perform the calibrations according to the given recommendations even when taking the qualifications into consideration, e.g., due to a fixed step width which is predetermined by their calibration equipment. In this case, calibrations can be performed as specified by the equipment. The pilot laboratory, PTB, will provide a comprehensive calibration of the autocollimator with high angular resolution and will make an effort to accommodate the measurements by means of a flexible data analysis.

4.5 Adjustment procedures

Each participating NMI may follow its own adjustment procedures for autocollimator calibration as specified in their manuals. In Figure 3, the measurement set-up for the calibration of electronic autocollimators against the primary angle reference of the PTB, the angle comparator WMT 220 ([7], manufactured by Dr. Johannes Heidenhain GmbH, Traunreut, Germany) is presented. 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 and a guideline, in Table 3, we provide a description of our own adjustment procedures at the PTB.

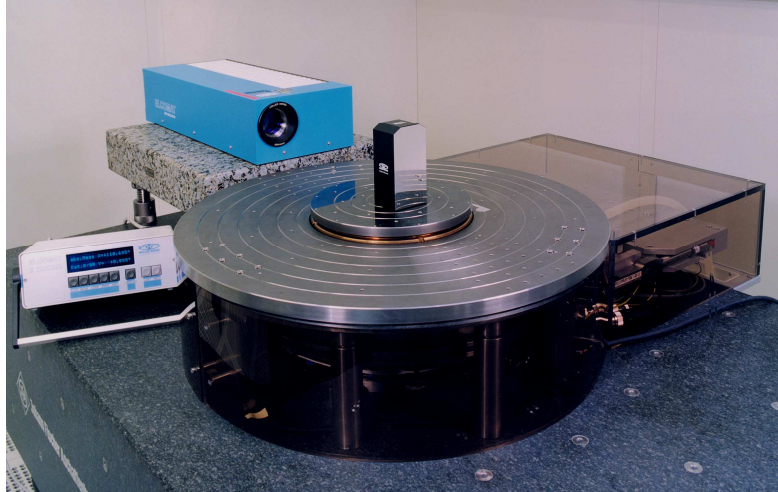


Figure 3. Set-up for the calibration of electronic autocollimators against the primary angle reference of PTB, the angle comparator WMT 220. The autocollimator and the plane mirror need to be adjusted relative to the comparator as described in the text.

Table 3. Adjustment procedures for autocollimator calibration at the PTB.

#	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 attachment ⁶ , 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.	$\leq 1 \text{ mm}$
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).	$\leq 1 \text{ mm}$
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 $\pm 1000 \text{ arcsec}$ must result in minimal change Δy in the y-axis reading.	$\Delta y / \Delta x < 0.001$
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).	$< 1 \text{ arcsec}$
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.	$< 1 \text{ arcsec}$
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.	$< 0.1 \text{ arcsec}$

4.6 Autocollimator settings

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

- Switch to 'abs' setting (E3000 Manual, p. 18).

⁶ For instructions on the use of the laser attachment (MWO no. 219 717), see the Elcomat 3000 manual.

- 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)

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

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 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 α_{AC} and α_{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 α_{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 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 5.

Table 4. 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_T	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	

Within the scope our comparison, we also would like to obtain information on the reliability of the sampling point α_{AC} , i.e., the x-angle measured by the autocollimator at which the angle deviation $\delta(\alpha_{AC})$ was obtained. The rationale behind this is as follows: Autocollimators show residual angle deviations on an angular scale of the order of a few arcseconds which corresponds to the pixel pitch of the CCD detector that is used to pick up the reticle image in the focal plane of the autocollimator's objective. Small variations in the placement of the sampling points α_{AC} between participants may lead to spurious differences between the calibrations which are not accounted for by their uncertainty budgets. Most probably, as the amplitude of these periodic angle deviations is small, this effect has a negligible influence on the analysis of the differences between the participant's calibration results. Nevertheless, we will estimate the magnitude of this effect by means of a calibration of the standard autocollimator used in this comparison with a sufficiently high angular resolution which will be obtained at the PTB.

Table 4 presents an overview of the measurands / parameters which have been explicated in this section and in Section 5 (optional parameters are marked accordingly).

5. Standard measurement uncertainty

The standard measurement uncertainty should be evaluated according to the *Guide to the Expression of Uncertainty in Measurement* [8]. Alternatively, participants may choose to use the approach according to the *Supplement 1 to the GUM* [9] 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)⁷. In this section, the standard approach is outlined.

For each measured deviation δ , its associated standard uncertainty $u(\delta)$ needs to be provided. For the derivation of the expanded uncertainty, provide the coverage factor k for a 95% coverage probability and, if appropriate⁷, its effective degrees of freedom $\nu_{\text{eff}}(\delta)$. Note that the standard uncertainty – not the expanded uncertainty – is the basic statement on the uncertainty of a measurement.

For deriving the uncertainty budget, the deviation $\delta = \alpha_{\text{AC}} - \alpha_{\text{REF}}$ of the autocollimator measurement from the measurement of the reference system, see Section 4.7, Equation (1), needs to be expressed as a function of the N input quantities x_i , $i \in [1, \dots, R]$, according to

$$\delta = f(x_1, \dots, x_i, \dots, x_R) \quad . \quad (2)$$

Their uncertainty contributions $u_i(\delta)$ are

$$u_i(\delta) = |c_i| \cdot u(x_i) \quad , \quad (3)$$

with the sensitivity coefficients c_i according to

$$c_i = \frac{\partial \delta}{\partial x_i} \quad . \quad (4)$$

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

$$u^2(\delta) = \sum_{i=1}^R u_i^2(x_i) = \sum_{i=1}^R c_i^2 u^2(x_i) \quad . \quad (5)$$

In some cases, higher order terms might have to be taken into account in Equation (5). If a correlation between the input quantities x_i is present, it also needs to be considered:

$$u^2(\delta) = \sum_{i=1}^R \sum_{l=1}^R c_i c_l \cdot u(x_i, x_l) = \sum_{i=1}^R c_i^2 u^2(x_i) + 2 \sum_{i=1}^{R-1} \sum_{l=i+1}^R c_i c_l \cdot u(x_i, x_l) \quad , \quad (6)$$

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 $\nu_{\text{eff}}(\delta)$ are given by the Welch-Satterthwaite equation⁷

$$\frac{u^4(\delta)}{\nu_{\text{eff}}(\delta)} = \sum_{i=1}^R \frac{u_i^4(\delta)}{\nu_i} = \sum_{i=1}^R \frac{c_i^4 u^4(x_i)}{\nu_i} \quad , \quad (7)$$

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

For the uncertainty estimation, the participants are encouraged to use all known and significant influencing parameters associated with their applied methods.

For documentation, the participants are required to report their measurement uncertainty budget in tabular format according to Table 5 (or, in the case of the PDF approach, provide equivalent documentation). State whether the input quantity x_i has been derived from a Type A or B evaluation and give its distribution (N = normal, R = rectangular, T = triangular, etc.).

⁷ Note that in case of the alternative PDF approach, the effective degrees of freedom, Equation (7), are no longer a valid concept and need not to be provided.

State the degree of freedom ν_i , the sensitivity coefficient c_i , and the uncertainty contribution $u_i(\delta)$ associated with each x_i . Some indicated standard uncertainties, might be based on a separate calculation, e.g., Monte Carlo simulations, which can be added to the report.

Table 5. Example scheme for the uncertainty budget.

Description of input quantity x_i	Symbol for x_i	Type A or B	Distribution	Std. meas. uncertainty $u(x_i)$ of input quantity (arcsec)	Degrees of freedom ν_i	Sensitivity coeff. $c_i = \frac{\partial \delta}{\partial x_i}$	Std.-meas. uncertainty contribution $u_i(\delta)$ (arcsec)
Angle deviations of the primary standard	$\Delta\alpha_{\text{WMT}}$	B	R	0.0006 arcsec	∞	1	0.0006 arcsec
...	
Combined standard measurement uncertainty $u(\delta)$ Coverage factor k for a coverage probability of 95% Effective degrees of freedom $\nu_{\text{eff}}(\delta)$ ⁷							

6. 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 (see Sections 5, 6, and Appendix A2). Electronic templates of the report forms in the Appendix of this document are sent by e-mail to all participating laboratories (MS Word documents and PDF files). 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). In any case, the printed and signed report must also be sent in paper form by mail. In case of any differences, the paper forms are considered to be the valid versions. The reports shall be sent to the pilot laboratory **no later than six weeks after completing the measurements**.

The measurement data (see Section 4.7) 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 6. For documentation, please also send a printed and signed version of the data file.

Table 6. Information on the data rows of the ASCII file.

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.

7. Comparison / analysis of results

After completion of the circulation, the pilot laboratory will prepare a first draft report and send it to the participants for comment. Subsequently, the procedure outlined in the BIPM *Guidelines for CIPM Key Comparisons* [10] will be followed. According to the MRA, a comparison should provide information on the degree of equivalence of the measurements of all participants. To discuss the degree of equivalence, normally, Key Comparison Reference Values (KCRV) are generated from the participants' results. Note that there is a small subset of participants which is not able to perform the calibrations according to the recommendations on the measurement ranges and steps given in Section 4.4. This poses a problem for the determination of the KCRV. In these cases, the comprehensive calibration of the autocollimator with high angular resolution provided by the PTB will be used to take this into account by means of a more flexible data analysis (which has not yet been finalised).

The main objective of the comparison is to provide reliable information on the degree of equivalence of the different angle realizations between the participating institutes. To

accomplish this, the measurement results of the participants, which are given as deviations δ of the angles measured by the autocollimator from the angles provided by the reference system have to be analyzed further. The pilot laboratory proposes the following procedure for analysing the comparison results, closely following the recommendations in [11]⁸:

(1) Input data

Input data are the values delivered by the participants according to Sections 4.7 and 5, specifically:

- The deviations $\delta_{jp} = \alpha_{AC,jp} - \alpha_{REF,jp}$ of the angles $\alpha_{AC,jp}$ measured by the autocollimator from the angles $\alpha_{REF,jp}$ provided by the reference system, with the index $j \in [1, \dots, N]$ of the angle position and the participant's index $p \in [1, \dots, M]$.
- The combined standard uncertainties $u(\delta_{jp})$ associated with the deviations δ_{jp} .

(2) KCRV

It is assumed that (I) the standard (i.e., the autocollimator) is stable, (II) that each participant's measurement of the standard is realized independently of the other participants' measurements, and (III) that a Gaussian distribution (with a mean equal to the participant's measurement and a standard deviation equal to the associated standard uncertainty) can be assigned to the measurand of which the participant's measurement is an estimate. The later will also be checked, for details, see item (3) in this section.

If these assumptions are valid, each reference angle deviation $\tilde{\delta}_j$, the KCRV, is simply given by the weighted mean of all of the participants' results, with the weights defined by the inverse square of the standard uncertainties, $u^{-2}(\delta_{jp})$, according to

$$\tilde{\delta}_j = \frac{\sum_{p=1}^M u^{-2}(\delta_{jp}) \cdot \delta_{jp}}{\sum_{p=1}^M u^{-2}(\delta_{jp})} \quad (8)$$

Along the lines of Equations (3) - (6), we can derive the sensitivity coefficients

$$c_{jp} = \frac{\partial \tilde{\delta}_j}{\partial \delta_{jp}} = \frac{u^{-2}(\delta_{jp})}{\sum_{p=1}^M u^{-2}(\delta_{jp})} \quad (9)$$

and the standard uncertainty (assuming uncorrelated measurements)

$$u(\tilde{\delta}_j) = \left(\sum_{p=1}^M c_{jp}^2 \cdot u^2(\delta_{jp}) \right)^{1/2} = \left(\sum_{p=1}^M u^{-2}(\delta_{jp}) \right)^{-1/2} \quad (10)$$

(3) Consistency testing

⁸ The procedure is only outlined here. Note that the final analysis of the comparison may include more advanced statistical methods.

The Birge ratio R_B is a parameter linked to the χ^2 test and it allows estimating whether the results of a comparison are consistent [12-13].

With the external and internal uncertainties of the weighted mean, u_{ext} and u_{int} , respectively, defined as

$$u_{\text{ext}} = \left(\frac{1}{M-1} \frac{\sum_{p=1}^M u^{-2}(\delta_{jp}) \cdot (\delta_{jp} - \tilde{\delta}_j)^2}{\sum_{p=1}^M u^{-2}(\delta_{jp})} \right)^{1/2} \quad \text{and} \quad (11)$$

$$u_{\text{int}} = u(\tilde{\delta}_j) \quad , \quad (12)$$

the Birge ratio is given as

$$R_B = \frac{u_{\text{ext}}}{u_{\text{int}}} = \left(\frac{1}{M-1} \sum_{p=1}^M u^{-2}(\delta_{jp}) \cdot (\delta_{jp} - \tilde{\delta}_j)^2 \right)^{1/2} . \quad (13)$$

A Birge ratio R_B significantly larger than one is indicating an underestimation of the measurement uncertainty by at least one participant, while a R_B significantly smaller than one is indicating an overestimation of the measurement uncertainty. The expectation value of R_B for a normal distribution is 1.

Following [11], we regard this χ^2 -based consistency check as failing if

$$\Pr\{R_B(\nu) > R_B[\text{observed}]\} < 0.05 \quad , \quad (14)$$

with the degrees of freedom $\nu = M - 1$ and ‘Pr’ denoting ‘probability of’. (As stated above, for this hypothesis testing, it is assumed that a Gaussian distribution can be assigned to the measurand of which the participant’s measurement is an estimate.)

If the results will found to be not consistent, the participants have to be informed about the inconsistency adequately and the recommendations of the *Guidelines for CIPM Key Comparisons* [10] will be followed, see [11] for additional mathematical aspects.

(4) Differences from reference values

From the participants’ measurements, the differences $\Delta\delta_{jp}$ from the reference angle deviations, the KCRV, and their associated uncertainties $u(\Delta\delta_{jp})$ are calculated according to

$$\Delta\delta_{jp} = \delta_{jp} - \tilde{\delta}_j \quad (15)$$

and

$$u(\Delta\delta_{jp}) = \left(u^2(\delta_{jp}) + u^2(\tilde{\delta}_j) - 2u(\delta_{jp}, \tilde{\delta}_j) \right)^{1/2} \quad , \quad (16)$$

with the covariance or mutual uncertainty $u(\delta_{jp}, \tilde{\delta}_j)$ [8] which accounts for the (trivial) correlation between the participants’ measurements δ_{jp} and the reference values $\tilde{\delta}_j$ which have been derived from them according to Equation (8).

Using Equation (8), the preceding Equation (16) can be expressed as

$$u(\Delta\delta_{jp}) = \left(u^2(\delta_{jp}) - u^2(\tilde{\delta}_j) \right)^{1/2} . \quad (17)$$

Differences $\Delta\delta_{jpq}$ between pairs of the participants' measurements δ_{jp} and δ_{jq} , $p, q \in [1, \dots, M]$, and their associated uncertainties $u(\Delta\delta_{jpq})$ are calculated accordingly as

$$\Delta\delta_{jpq} = \delta_{jp} - \delta_{jq} \quad (18)$$

and

$$u(\Delta\delta_{jpq}) = \left(u^2(\delta_{jp}) + u^2(\delta_{jq}) \right)^{1/2} . \quad (19)$$

(As stated above, it is assumed that each participant's measurement of the standard is realized independently of the other participants' measurements.)

(5) Degree of equivalence

The E_N criterion is proposed to give information on the degree of equivalence of the different angle realizations of the participants, e.g. [14-15]. With respect to the differences $\Delta\delta_{jp}$ from the reference angle deviations, the KCRV according to Equation (15), the definition of the E_N criterion is

$$E_N = \frac{1}{k} \frac{\Delta\delta_{jp}}{u(\Delta\delta_{jp})} , \quad (20)$$

with the coverage factor k according to [8] and the standard uncertainty $u(\Delta\delta_{jp})$ according to Equation (17).

For $k = 2$, often the compatibility criterion $|E_N| \leq 1$ is proposed to indicate that the measurement of a participant is in satisfactory agreement, at 95% coverage probability, with the KCRV as defined within a comparison.

The same criterion can be used for the evaluation of the degree of equivalence of the measurements between pairs $p, q \in [1, \dots, M]$ of participants

$$\tilde{E}_N = \frac{1}{k} \frac{\Delta\delta_{jpq}}{u(\Delta\delta_{jpq})} , \quad (21)$$

with the definitions according to Equations (18) and (19).

8. References

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- [9] JCGM 101:2008 "Evaluation of measurement data - Supplement 1 to the 'Guide to the expression of uncertainty in measurement' - Propagation of distributions using a Monte Carlo method", Joint Committee for Guides in Metrology (JCGM: 2008) <http://www.bipm.org/en/publications/guides/gum.html>
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Telefax Telefax Telefax Telefax Telefax

To: PTB

5.21 Length and Angle Graduations

Bundesallee 100

D-38116 Braunschweig

Germany

Fax: ++49 531 592 69 5221

Email: andreas.just@ptb.de (send copy to ralf.geckeler@ptb.de)

From: (participating NMI)

We confirm having received the standard of the *EURAMET.L-K3.2009 Angle Comparison Using an Autocollimator*:.....(date).

After visual inspection:

No damage has been noticed.

Damage(s) must be reported. Please specify details of the damage (use additional page for description), if possible add image of the damage.

Shockwatch sensor (attached to aluminium transportation container, Appendix A3) was activated.

Tiltwatch sensor (also attached to container) was activated.

Date

Signature

.....

.....

Documentation of measuring conditions

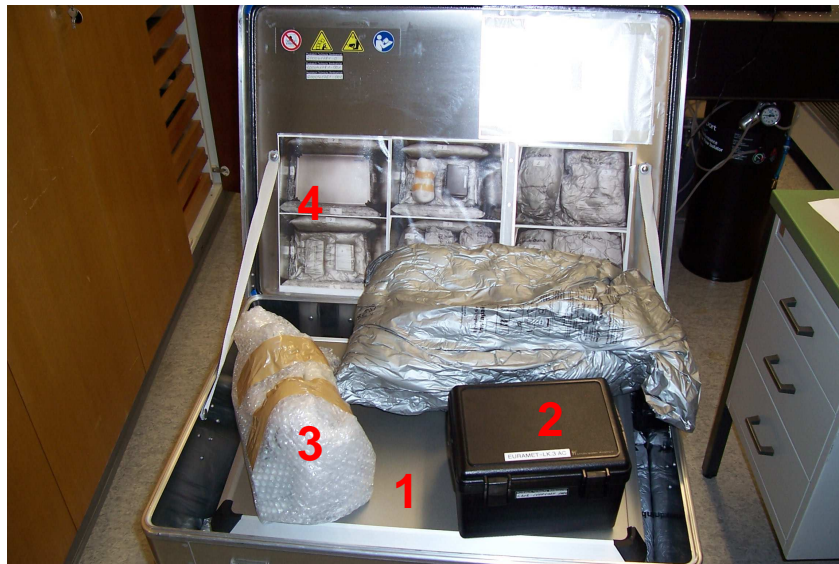
1. General information on the measuring conditions
 - 1.1 Mounting
 - Horizontal orientation of the AC x-axis
 - Vertical orientation of the AC x-axis
 - Use of additional optics for beam rotation (If yes, please provide a short description)
 - 1.2 Plane mirror
 - Use of the plane mirror provided by the PTB
 - Use of the plane mirror owned by the NMI
 - Reflectivity %
 - Size mm x mm
 - Flatness deviation (rms or pv, if know) nm
 - 1.3 Distance between autocollimator and reflector
 - Distance mm
 - 1.4 Temperature of the measurement room
 - Temperature °C
 - 1.5 Autocollimator settings
 - 1.5.1 Automated measurements
 - Use of the RS232 interface 'text' protocol
 - Use of the RS232 interface 'compatible' protocol
 - Use of the USB interface
 - 1.5.2 Manual measurements
 - Resolution setting arcsec
 - 1.6 Details to the measurement procedure
 - Static measurement
 - Dynamic measurement
 - Number of repeat measurements $n_r =$
 - Repeat measurements in different relative angular orientations between the autocollimator and the reference system yes no
 - Number or repeat measurements of the autocollimator in each measuring position $n_{AC} =$
 - Number or repeat measurements of the reference in each measuring position $n_{REF} =$

Date NMI Signature

.....

Transport packaging

Photograph A3-1 shows the outer aluminium container (dimensions 800x600x630 cm³) together with the special protecting case for the autocollimator and its accessories (1), the protecting case for the precision plane mirror (2), the adjustable holder for the autocollimator with a double-sided clam packed in protective bubble wrap (3), and customized and numbered damping foam material. On the inside of the top cover of the aluminium container, photographs are attached (4) which show the steps of the packaging in detail.



Photograph A3-1

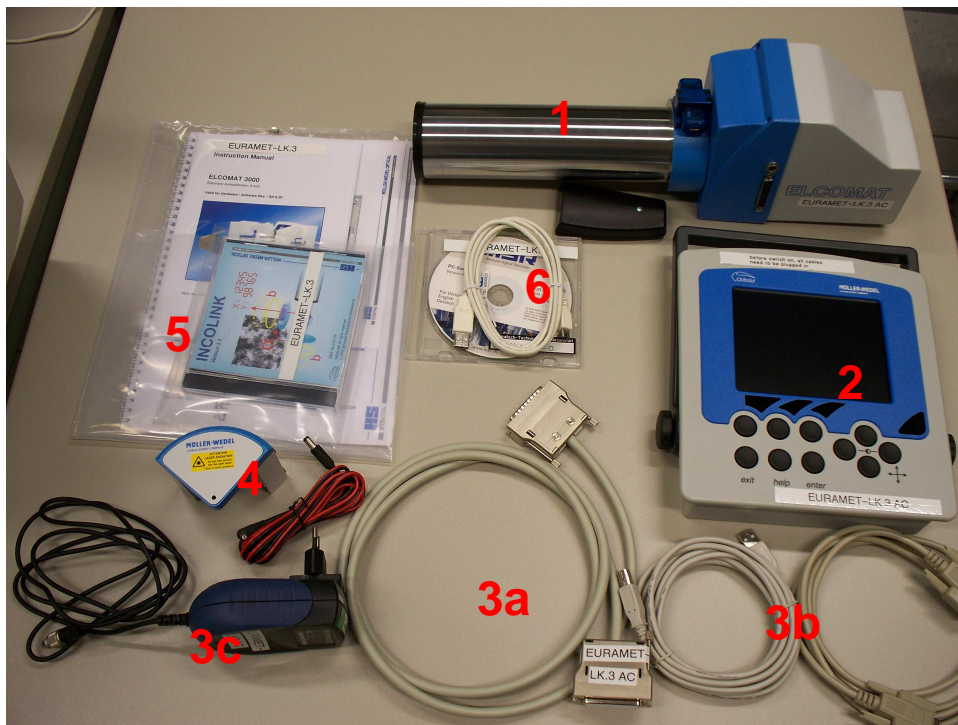
Photograph A3-2 shows the special protecting case of the autocollimator and its accessories.



Photograph A3-2

Photograph A3-3 shows content of the protecting case in detail:

- (1) The autocollimator with a fixed external data logger
- (2) The Control Unit 3000.
- (3) Cables for connecting
 - (3a) the autocollimator to the Control Unit,
 - (3b) the Control Unit to the PC, and
 - (3c) the Control Unit to the voltage supply.
- (4) The laser finder with its power supply.
- (5) The autocollimator manual and a software CD.
- (6) Cable for connecting the external data logger to the PC, a software CD, and a manual.



Photograph A3-3