Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin

EURAMET. L-K7.n01 Key Comparison
Linescales

Technical Protocol

Physikalisch-Technische Bundesanstalt (PTB)

Braunschweig, November 2024

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Final Version Issued on 21.11.2024

2 Introduction

The metrological equivalence of national measurement standards and of calibration certificates issued by national metrology institutes is established by a set of key and supplementary comparisons chosen and organized by the Consultative Committees of the CIPM or by the regional metrology organizations in collaboration with the Consultative Committees.

At its meeting in June 2018, the WG-MRA of the Consultative Committee for Length, CCL, decided upon a key comparison on linescales to be prepared by PTB as the pilot laboratory. The comparison was intended to start in 2019, organised as an CCL-RMO comparison as EURAMET.L-K7.2019.

The procedures outlined in this document cover the technical procedure to be followed during the measurements of the line scales. The procedures are principally intended to allow a clear description of the required measurements, handling and transportation of the circulating standards, and to complete the comparison in the defined time scale. This technical protocol was prepared following the Guidance Document CCL-WG/-MRA-GD-3.1 (Technical protocol template). It is also aligned to the previous protocols for CCL-S3 (Nano3; 2000 - 2002) drawn by the Physikalisch-Technische Bundesanstalt (PTB), Germany, for EUROMET.L-K7.2006 (2006 - 2008) drawn by the Metrology Institute of the Republic of Slovenia (MIRS) and the APMP.L-K7.2014 (2015 - 2017) key comparison drawn by the Korea Research Institute of Standards and Science (KRISS).

A goal of the CCL key comparisons for topics in dimensional metrology is to demonstrate the equivalence of routine calibration services offered by NMIs to clients, as listed in Appendix C of the CIPM Mutual Recognition Agreement (MRA). To this end, participants in this comparison agree to use the same apparatus and methods as routinely applied to client artefacts.

By their declared intention to participate in this key comparison, laboratories accept the general instructions and agree to strictly follow the technical protocol of this document. Due to the large number of participants, it is very important that participating NMIs perform their measurements during assigned dates. Participants should keep in mind that the allocated time period is not only for measurements, but also for transportation and customs clearance as well. Once the protocol and list of participants has been agreed to, no change to the protocol or list of participants may be made without prior agreement of all participants.

3 Organization

3.1 Participants

Table 1. List of participant laboratories and their contacts.

Laboratory Code	Contact person, Laboratory	Phone, Fax, email
APMP		
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COOMET		
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3.2 Schedule

Due to the different measurement capabilities (measurement range and measurement uncertainty) of the participants, and to optimize the duration of the entire comparison the comparison will be performed in 3 different groups and loops.

Group 1 consists of all participants that are not able to measure line scales longer than 100 mm. The members of this group will perform measurements on a 100 mm quartz line scale.

The other participants will either measure a 400 mm glass scale or a 300 nm Zerodur scale. The quality of the 400 mm glass scale will not allow to verify measurement capabilities (CMCs) of a quarter of the participating laboratories. Therefore, the half of the participants with smaller measurement uncertainties (calculated for the 300 mm line scale) will perform measurements on the 300 mm Zerodur scale. They constitute the 2nd group. The remaining participants are in group 3 and will use the 400 mm glass scale for the measurements.

The linking of the groups will be realized by 2-3 laboratories who will measure all 3 line scales, including the pilot laboratory.

In general, the order of the participants was arranged according to their measurement capabilities (smallest uncertainties first). There are a few exceptions. Some participants asked to perform measurements at the end of the comparison. In addition, the participants of countries that require an ATA Carnet were grouped.

Each laboratory has five weeks that include customs clearance, calibration and transportation to the following participant. With its confirmation to participate, each laboratory is obliged to perform the measurements in the allocated period and to allow enough time in advance for transportation so that the following participant receives the transfer standard in time. **The artefact should arrive at the next participant before starting date of measurement in Tables 2, 3 and 4.** If a laboratory has technical problems to perform the measurements or customs clearance takes too long, the laboratory has to contact the pilot laboratory as soon as possible and, according to whatever it decides, it might eventually be obliged to send the standards directly to the next participant before completing the measurements or even without doing any measurements.

Table 2. Schedule of the comparison for **group 1** (100mm line scale).

RMO	Laboratory	Starting date of measurement	ATA Carnet
EURAMET	PTB (pilot)		n
EURAMET	METAS (linking lab)	30.9.2024	y
EURAMET	DMDM	4.11.2024	y
EURAMET	CEM	9.12.2024	n
EURAMET	SMU	27.1.2025	n
EURAMET	NPL	24.2.2024	y
EURAMET	NSAI	7.4.2025	n
EURAMET	MIKES (linking lab)	12.5.2025	n
COOMET	KazInMetr	30.6.2025	Y
COOMET	NSC	4.8.2025	y
EURAMET	PTB (pilot)	8..9.2025-	n

Table 3. Schedule of the comparison for **group 2** (300 mm line scale).

RMO	Laboratory	Starting date of measurement	ATA Carnet
EURAMET	PTB (pilot)	4.11.2024	n
EURAMET	VTT MIKES (linking lab)	9.12.2024	n
EURAMET	BIM	27.1.2025	n
EURAMET	CMI	3.3.2025	n
EURAMET	GUM	7.4.2025	n
EURAMET	VSL	12.5.2025	n
EURAMET	CEM	16.6.2025	n
EURAMET	PTB (pilot)	21.7.2025	
EURAMET	METAS (linking lab)	25.8.2025	y
EURAMET	DMDM	29.9.2025	y

APMP	KRISS	3.11.2025	y
APMP	NIM	8.12.2025	y
APMP	NPLI	12.1.2026	y
EURAMET	NPL	16.2.2026	y
SIM	NIST	23.3.2026	Y
COOMET	MIRS	27.4.2026	N
EURAMET	NSC	1.6.2026	Y
EURAMET	PTB (pilot)	6.7.2026	Y

Table 4. Schedule of the comparison for **group 3** (400 mm line scale).

RMO	Laboratory	Starting date of measurement	ATA Carnet
EURAMET	METAS (linking lab)	2.12.2024	Y
EURAMET	MIKES (linking lab)	13.1.2025	n
APMP	NMIM	17.2.2025	y
APMP	NMIA	24.3.2025	y
APMP	SNSU-BSN	28.4.2025	y
SIM	CENAM	2.6.2025	y
EURAMET	PTB (pilot)	7.7.2025	n
EURAMET	LNE	15.9.2025	n
EURAMET	FSB-LPMD	20.10.2025	n
EURAMET	BEV	24.11.2025	n
EURAMET	EIM	12.1.2026	n
EURAMET	INM	16.2.2026	n
EURAMET	BFKH	23.3.2026	n
EURAMET	PTB	27.4.2026	n
EURAMET	UME	1.6.2026	Y
EURAMET	DMDM	6.7.2026	Y

EURAMET	MIRS	10.8.2026	N
APMP	NPLI	14.9.2026	Y
GULFMET	SASO-NMCC	19.10.2026	Y
EURAMET	PTB	23.11.2026	N

3.3 Reception, transportation, insurance, costs

The artifact shall be examined immediately after receipt. The condition of the artifact shall be noted (a microscope image or a drawing in case the artifact is damaged) and all discrepancies communicated to the pilot laboratory before the start of the measurements. The fax form in Appendix A should be used for this purpose, which may also be emailed to the pilot laboratory.

In order to prevent any damage, the artifacts should only be handled by authorized persons and stored in a proper way.

The artifacts shall be examined before dispatch and any change in condition during the measurement shall be communicated to the pilot laboratory.

Please inform the pilot laboratory and the next laboratory via fax or e-mail when the artefact is about to be sent to the next recipient.

The artifacts shall be packed according to the instructions in the related package. Ensure that the content of the package is complete before shipment. Always use the original packaging.

Fig. 1: Transport suitcases of the artefacts. Left: long scales, right 100 mm scale

The packaging for the artifacts is suitably robust to protect the artifacts from being deformed or damaged during transit. The long artefacts (300 and 400 mm scales) are stored in plastic boxes, which are encased in sealed plastic suitcases. See Fig. 1 left for details. A key to open the plastic box of the 400 scale are also located in its suitcase. These suitcases also contain a data logger, an USB stick, clean room gloves and one of the two short test scales (see section 4.1.4 for details). The data logger records temperature, pressure and humidity with a rate of 1 value per sec. In case of a shock event, the acceleration of all 3 directions will be recorded with a rate of about 1.5 ksamples / sec. Assuming that not too many shock events will occur, the recording can proceed for 20 months, before the battery needs to be reloaded. Usually, the pilot lab will take care of collecting this data and charging the battery. However, if for some reasons large delays occur, the pilot may ask the participant that currently has the artefacts, to charge the battery. For this purpose, the USB-cable required to charge the battery is also in the suitcase. The USB stick will contain the documents related to the comparison and the manual of the data logger.

The 100 mm scale is wrapped in lens tissue and stored in a wooden box. See Fig. 1 right for details. It is also encased in an aluminum suitcase.

The artifacts will be accompanied by a suitable customs carnet (where appropriate) and documentation identifying the contents. The ATA carnet shall always be shipped with the package, never inside the box, but apart. Please be certain, that when receiving the package, you also receive the carnet! Every time the carnet is used, it is stamped TWICE – on exit from one country and on entry into the next. Please examine the carnet and assure that the transportation company used has arranged for correct stamping of the carnet. Failure to ensure both stamps (exit, entry) subjects the carnet holder to a penalty.

Transportation is at each laboratory’s responsibility and cost. Each participating laboratory covers the costs for its own measurements, transportation and any customs charges as well as for any damages that may have occurred within its country. The overall costs for the organization, initial and interim measurements and the processing of results are covered by the pilot laboratory. The pilot laboratory has no insurance for any loss or damage of the standards during transportation.

After measurement, the artefacts should be sent to the next participant as quickly as possible. After shipping the artifacts, the shipping information should be emailed to the next participant and pilot.

4 Artefacts

4.1 Description of artefacts

4.1.1 <u>100 mm line scale</u>

The 100 mm quartz line scale has been provided by NPL. The artefact is shown in Fig. 2.

Fig. 2: NPL line scale

The width of the scale lines is approx. 10 µm. The location of the measurement trace is provided by two parallel horizontal lines at the beginning and at the end of the scale. The distance between those 2 lines is approx. 50 µm. Some details of the scale are provided in Fig. 3.

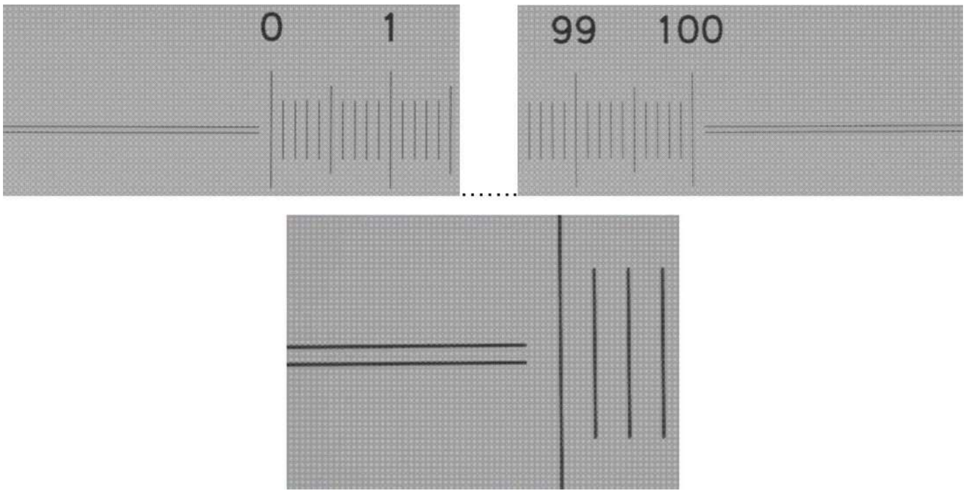


Fig. 3: Details of horizontal alignment lines

The dimensions of the artefact are shown in Fig. 4.

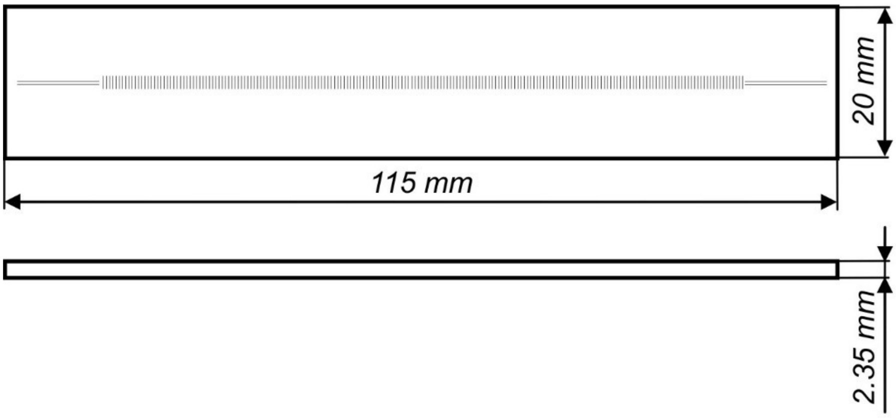


Fig. 4: Dimensions of the 100 mm line scale.

The artefact is shipped without any special mounting fixtures. It is recommended to support the measurement objects at the Airy points (distance of x = 0.2113·L from both ends), held only by their gravity forces. It is not allowed to use any type of glue or wax for mounting the scale. If additional clamping of the scale is required during measurement, e.g. because of a strongly accelerating carriage, it is recommended to lightly pinch the scale on the sides at one of the Airy support points. If other support or clamping conditions are applied during measurement, it is the responsibility of the participant to refer his results to the Airy point support conditions. Because this line scale is rather short it is sufficient to use the standard values for the thermal expansion and length compressibility of quartz, e.g. $\alpha = 5 \cdot 10^{-7}$ K^{-1} and $\kappa = -8.9 \cdot 10^{-10}$ hPa^{-1}.

4.1.2 <u>300 mm line scale</u>

This Heidenhain Zerodur standard is kindly provided by METAS for the use in this comparison. Samples of the same design also provided by Heidenhain were already used in the Nano3 comparison (2000-2003). The layout is shown in figure 5. The chromium lines have a nominal width of about 4 μm. Here only the main graduation is used. It is 282 mm long and contains a total of 283 lines. It also has lateral line structures to define the measurement trace in front and behind the main graduation, which are shown in Fig. 6. Note that there is a line before the line 0 and behind the line 280 respectively.

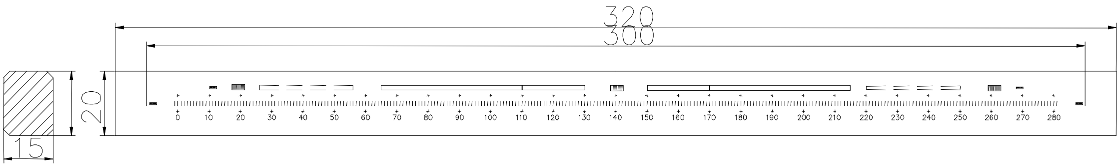


Fig. 5: Layout of the 300 mm line scale (Nano 3 design). Main graduation: 280 mm length, 1 mm pitch, CD 4 µm, 1 mm line length.

the measurement trace in front and behind the main

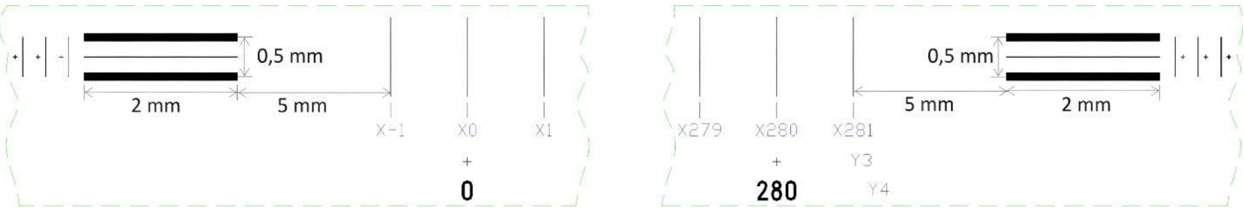


Fig. 6: Details of the horizontal alignment lines

It is also supported at the Airy points (distance of x = 0.2113·L from both ends). The thermal expansion α and the length compressibility κ are:

α = [1,826 - 0,229(t-20)]·10^{-8} K^{-1}, U_α = 6·10^{-10} K^{-1}

κ = -5,76·10^{-10} hPa^{-1}, U_κ = 0,08·10^{-10} hPa^{-1}

These values were determined for gauge blocks made out of the same piece of material as the Nano3 line scales. Heidenhain confirmed that the line scale was produced from the same charge / very similar material.

4.1.3 <u>400 mm line scale</u>

This line scale was donated by the Carl Zeiss Jena GmbH. It was produced from float glass F7. The layout is shown in Fig. 7. This scale is supported as indicated in Fig. 7, i.e. *not* at the Airy points.

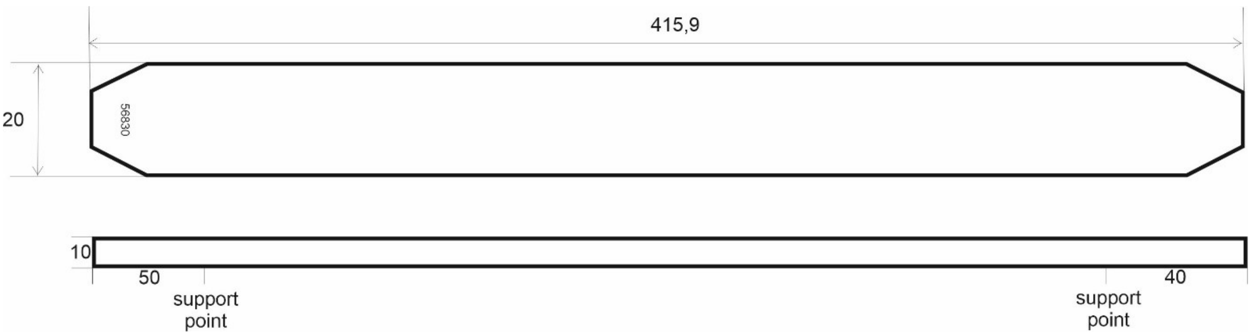


Fig. 7: Layout of the 400 mm line scale.

The position of the support points were marked using a pencil.

It contains a graduation of 400 mm length consisting of 10 μm wide lines with a nominal distance of 1 mm. The thermal expansion α and the length compressibility κ are:

$\alpha = 10{,}2\cdot10^{-6}\,K^{-1}$, $U_\alpha = 0{,}2\cdot10^{-6}\,K^{-1}$

$\kappa = -9{,}5\cdot10^{-10}\,hPa^{-1}$, $U_\kappa = 1\cdot10^{-10}\,hPa^{-1}$

The thermal expansion has been measured by Zeiss and will be redetermined with the Nanometer Comparator at PTB. The length compressibility was calculated using the values provided in the data sheet according to

$\kappa = -(1-2\nu)/E$,

where ν denotes the Poisson number and E the young modulus. The scale is over 20 years old but has not been measured on a regular basis. Therefore, the pilot laboratory will measure the scale frequently during this comparison to be able to provide an ageing correction if required.

4.1.4 Test scales

Finding suitable line scales for the use in this comparison has been a difficult and time-consuming task. Heidenhain no longer provides line scales that follows the classical design of isolated chromium lines on some glass substrate. Instead Heidenhain offered to produce novel scales that use phase shift effects to generate line signals because these can be produced using their standard production processes up to a length of 450 mm. The highest accuracy scales provide a very good contrast and are easy to clean. In addition, because the geometrical edge height is very low (below 10 nm), the width can be calibrated by AFM measurements.

However, some NMIs reacted reluctantly to the suggestion to use the scales. Therefore, 2 test samples, one with a nominal width of the graduation lines of 4 μm and one with 10 μm, will be shipped together with the longer traditional line scales (280 mm and 400 mm) as well. The have the dimensions (22.6 mm x 87.0 mm x 6.35 m). A picture is shown in Fig. 8. There also the lateral alignment marks used to define the measurement trace can be recognised.

Fig. 8: Picture of the phase shifting test scale.

5 Measuring instructions

5.1 Mounting the artefacts

Within this comparison it is recommended to support the measurement objects at the suggested support points, held only by their gravity forces. These are provided for the different artefacts in chapter 4.

5.2 Handling the artefact

5.2.1 General handling

Open the transport container carefully and only in clean environment. Use clean room gloves which are in the box in order to handle the scale and **never touch the top surface of the scale.** It is not allowed to use any type of glue or wax for fixing the scale. When not in use, place the scale back into its container to avoid dust or dirt deposits.

5.2.2 Cleaning

Cleaning must be avoided! No cleaning of the scales should be tried besides blowing away dust particles using dry, clean air or other clean gases. Try to keep the flow parallel to the graduation lines. Especially, rubbing the surface with soft tissues or any other firm physical contact will possibly damage the line structures of the standards. Application of solvents such as acetone or alcohol is strictly forbidden.

If it seems to be necessary to clean the scale before the measurement, please get in contact with pilot laboratory before taking any action in cleaning.

5.2.3 Temperature measurement of the artefact

For temperature measurement of the artefact, it is not allowed to fix the temperature sensor to the artefact using any type of glue or wax or clamping fixture because it will be the cause of severe contamination or deformation of the artifact. It is recommended to measure the temperature of the dummy material or the mounting fixtures.

5.2.4 Storage

Use the original transportation container to avoid dust deposits. Always try to keep the artefact under good measuring room conditions, i.e. within the room, where it will be calibrated.

5.3 Traceability

Length measurements should be traceable to the latest realisation of the metre as set out in the current "*Mise en Pratique*". Temperature measurements should be made referring to the International Temperature Scale of 1990 (ITS-90).

5.4 Measurands

The measurand is the distance between the center line position of the reference line (position "0") and the center line position of the measured line minus their nominal values. To increase comparability of the results, all measurements should be performed over the defined sections (see descriptions of the different artefacts below) with a width of approx. 100 µm. That is, it should be tried to apply an effective slit height or CCD image window **height of 100 µm** for the analysis of measurements. If the effective height cannot be set exactly to 100 µm, a value close to it should be chosen. In any case it is the responsibility of the participant to refer its results to those that would be obtained if a window height of 100 µm would have been used. In the following a more detailed description of the measurement task for each of the line standards is provided.

5.4.1 100 mm line scale

Figure 9 shows the location of the proposed measurement window relative to the 2 horizontal alignment lines.

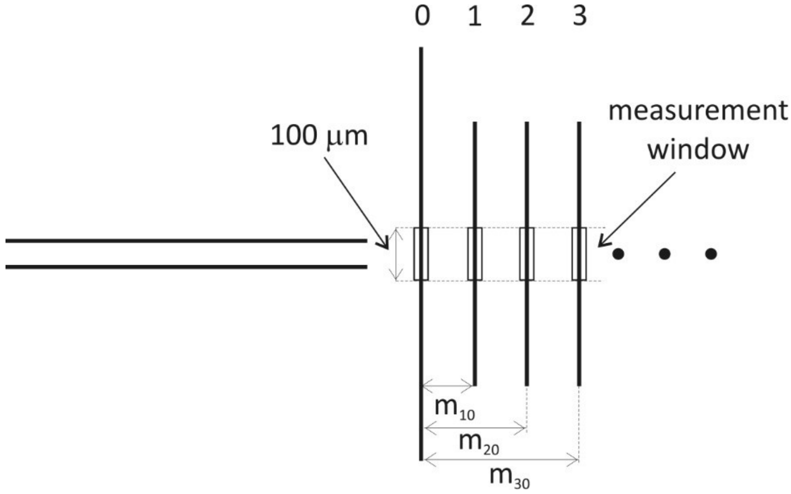


Fig. 9: Definition of the measurement window for the 100 mm line scale.

The nominal distances of the lines to be measured are provided in Tab. 3.

Nominal distance from line 0 in mm									
1	2	3	4	5	6	7	8	9	10
20	30	40	50	60	70	80	90	100	

Tab. 3: Definition of lines to be measured on the 100 mm line scale.

5.4.2 300 mm line scale

As already mentioned in the description of the scale there are 283 lines. The 1st and the last line are not measured. Here also a measurement window of 100 µm height is used as illustrated in figure 10.

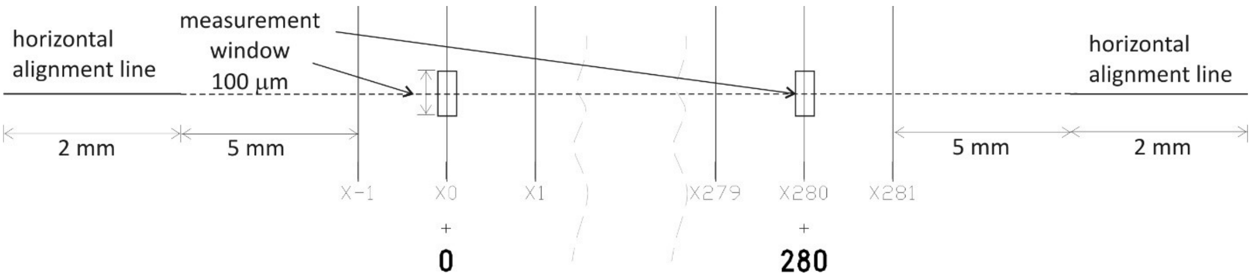


Fig. 10: Definition of the measurand on the 280 mm line scale.

Note: There are 3 horizontal alignment lines at each side of the scale. Here the one in the mid position, which is about 10 µm wide, is to be used. To restrict the number of lines a measurement distance of 10 mm is chosen. That is the distances of the lines with nominal distances of 10 mm, 20 mm, 30 mm … 280 mm from the line x0 are to be measured. The measured distances minus their nominal values are to be reported.

5.4.3 400 mm line scale

This line standard offers a graduation line every 1 mm. To restrict the number of lines to be measured, the nominal distance of 20 mm is chosen. Thus, the distances of the line at 20 mm, 40 mm … 360 mm, 380 mm and 400 mm from the zero line minus their nominal values using a measurement window of 100 µm in height (see fig. 11) are to measured. This scale has no lateral alignment marks so that the measurement line has to be defined in another way. On one side the midpoint of the numeral 8 of the scale number is used. On the other side there are marks / contaminations on the last line that can be employed. The definition of the zero line and the lateral position of the measurement trace are shown in Fig. 11.

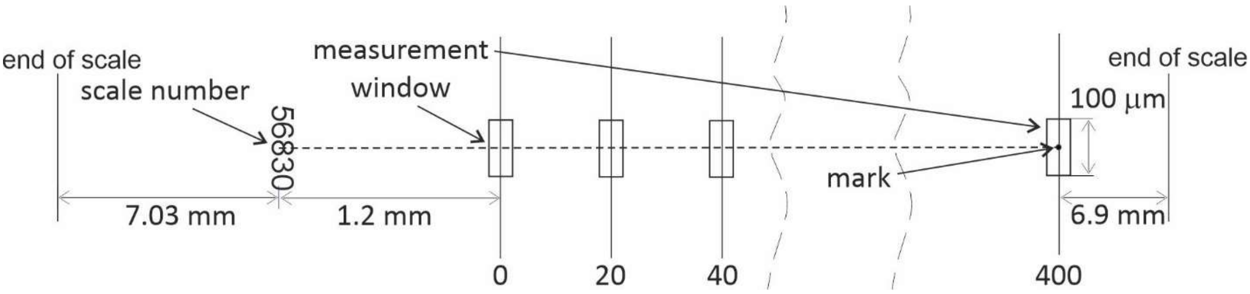
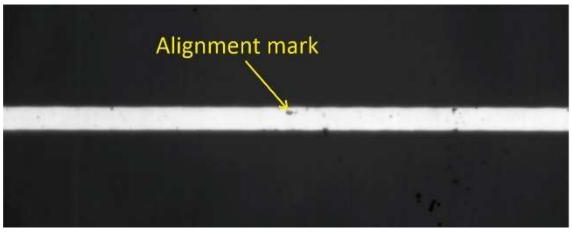


Fig. 11: Definition of the zero line and the measurement line at the 400 mm line scale.

Microscopic images of the alignment on the last line are provided in Fig. 12. The images were acquired with a 100x, NA=0.75 and 16x NA=0.2 microscope, respectively.



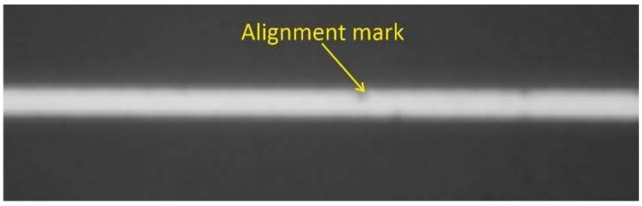


Fig. 12: Microscopic images of the mark on the last line used to define the measurement trace on the scale. Left: Image of 100x, NA=0.75 brightfield reflection type microscope. Right: Image of 16x, NA=0.2 microscope.

We like to note that missing lateral alignment marks on a line scale are not unusual so that similar arrangements to define a measurement trace have to be made with customers before the calibration.

5.5 Measurement uncertainty

The uncertainty of measurement shall be estimated according to the ISO Guide to the Expression of Uncertainty in Measurement (GUM). The participating laboratories are encouraged to use their usual model for the uncertainty calculation.

All measurement uncertainties shall be stated as standard uncertainties. If appropriate the corresponding effective degree of freedom might be stated by the participants. If none is given, ∞ is assumed. For efficient evaluation and subsequent assessment of CMC claims an uncertainty statement in the functional form (1) is preferred:

$$u\left(e_{\mathrm{c}}\right)=Q\left[a, b \cdot l_{\mathrm{n}}\right]=\sqrt{a^{2}+\left(b \cdot l_{\mathrm{n}}\right)^{2}} \; . \tag{1}$$

5.6 Reference condition

Measurement results should be referred to a reference temperature of 20 °C, standard pressure of 1013.25 hPa and the suggested sample support. For corrections the thermal expansion coefficients and length compressibility provided in chapter 4 of this document for each of the standards should be used.

6 Reporting of results

6.1 Results and standard uncertainties as reported by the participants

As soon as possible after measurements have been completed, the results should be communicated to the pilot laboratory. In any case the results must be reported **within six weeks** at the latest.

The measurement report forms in appendix C of this document will be sent by e-mail (Word document) to all participating laboratories. It would be appreciated if the report forms (in particular the results sheet) could be completed by computer and sent back electronically to the pilot. In any case, the signed report must also be sent in paper form by mail or electronically as a scanned pdf document. In case of any differences, the signed forms are considered to be the definitive version.

Following receipt of individual measurement reports the pilot will check the measurement results for any obvious deviations from preliminary reference values and inform the participant accordingly, to allow the participant to check his results for possible errors. Following receipt of all measurement reports from the participating laboratories, the pilot laboratory will analyse the results and prepare within 3 months a first draft A.1 report on the comparison. This will be circulated to the participants for comments, additions and corrections.

7 Analysis of results

7.1 Calculation of the KCRV

The key comparison reference values (KCRVs) are calculated as the weighted mean of the participant results for each of the line standards separately. In addition, the values will be calculated for each distance on each standard. The check for consistency of the comparison results with their associated uncertainties will be made based on the Birge ratio and the degrees of equivalence (DoE) for each laboratory and each line interval with respect to the KCRV will be evaluated using E_{n} values. Both procedures will be performed along the lines of the *CCL WG-MRA KC-report-template*. Because not all participants will measure all lines scales circulated the results obtained at the different line scales will be linked.

The main objective of this comparison is to provide reliable information on the degree of equivalence of line scale measurements performed by the participating institutes. The different institutes offer very different measurement ranges. To assure the equivalence of measurements made over larger measurement ranges as investigated in this comparison the different length scale realizations among the participants have to be in agreement. For a verification of this agreement, the measurement results of the participants have to be analysed further. The pilot laboratory proposes the following procedure for analysis of the comparison results on all defined measurands, which are given as deviations of lengths **d*l*** from nominal values $\boldsymbol{L}_{\mathbf{nom}}$

1) Input data:

- deviation from nominal length, referred to reference line: $\mathrm{d}l_{\mathrm{i,j}}$
- combined standard uncertainty for $\mathrm{d}l_{\mathrm{i,j}}$: $u_{\mathrm{d}l\mathrm{i,j}}$

  with: i = line number of measurand in question; i = 0 ... n-1

  and j = participant number; j = 1 ... m

2) Least squares method to deduce mean length deviations as reference values:

It is assumed and it will also be checked by means of statistical test procedures that the observed measurement results will be normally distributed. If this assumption is valid then the reference length deviation data can be determined by means of least squares approximation (LSA) methods. If the measurement objects are stable, the result of the LSA method simply is the weighted mean of all results, with the weights defined by the inverse square of the standard uncertainties:

- reference length deviations:

$$\mathrm{dl}_{\mathrm{ref,\,i}} = \frac{\sum_{j=1}^{m} u^{-2}_{\mathrm{dli,j}} \cdot \mathrm{dl}_{\mathrm{i,j}}}{\sum_{j=1}^{m} u^{-2}_{\mathrm{dli,\,j}}} \qquad (2)$$

- uncertainty of reference length deviations:

$$u_{\mathrm{dlref,\,i}} = \frac{1}{\sqrt{\sum_{j=1}^{m} u^{-2}_{\mathrm{dli,\,j}}}} \qquad (3)$$

3) Differences from reference values:

For all participants, the differences from the reference length deviations and their uncertainties are calculated. For these differences the influence of possible line position irregularities and mean pitch deviations of the individual material measures of length used is now widely eliminated. The differences therefore do only contain the information of the length scale realizations and the reproducibilities of centre line position measurements of the participants.

- difference to reference length deviations: $\Delta \mathrm{dl}_{\mathrm{i,\,j}} = \mathrm{dl}_{\mathrm{i,\,j}} - \mathrm{dl}_{\mathrm{ref,\,i}}$ (4)
- uncertainty of this difference: $u_{\Delta \mathrm{dli,\,j}}$

4) Determination of length dependent deviations from reference values:

The differences as calculated in 3) will be further analyzed to determine their length dependency. The length dependent deviations are a measure of the different length scale realizations of the participants. An unweighted linear least squares fit to the data $\Delta dl_{i,\,j}$ over L_{nom} yields slope values m_j which represent the deviations of the individual length scale realizations from the common weighted mean. The uncertainty u_{mj} will be estimated on the basis of the statistical uncertainty $u_{stat,mj}$ resulting from the unweighted fit (type A) and the length dependent uncertainty contributions $u_{l,k}$ quoted by the participants (type B):

- linear least squares fit to data: $\Delta dl_{i,\,j}$ over L_{nom}: => slope m_j

- uncertainty of m_j: $u^2_{mj} = u^2_{stat,mj} + \Sigma\, u^2_{l,k}$ (5)

5) <u>Degree of equivalence of length dependent deviations:</u>

The E_N-criterion provides information on the degree of equivalence (at a 95% confidence level) of the different length scale realizations of the participants.

The definition of the E_N-criterion is (here x_{lab} and x_{ref} are assumed to be uncorrelated):

$$E_N = \frac{1}{k}\frac{x_{lab} - x_{ref}}{\sqrt{u^2_{xlab} + u^2_{xref}}}\text{; k = coverage factor}$$

In our case x_{ref} is equal to m_{ref}, which is zero by the above definition. However, the values m_j and m_{ref} are now correlated and thus the E_N-value has to take into account this correlation (u^2_{mref} usually is small, it is given by the statistical uncertainty of a weighted linear regression to $dl_{ref,i}$ over L_{nom}):

$$E_{N,\,j} = \frac{1}{k}\frac{m_j}{\sqrt{u^2_{mj} - u^2_{mref}}} \quad (6)$$

As long as $|E_{N,j}| <1$ with $k = 2$, the result of participant number j is in satisfactory agreement (equivalent) with the reference length scale realization as defined within this comparison. This concept can easily be extended to define a measure of the pairwise equivalence between two participants (assumed to be uncorrelated):

$$E_{N,\,j,\,j+1} = \frac{1}{k}\frac{m_j - m_{j+1}}{\sqrt{u^2_{mj} + u^2_{mj+1}}} \quad (7)$$

6) <u>Determination of length independent deviations:</u>

Although the differences in realization of the length scale are of major importance for this comparison, another quality measure for the results is the observed spread around the reference values. The residuals of the linear regression ($\Delta dl_{i,\,j}$ - m_j*L_{nom}) can be used to calculate their standard deviation $\sigma_{res,j}$ as a measure describing the length independent degree of equivalence with the reference values $dl_{ref,i}$. The $\sigma_{res,j}$-values will be quoted and they are expected to be comparable with the length independent uncertainty contribution estimated by the participants.

7) <u>Determination of overall deviation from reference values:</u>

We propose the term $\Delta_j = (\sigma_{res,j} + m_j{*}L_{nom})$ to be regarded as an overall measure for the degree of equivalence of the results of participant j with the reference values for the measurand in question. The values for Δ_j and $\sigma_{res,j}$ will be quoted in the final report to give further information about the comparison results. However, we consider the differences in the length scale realizations to be of primary importance for customers of NMI´s and therefore would propose to limit the application of formal criteria for equivalence to reference values and pairwise equivalence, like the E_N-criterion, to the length dependent results as given in 5).

If necessary, artifact instability, correlations between institutes, and the necessity for linking to another comparison will be taken into account.

7.2 Artefact instability

The stabilities of the artefacts were partly not accessed before the comparison. In addition, during the transportation the artefacts may be subject to temperature changes or mechanical shock that may lead directly to changes of their length or trigger processes that introduce length changes. Therefore, the instability of the artefact must be determined in course of the comparison. For this check the measurements of the pilot laboratory are used exclusively, and not those of any of the other participants. To this data a low order polynomial, preferable a straight line, is fitted and an approximation together with its uncertainty is determined.

Three cases can be foreseen:

a) The regression model is an acceptable drift model and the absolute drift is smaller than the related uncertainty. The artefact is considered to be stable and no modification to the standard evaluation procedure will be applied. Therefore, the results of the pilot's stability measurements will not influence the numerical results in any way.
b) The regression model is an acceptable drift model and the absolute drift is larger than the uncertainty of the model, i.e. there is a significant drift of the artefact. In this case an analysis similar to [Nien F Z et al. 2004, Statistical analysis of key comparisons with linear trends, *Metrologia* **41,** 231] will be followed. The pilot's result influences the KCRV by the drift correction only, not by the measured absolute distances.
c) Regarding the uncertainties of the pilot's measurements the data is not compatible at all with a simple drift model. In this case the artefact is either unpredictably unstable or the pilot has problems with its measurements. The pilot will measure a stable artefact each time an artefact of the comparison is measured to exclude the occurrence of problems with its measurements. However, if severe problems appear TC-L has to determine the further approach.

7.3 Correlation between laboratories

Since the topic of this project is the comparison of primary measurements, correlations between the results of different NMIs are unlikely. Thus, correlations are normally not considered in the analysis of this comparison. However, if a significant drift exists then correlations between institutes are introduced by the analysis proposed in section 7.2 and will be included in the analysis of the comparison results.

7.4 Linking of result to other comparisons

The CCL task group on linking CCL TG-L will provide guidance for linking the results of the different groups within this comparison and this comparison to any other key comparison within CCL for the same measurement quantity and will support the pilot laboratory to perform the linking.

Appendix A – Reception of Standards

Telefax Telefax Telefax Telefax Telefax

To:

Physikalisch-Technische Bundesanstalt Braunschweig
Department 5.2
Bundesallee 100
D-38116 Braunschweig
Fax: ++49 531 592 5205
e-mail: rainer.koening@ptb.de

From: (participating laboratory)

We confirm having received the 100 mm line scale / 300 mm line / 400 mm line standard of the EURAMET.L-K7.n01 *line scale comparison* on ....(date).

After visual inspection

no damage has been noticed.

the following damage(s) must be reported: (please specify scale, position, size and kind of damage; if possible add image of damage(s), if necessary use additional page for description)
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....
....

Laboratory:

Date: .... Signature:..

Appendix B – Measurement report

In A) a free description can be given including drawings and references, whereas in B) a tabular form has to be filled out. Please add requested line profile image on "0" line under A), see 4).

A) Description of the measurement methods and instruments..

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Laboratory:

Date: .... Signature:..

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B) Tabular description of the measurement methods and instruments

Line detection

Parameters	Parameters used for the measurement
Microscope type: (brightfield, confocal, interference, transmission, reflected, etc)	
Light source	
Wavelength(s)	
Polarization	
NA of illumination	
Camera type / Interface	
Pixel size	
Slit length	
Slit width	

Laboratory:

Date: .... Signature:..

Aperture/magnification	
Correction state of the objective (Achromat, Aprochromat, Plan Aprochromat etc)	
Focus criterion / focussing uncertainty	
Measurement velocity	
Sampling frequency (image/interferometer)	
Synchronisation of line signal / image acquisition and interferometer	
Edge detection criterion / algorithm	
Edge detection short term repeatability (1s)	

Displacement measurement

Parameters	Parameters normally used for the measurement equipment	Achievable measurement uncertainty for measurands
Interferometer light source / wavelength		
Interferometer type		
Resolution of displac. Interferometer		
Nonlinearity of displacement interferometer		
Diffraction / wavefront related errors		
Interferometer medium		
Refractive index:		
=> refractometer:		

Laboratory:

Date: .... Signature:...

=> refractive index correction formula:		
Air temperature		
Air pressure		
Air humidity		
CO_2-content		
Angular deviations (Yaw, /Pitch) of slide		
Abbe offset		
Alignment error:		
Scale		

Other measurement conditions

Parameters	Parameters normally used for the measurement equipment	Achievable measurement uncertainty for measurands
Scale temperature		
Air pressure		
Number of repeat measurements in one scale position		
Number of scale orientations		
kind of support		
clean room class		

Laboratory:

Date: .... Signature:...

Measurement results for scale:

☐ **100 mm** ☐ **280 mm** ☐ **400 mm**

Measurand: Deviation from nominal total length

Nominal distance from zero line *l* (mm)	Deviation from nominal total length *dl* (nm)	uncert. (1σ) u_c (nm)	eff. deg. of freedom ν_{eff}

The length deviation value is referred to the position of the zero reference line, thus the uncertainty of determination of the reference line position has to be taken into account for the uncertainty estimation of the measured deviations from nominal total length.

Combined standard uncertainty: $u_c(dl)$ =

Effective degree of freedom: $\nu_{eff}(dl)$ =

Expanded uncertainty: $U_{95}(dl$